

A Systematic Review of Urban Heat Island (UHI) Impacts and Mitigation: Health, Equity, and Policy

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Abstract

Urban heat islands pose intensifying threats to public health, equity, and urban livability as climate change amplifies temperature extremes. This systematic review synthesizes evidence from 33 primary studies (2021–2025) examining health impacts, mitigation strategies, and policy integration. The analysis focuses on interaction mechanisms, specifically how mitigation strategies differentially reduce health burdens across vulnerable populations, to advance systems-level understanding of urban heat dynamics. Following PRISMA guidelines, the review examined these mechanisms across three interconnected domains: health burdens, physical mitigation effectiveness, and post-pandemic policy synergies. Findings reveal profound inequities in heat exposure and associated health outcomes, with disadvantaged populations experiencing 26–45% higher heat-related mortality risk and 3–4 °C greater exposure than affluent communities, even after controlling for income. Physical mitigation strategies show measurable effectiveness, providing 1–6 °C cooling from green infrastructure and 2–22 °C from cool surfaces. Optimal interventions vary by socioeconomic context, with urban trees being more effective in disadvantaged areas, while cool roofs are better suited to affluent zones. COVID-19 natural experiments demonstrated 30–50% anthropogenic heat reductions, revealing strategic opportunities for integrating heat mitigation with 15-Minute City planning and work-from-home normalization. Effective implementation requires moving beyond isolated interventions toward spatially differentiated, equity-centered strategies aligned across planning, transportation, and governance domains. The post-pandemic period presents a critical window for embedding heat mitigation into broader urban transformation agendas.

Keywords: urban heat island; environmental justice; green infrastructure; 15-Minute City; climate adaptation; systematic review



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1. Introduction

Urban heat islands represent one of the most significant climate-related challenges facing contemporary urban environments, with intensifying effects as global urbanization accelerates and climate change amplifies temperature extremes. The phenomenon occurs when urban areas experience elevated temperatures compared to their surrounding rural counterparts, primarily due to altered land surfaces, reduced vegetation cover, increased heat-absorbing materials, and anthropogenic heat generation from human activities [1,2]. This temperature differential, ranging from 1 to 12 °C in major cities worldwide, creates cascading impacts across public health, economic systems, social equity, and urban livability.

Urban heat island intensity is measured using multiple complementary metrics that capture distinct dimensions of thermal exposure. Air temperature-based UHI (AUHI) reflects atmospheric conditions experienced directly by populations at breathing height, typically measured at 1.5–2 m above ground, and is commonly used in epidemiological studies linking heat exposure to health outcomes [3]. Surface urban heat island (SUHI) intensity, derived from satellite-based land surface temperature measurements using thermal infrared sensors such as MODIS and Landsat, captures spatial patterns of heat absorption and emission associated with land cover characteristics and urban form rather than air temperature experienced by humans [4,5]. Cumulative measures such as UHI degree-hours integrate both intensity and duration of heat exposure, which are critical for assessing physiological stress during prolonged heat events [6,7]. These metrics are not interchangeable: SUHI values typically exceed AUHI by 5–10 °C and exhibit different spatial patterns, as surface temperatures respond more rapidly to solar radiation and material properties while air temperatures reflect broader atmospheric mixing processes [8–10]. Recognizing these distinctions is essential for interpreting variability across studies in this review, as health impacts primarily correlate with air temperature exposure [11], while mitigation strategies are often evaluated using surface temperature reductions [12,13], requiring careful translation between metrics when synthesizing interdisciplinary evidence.

The urgency of addressing UHI effects has intensified as recent evidence reveals accelerating health burdens and economic costs. Globally, approximately 489,000 heat-related deaths occur annually, with 45% in Asia and 36% in Europe [14]. The 2022 European summer alone witnessed an estimated 61,672 heat-related excess deaths [15]. In the United States, heat-related mortality reached new highs in 2021–2022, with over 14,000 Americans dying directly from heat-related causes since 1979 [16]. Recent projections indicate that heat-mortality levels characteristic of a 1-in-100-year summer in the climate of 2000 can now be expected once every 10–20 years in the climate of 2020, with return periods projected to shorten further under 1.5 °C and 2 °C warming scenarios [17]. Urban heat islands amplify these risks substantially: studies estimate that urban heat island effects account for over 50% of total heat-related mortality during extreme events in major metropolitan areas [3].

Urban heat islands form through multiple interacting physical processes. Built surfaces with high thermal mass and low albedo absorb and store solar radiation during daytime, releasing heat gradually during nighttime hours and preventing nocturnal cooling [18]. The replacement of natural vegetation with impervious surfaces eliminates evapotranspirative cooling while increasing sensible heat flux [19]. Urban canyon geometry created by tall buildings traps longwave radiation, creating positive feedback that amplifies warming [20,21]. Anthropogenic heat from vehicles, buildings, and industrial processes directly inputs energy into the urban atmosphere, with contributions varying substantially by land use intensity and activity patterns [22]. Temperature differences between urban centers and surrounding areas can reach 15–20 °F (8–11 °C) during peak periods, with variations strongly correlated to vegetation cover, built-up area, and population density [23,24].

Beyond aggregate mortality statistics, emerging research reveals profound inequities in heat exposure structured by race, income, and social vulnerability rather than random distribution. Spatial analyses demonstrate that persons of color live in census tracts with higher surface urban heat island intensity than non-Hispanic whites in the vast majority of examined U.S. cities, with disparities persisting after controlling for income [25]. Low-income urban areas have been found to be 5–12 °F hotter than higher-income neighborhoods due to fewer trees and parks and more asphalt, which retains heat [26,27]. Similar findings were found in a mapping of over 60 US cities, which confirms that poor communities tend to be hotter than wealthier neighborhoods, with these low-income areas often lining up with historical redlining policies [28]. Global analyses also reveal that cities in the Global

South experience larger increases in extreme heat days despite contributing far less to greenhouse gas emissions driving climate change, highlighting climate justice concerns [29]. Studies from tropical cities further document these equity patterns, with [30] finding that heat-related health symptoms, including heat exhaustion and respiratory ailments, varied significantly across neighborhoods in Kuala Lumpur, corresponding to differences in vegetation cover and building density.

Research on physical mitigation strategies spans green infrastructure, cool surfaces, and blue infrastructure interventions. Meta-analyses indicate that urban green spaces, including parks, green roofs, and street trees, can lower air and surface temperatures by as much as 5 °C, though cooling efficiency varies substantially by plant density and spatial distribution [31,32]. Urban parks demonstrate clear dose–response relationships between size and cooling magnitude, with larger parks providing proportionately greater cooling [33]. Cool surface interventions, including reflective roofs and pavement, can reduce urban air temperatures by 1–3.5 °C through increased solar reflectance [34]. However, cool surfaces face rapid performance degradation and mean radiant temperature trade-offs requiring careful site-specific evaluation [35,36]. Extending this evidence, ref. [37] synthesized 202 studies on 51 types of green–blue–gray infrastructure, identifying botanical gardens as the most cooling-efficient (mean 5.0 ± 3.5 °C) and highlighting that interconnected green corridors enhance overall cooling performance. However, mitigation effectiveness depends substantially on local climate context and human thermal perception. Ref. [38] demonstrated that in tropical Kuala Lumpur, over half of urban dwellers reported thermal discomfort despite strong adaptive behaviors, with urban morphology and land cover patterns significantly influencing outdoor thermal comfort levels independently of absolute temperature reduction.

Despite substantial research examining urban heat islands from health, physical science, environmental justice, and policy perspectives, knowledge remains siloed within disciplinary boundaries. Public health researchers document mortality and morbidity outcomes but rarely engage with physical mitigation effectiveness or implementation mechanisms [39,40]. Climate scientists and urban planners evaluate cooling interventions through technical performance metrics while often overlooking distributional consequences [41]. Scholars analyzing exposure disparities infrequently connect findings to specific mitigation strategies or governance reforms [42]. These disconnected research streams mirror institutional structures where heat, transportation, land use, and economic development are assigned to separate agencies with distinct mandates, funding streams, and performance metrics [43]. Effective heat mitigation requires both integrated knowledge frameworks and governance mechanisms enabling multi-sectoral collaboration across multiple objectives simultaneously [44,45].

The COVID-19 pandemic created unprecedented natural experiments, particularly during lockdown periods, while also accelerating longer-term structural shifts in work patterns that extend into the post-pandemic phase. In this review, post-pandemic evidence encompasses both short-term lockdown-induced reductions in anthropogenic heat and more persistent changes in urban systems, including the normalization of remote work and evolving urban planning approaches. Lockdown measures and work-from-home transitions reduced transportation activity and associated anthropogenic heat emissions, demonstrating that human activity patterns constitute first-order controls on urban temperatures, particularly in dense commercial districts [46,47]. Remote work adoption stabilized around 20% of working days post-pandemic, representing a fourfold increase from pre-pandemic levels, with this structural shift dispersing economic activity away from city centers [48–50].

These shifts coincided with the growing prominence of proximity-based urban planning frameworks, such as the 15-Minute City concept adopted by Paris in 2020, which emphasizes walkable access to daily necessities [51]. This design inherently reduces motorized transportation while creating opportunities for green infrastructure integration along pedestrian corridors [52–54]. However, critics argue that implementations risk gentrification and displacement of lower-income residents due to rising property values [55,56]. Together, these changes illustrate how urban heat outcomes are shaped not only by physical mitigation measures, but also by broader policy choices governing mobility, land use, housing, and economic development.

Together, these changes in work patterns and urban planning paradigms illustrate how urban heat outcomes are shaped not only by physical mitigation measures but also by broader policy choices governing mobility, land use, housing, and economic development. The post-pandemic period therefore presents a critical opportunity to move beyond isolated assessments of individual interventions toward integrated, systems-oriented approaches that embed heat mitigation within wider urban transformation agendas.

This review advances the literature by adopting an explicit systems-oriented integration of urban heat research. Rather than synthesizing health impacts, mitigation technologies, or policy instruments in isolation, it conceptualizes urban heat islands as outcomes of interacting physical, social, and governance systems. The review introduces an integrative analytical lens connecting (i) health and equity impacts, (ii) context-dependent effectiveness of physical mitigation strategies, and (iii) cross-sectoral policy integration opportunities revealed through post-pandemic urban transformations. By examining how these domains interact, the review moves beyond descriptive aggregation toward explaining why mitigation outcomes vary across socioeconomic, climatic, and institutional contexts.

2. Methodology

2.1. Literature Search Strategy

This systematic review followed PRISMA 2020 guidelines and Cochrane Handbook standards to minimize bias through explicit, systematic methods. The review protocol was developed following established systematic review methodological standards, incorporating recent advances in interdisciplinary evidence synthesis and analytical approaches appropriate for synthesizing diverse methodological designs across complex urban interventions.

The search strategy employed multiple databases to ensure disciplinary coverage, including Web of Science Core Collection for multidisciplinary scope, Scopus, PubMed/MEDLINE for health-related UHI impacts, and specialized databases including GeoRef for geographical aspects, Environment Complete for an environmental science focus, and Sociological Abstracts for social science perspectives.

The search employed combinations of keywords organized into three primary categories, (1) urban heat island terms (“urban heat island” OR “UHI” OR “urban heat effect” OR “surface urban heat island” OR “SUHI”); (2) impact and mitigation terms (“health impact” OR “mortality” OR “morbidity” OR “environmental justice” OR “green infrastructure” OR “cool surface” OR “blue infrastructure” OR “mitigation” OR “adaptation”); and (3) policy integration terms (“urban planning” OR “15-Minute City” OR “work from home” OR “remote work” OR “COVID-19” OR “policy integration” OR “governance”), with proximity operators and field codes optimized for each database platform. Boolean operators (AND, OR) were used to combine search terms, and wildcard symbols (*) enabled capture of term variations.

The search prioritized studies published in 2021–2025 to capture recent developments in UHI research, particularly post-COVID-19 insights regarding anthropogenic heat and emerging policy frameworks, including 15-Minute City concepts and work-from-home

arrangements. Geographic coverage emphasized studies from diverse climate zones and urban contexts to enhance generalizability, encompassing cities across various stages of UHI mitigation implementation. The final search was conducted in December 2025.

2.2. Study Selection Criteria

Studies were systematically evaluated against predefined inclusion and exclusion criteria to ensure relevance and methodological rigor. Table 1 presents the criteria applied during the screening process.

Table 1. Inclusion and exclusion criteria for study selection.

Criterion Domain	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed academic journal articles	Review articles, meta-analyses, commentaries, editorials, conference proceedings, dissertations, gray literature
Publication Period	Published between January 2021 and December 2025	Published before 2021 or after 2025
Research Type	Primary empirical research (field measurements, remote sensing analysis, modeling studies, epidemiological analyses)	Secondary research without original data collection or analysis
Geographic Focus	Urban areas with clear urban heat island context	Exclusively rural or suburban areas without urban heat island context
Spatial Scale	Neighborhood-scale, city-scale, or metropolitan-scale studies	Building-scale-only interventions without broader urban implications
Topic Relevance	Studies examining urban heat island phenomena, impacts (health, socioeconomic), mitigation strategies, or policy integration	Studies not addressing urban heat islands or their management
Evidence Quality	Quantitative findings or evidence-based policy analysis with clear empirical basis	Studies lacking quantitative data or clear empirical findings
Language	Published in English	Published in languages other than English
Content Focus	Studies addressing health impacts, socioeconomic consequences, physical mitigation effectiveness, or policy integration opportunities	Studies focusing on topics outside review scope (e.g., exclusively atmospheric science without application implications)

Exclusion decisions prioritized maintaining a focus on urban heat island phenomena while retaining comparative studies establishing UHI baselines. Studies comparing urban and rural areas were included when examining UHI effects (e.g., quantifying urban-rural temperature differentials or mortality disparities). Only studies focusing exclusively on rural or suburban environments without a UHI context were excluded. This approach retained 6 studies (18%) employing urban–rural comparisons while excluding studies examining rural heat exposure or suburban mitigation disconnected from urban thermal dynamics. Studies meeting all inclusion criteria and containing none of the exclusion criteria were retained for full-text review and potential inclusion in the systematic review.

2.3. Study Selection and Data Extraction

The study selection followed a multi-stage screening process illustrated in Figure 1. First, duplicate records were identified and removed using Mendeley (Elsevier, Amsterdam, The Netherlands), supplemented by manual verification. Second, titles and abstracts of remaining records were screened against inclusion/exclusion criteria using Rayyan (Rayyan Systems Inc., Cambridge, MA, USA). Studies clearly not meeting criteria were excluded at this stage. Third, full-text articles of potentially eligible studies were retrieved and assessed for eligibility against inclusion criteria, with reasons for exclusion documented and categorized (Figure 1).

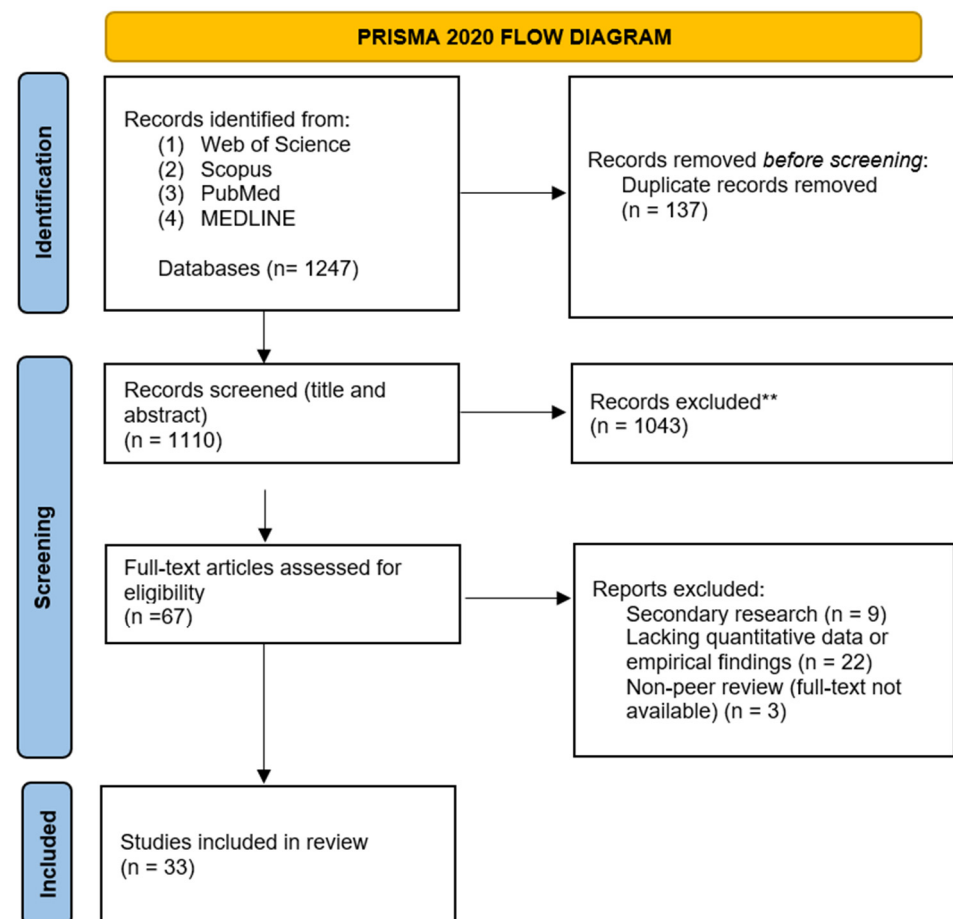


Figure 1. PRISMA 2020 flow diagram of study selection process. Note: ** Exclusions at screening stage were based on eligibility criteria applied during title and abstract review, including geographical scope, study design, publication timeframe, and relevance to research objectives.

The systematic search strategy yielded 1247 potentially relevant articles from all databases (Web of Science, Clarivate Analytics, Philadelphia, PA, USA; Scopus, Elsevier, Amsterdam, The Netherlands; PubMed/MEDLINE, National Library of Medicine, Bethesda, MD, USA). After removing duplicates ($n = 137$), 1110 articles underwent title and abstract screening. Following application of inclusion and exclusion criteria, 67 articles were selected for full-text review. Of these, 34 were excluded for the following reasons: secondary research without original data ($n = 9$), lacking quantitative data or empirical findings ($n = 22$), and non-peer reviewed or full-text not available ($n = 3$). Ultimately, 33 studies met all inclusion criteria and were included in the final systematic review.

A standardized data extraction form captured relevant information from each included study, including: (1) bibliographic information; (2) study characteristics (study type, location, geographic scale, time period); (3) methodological approach; (4) sample size and scope; (5) key findings with quantitative effect sizes where available; and (6) policy implications or recommendations. Data extraction and synthesis were conducted using Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA). Quality assessment procedures are detailed in Section 2.5. Four reviewers independently screened titles, abstracts, full texts and extracted qualitative and descriptive information from included studies, including study characteristics, methodological approaches, key findings, and policy implications. Discrepancies were resolved through discussion.

2.4. Synthesis Approach

Evidence synthesis employed a narrative approach organized thematically to address the three primary review objectives: (1) documenting health and economic impacts with attention to equity dimensions; (2) evaluating physical mitigation strategy effectiveness; and (3) analyzing policy integration opportunities. This approach was selected given the diversity of study designs, outcome measures, and geographic contexts, which precluded quantitative meta-analysis.

Synthesis across studies examined convergent findings, contradictory results, and gaps in the evidence base. For mitigation effectiveness, synthesis compared cooling magnitudes, spatial extents, temporal dynamics, and context dependencies across interventions. For health impacts, the synthesis examined dose–response relationships, vulnerability patterns, and economic valuations. For policy integration, synthesis assessed cross-sectoral collaboration through intervention scope spanning multiple domains, documented coordination mechanisms across departments, and explicit discussion of governance challenges. Studies demonstrating cross-sectoral approaches addressed multiple objectives simultaneously, revealing that governance fragmentation consistently hindered implementation, while integrated assessment frameworks facilitated coordination across contexts.

2.5. Evidence Weighting and Synthesis of Heterogeneous Evidence

Given methodological diversity spanning epidemiological analyses, remote sensing studies, field measurements, modeling, machine learning, and COVID-19 natural experiments, evidence synthesis required explicit consideration of how different study designs contribute to review objectives. Rather than applying uniform weighting, findings were evaluated based on methodological appropriateness for specific research questions, convergence across independent approaches, and transferability across contexts.

For health impacts and mortality outcomes, epidemiological studies with large samples and established dose–response modeling were weighted most heavily ($n = 6$). For mitigation effectiveness, convergent findings from remote sensing ($n = 5$), field measurements ($n = 5$), and modeling studies ($n = 7$) were synthesized to establish robust effect size estimates, with priority given to studies demonstrating multiple validation points or consistency across independent measurement approaches. For policy integration, studies documenting actual implementation experiences and governance mechanisms were prioritized over conceptual frameworks or simulations without empirical validation.

Evidence was characterized as showing strong convergence when multiple independent studies using different methodologies reported consistent findings across diverse geographic contexts. Evidence was noted as limited when based on single studies, single methodologies, or contexts with unclear transferability. For COVID-19 natural experiments, synthesis distinguished empirically demonstrated effects from speculative extrapolations to long-term planning, acknowledging differences between emergency restrictions and sustained voluntary behavior change.

This review focused on primary empirical studies (2021–2025) rather than existing systematic reviews or meta-analyses, enabling (1) capture of recent post-pandemic evidence not yet incorporated in prior syntheses; (2) avoidance of double-counting; and (3) cross-disciplinary integration from independent primary studies. This approach enabled evidence-based conclusions while acknowledging methodological diversity and context-specific factors moderating intervention effectiveness.

2.6. Risk of Bias and Quality Considerations

Given the interdisciplinary nature of the included studies, encompassing epidemiological analyses, remote sensing, field measurements, modeling, machine learning, and

COVID-19 natural experiments, a single standardized risk of bias assessment tool was not appropriate. We conducted qualitative assessments across eight study types following PRISMA 2020 guidance for heterogeneous evidence [57] (see Supplementary Materials).

Quality assessment was conducted separately for epidemiological studies ($n = 6$), health impact assessments ($n = 4$), remote sensing and systems analysis ($n = 5$), field measurements ($n = 5$), modeling and simulation-based studies ($n = 7$), machine learning and data science approaches ($n = 2$), COVID-19 natural experiments ($n = 3$), and cool surface/blue infrastructure field validation studies ($n = 4$). Studies were rated as low-to-moderate risk of bias across type-specific quality criteria. No included study was judged to have critical methodological limitations that would invalidate its findings. Detailed quality assessment results are presented in Section 3.1. All 33 studies were judged suitable for qualitative synthesis.

3. Results

Table 2 presents the characteristics and key findings of the 33 studies included in this systematic review, organized by study type, location, key findings, and key focus sample or scope.

Table 2. Summary of 33 included urban heat island studies (2021–2025).

Author	Title	Study Type	Location	Key Findings	Sample/Scope	Category
Cleland et al., 2023 [58]	Urban heat island impacts on heat-related cardiovascular morbidity: A time series analysis of older adults in US metropolitan areas	Time-series analysis with distributed lag non-linear models	North America: 120 metropolitan statistical areas, United States	Extreme heat increased CVD hospitalization risk by 1.5% overall. High UHI areas showed 2.4% increased risk vs. 1.0% in low UHI areas, accounting for 35% of total heat-related CVD burden.	Medicare enrollees aged 65–114, ZIP code-level daily CVD hospitalizations, 2000–2017, 37,028 heat-attributable CVD admissions	Health impacts
Cuerdo-Vilches et al., 2023 [59]	Impact of urban heat islands on morbidity and mortality in heat waves: Observational time series analysis of Spain's five cities	Observational time-series analysis with generalized linear models	Europe: Madrid, Barcelona, Seville, Valencia, Murcia, Spain	UHI effect in minimum temperatures ranged from 1.2 °C (Murcia) to 4.1 °C (Valencia). Statistically significant associations ($p < 0.05$) with maximum temperatures for mortality and hospital admissions in inland cities.	Daily natural-cause mortality and unscheduled emergency hospital admissions, 2014–2018	Health impacts
Ho et al., 2023 [60]	Urban heat island effect-related mortality under extreme heat and non-extreme heat scenarios: A 2010–2019 case study in Hong Kong	Case-crossover study with distributed lag non-linear models	Asia: Hong Kong, China	High UHI degree-hour areas showed increased mortality risk during extreme heat events. Temperature-mortality associations varied across 248 planning units based on UHI levels.	Non-external mortality and non-cancer mortality mapped to 248 tertiary planning units, 2010–2019 hot seasons	Health impacts
Simpson et al., 2024 [61]	Estimated mortality attributable to the urban heat island during the record-breaking 2022 heatwave in London	Health impact assessment with advanced urban climate modeling (WRF model at 1 km resolution)	Europe: Greater London, United Kingdom	During 10–25 July 2022 heatwave: 370 heat-related deaths (21% of total mortality). UHI contributed 141 deaths, representing 38% of heat-related mortality.	Record-breaking 2022 UK heatwave with temperatures exceeding 40 °C	Health impacts

Table 2. Cont.

Author	Title	Study Type	Location	Key Findings	Sample/Scope	Category
Wicki et al., 2024 [62]	Socio-environmental modifiers of heat-related mortality in eight Swiss cities: A case time series analysis	Case time-series analysis with conditional quasi-Poisson and distributed lag non-linear models	Europe: Zurich, Geneva, Basel, Bern, Lausanne, Lucerne, St. Gallen, Lugano, Switzerland	Mortality risk increased 31% (RR: 1.31) between 22.5 °C and 35 °C. Heat-related mortality risk at 35 °C was 26% higher in UHI areas vs. non-UHI areas.	53,593 deaths during warm season, 2003–2016, linked to 100 m resolution temperature estimates	Health impacts
Huang et al., 2023 [63]	Economic valuation of temperature-related mortality attributed to urban heat islands in European cities	Modeling study combining high-resolution urban climate simulations and epidemiological assessment with quantitative spatial analysis and econometric modeling based on the Value of Statistical Life (VSL) framework.	Europe: 85 European cities across multiple climate zones	During heat extremes, UHI increased mortality risk by median of 45% (IQR: 30–61%), equivalent to 0.25 additional deaths per 100,000 per day. Median economic impact: EUR 192 per adult inhabitant per year (IQR: EUR 142–296) for heat-related mortality. Comparable to air pollution costs (one-fifth of PM _{2.5} mortality, 1.2 times ozone mortality).	500 m resolution temperature and mortality data, 2015–2017, population-weighted analysis across 85 cities; city-level exposure–response relationships; EUR 3.91 million VSL valuation	Health impacts Socioeconomic impacts— Economic quantification
Hsu et al., 2021 [64]	Disproportionate exposure to urban heat island intensity across major US cities	Cross-sectional spatial analysis with statistical regression	North America: 175 largest urbanized areas, Continental United States	In 169 cities (97%), average person of color lives in census tracts with higher SUHI intensity than non-Hispanic whites. Black residents: 3.12 ± 2.67 °C SUHI vs. 1.47 ± 2.60 °C for non-Hispanic whites. Racial disparities persist, controlling for income	175 urbanized areas covering ~65% of total US population; census tract-level analysis using satellite-derived SUHI data	Socioeconomic impacts— Environmental justice
Blackford et al., 2024 [65]	Synergy of urban heat, pollution, and social vulnerability in one of America’s most rapidly growing cities: Houston, we have a problem	Longitudinal spatial analysis using remote sensing and regression (2001–2019)	North America: Houston Metropolitan Area, Texas, United States	Urban land cover increased by 1345.09 km ² . Daytime UHI expanded by 171.92%, nighttime UHI by 73.93%. Combined heat stress and particulate pollution: 250% mortality risk increase.	Houston metro area; Landsat, MODIS products; census tract-level social vulnerability data spanning 20 years	Socioeconomic impacts— Social vulnerability and environmental justice
Fung et al., 2024 [66]	Prioritizing social vulnerability in urban heat mitigation	Experimental modeling study using WRF with Universal Thermal Climate Index and social vulnerability analysis	North America: Houston, Texas, United States	Urban trees: 0.27 K cooling vs. cool roofs 0.30 K, but trees are more effective in socially vulnerable areas: −1.41% vulnerability-weighted heat stress reduction vs. −1.28% for cool roofs. Vulnerable neighborhoods (SVI > 0.9) have greater street fraction but less roof area.	City-scale simulations across 5 heatwave events (2009–2015); analysis of 180+ urban form alternatives across different social vulnerability zones	Socioeconomic impacts— Social vulnerability with mitigation effectiveness
Ettinger et al., 2024 [67]	Street trees provide an opportunity to mitigate urban heat and reduce risk of high heat exposure	Field measurement study with temperature sensors	North America: Tacoma, Washington, USA	Air temperature varied by 2.57 °C across neighborhoods. Street trees reduced temperatures by 0.01 °C per 1% canopy cover increase within 10 m (1.0 °C cooling from 0 to 100% canopy). Probability of exceeding 32.2 °C was 2–5 times greater with no canopy vs. 100% canopy.	46 temperature monitoring stations, June–August 2022, with tree characteristics measured within 10 m	Physical mitigation— Green infrastructure (street trees)

Table 2. Cont.

Author	Title	Study Type	Location	Key Findings	Sample/Scope	Category
Ching et al., 2025 [68]	Park cool island modifications to assess radiative cooling of a tropical urban park	Field measurement study with meteorological sensor network	Asia: Singapore (tropical climate)	Mean daytime park cool island intensity: 2.21 °C, nighttime: 1.69 °C. Parks exhibited consistently cooler air temperatures throughout 24 h periods.	18 fixed meteorological stations for full year of 2022 in Bishan-Ang Mo Kio Park	Physical mitigation—Green infrastructure (urban parks)
Wu et al. (2025) [69]	Impact of newly constructed parks on urban thermal environment: A comparative analysis of 20 parks before-and-after construction	Remote sensing analysis using Landsat 8 satellite imagery	Asia: Hangzhou, China	Newly constructed parks reduced temperatures by 0.31 °C inside parks and 0.64 °C in surroundings initially. As parks matured, 0.84 °C inside and 1.08 °C in surroundings. Park cooling distance expanded from 104.40 m to 147.50 m.	20 newly constructed parks analyzed using three years of Landsat 8 data (2021–2023)	Physical mitigation—Green infrastructure (urban parks)
Mentes et al., 2024 [70]	The cooling effect of different scales of urban parks on land surface temperatures in cold regions	Remote sensing analysis using satellite imagery	Asia: Elazığ, Turkey (cold region)	Small-scale park (0.58 ha): 2.4 °C LST reduction; medium-scale (1.50 ha): 4.3 °C; large-scale (17.0 ha): 5.7 °C compared to downtown temperature of 43.5 °C. Clear dose–response relationship with park size.	Three urban parks of varying scales analyzed during July 2021 hot period	Physical mitigation—Green infrastructure (urban parks)
Zhang et al., 2022 [71]	Cooling effects revealed by modeling of wetlands and land-atmosphere interactions	Modeling study with updated dynamic wetland module in Noah-MP land surface model	North America: Prairie Pothole Region, USA and Canada	Wetlands cooled air temperature by 1–3 °C in summer, especially in high wetland coverage regions. Mechanisms involve increasing latent heat/evapotranspiration while suppressing sensible heat.	Regional application with 13-year climate forcing from high-resolution convection-permitting model	Physical mitigation—Green infrastructure (wetlands)
Deng et al., 2023 [72]	Analysis of urban wetland park cooling effects and their potential influence factors: Evidence from 477 urban wetland parks in China	Remote sensing analysis with machine learning models (random forest and PLS regression)	Asia: China (477 wetland parks nationwide)	Lake-based parks: higher largest cooling intensity; river-based parks: higher largest cooling distance. Water cover fraction (minimum 70%) most influential. Parks should limit impervious surfaces to <13%.	477 urban wetland parks analyzed during warm and cold seasons	Physical mitigation—Green infrastructure (wetlands)
Brousse et al., 2024 [73]	Cool roofs could be most effective at reducing outdoor urban temperatures in London (United Kingdom) compared with other roof top and vegetation interventions: A mesoscale urban climate modeling study	Mesoscale modeling study using Weather Research and Forecasting model v4.3 with BEP-BEM	North America: Greater London, United Kingdom	Cool roofs achieved greatest outdoor 2 m air temperature reduction at city scale. Maximum temperature reduction: 3.2 °C at 33 °C daily average and 2.8 °C at 37 °C. Green roofs: daytime cooling up to ~1.0 °C but increased overnight temperatures. Cool roofs reduced urban temperatures during day and extended into nighttime with sufficient coverage.	City-wide modeling on two hottest days of summer 2018 (July 26–27), using WRF at 1 km resolution	Physical mitigation—Green infrastructure (cool/green roofs)—Cool surfaces

Table 2. Cont.

Author	Title	Study Type	Location	Key Findings	Sample/Scope	Category
Jia et al., 2024 [74]	Building energy savings by green roofs and cool roofs in current and future climates	Integrated modeling study combining climate change modeling and building energy simulation	Multi-region/Global Six global cities (Cairo, Hong Kong, Seoul, London, Los Angeles, São Paulo)	By 2100, green roofs could reduce HVAC consumption by up to 65.51%, cool roofs by 71.72%. Cool roofs demonstrated higher energy savings than green roofs across different climatic zones.	Six cities across different climate zones analyzed under current and future climate scenarios through 2100	Physical mitigation—Green infrastructure (green/cool roofs)
Lee et al., 2023 [75]	The evaluation of the temperature reduction effects of cool roofs and cool pavements as urban heatwave mitigation strategies	Field experiment with thermal imaging and temperature monitoring	Asia: Jangyumugye district, Gimhae, Republic of Korea	Cool roofs reduced surface temperatures by average 15.5 °C (maximum 22.9 °C) and indoor air by 2.7 °C during daytime. Cool pavements: 1.8–5.8 °C in parking lots (maximum 10.8 °C), 2.5–4.3 °C in alleys.	Field measurements at 6 cool roof sites and multiple pavement sites using thermal imaging at 1–2 h intervals from 7:00 to 21:00	Physical mitigation—Cool surfaces
Schneider et al., 2023 [76]	Evidence-based guidance on reflective pavement for urban heat mitigation in Arizona	Field study with micrometeorological observations	North America: Phoenix, Arizona, USA (Garfield, Maryvale, Westcliff Park neighborhoods)	Reflective pavement reduced surface temperatures by maximum −8.4 °C (Westcliff), −6.8 °C (Maryvale), −5.4 °C (Garfield). Mean radiant temperature elevated during noon/afternoon but reduced after sunset. Solar reflectivity degraded from 33 to 38% to 19–30% over 7 months.	58 km of residential streets treated with reflective pavement seal; mobile measurements at four time windows; monthly reflectivity measurements across 8 neighborhoods	Physical mitigation—Cool surfaces
Ampatzidis et al., 2023 [77]	Impact of blue space geometry on urban heat island mitigation	Computational fluid dynamics modeling with RANS simulations using original evaporation model	Idealized urban neighborhood (scaled to real conditions: 10 m buildings, 30 m spacing)	Under warmer water (+2 K), larger square water bodies disrupted canyon flow creating vertical plumes. Smaller bodies trapped effects below roof level, increasing effectiveness ratio to 10.0. For cooler water (−2 K), 1:4 configuration showed highest cooling effectiveness.	23 simulations examining 5 water body sizes and 6 shapes under ±2 K temperature scenarios using validated OpenFOAM CFD	Physical mitigation—Blue infrastructure
Azarijafari et al., 2021 [78]	Urban-scale evaluation of cool pavement impacts on the urban heat island effect and climate change	Context-sensitive modeling framework combining building energy, pavement thermal models, and radiative forcing analysis	North America: Boston, Massachusetts and Phoenix, Arizona, USA	Cool pavement strategies offset 1.0–3.0% of total GHG emissions in Boston and 0.7–6.0% in Phoenix over 50 years. Increasing pavement albedo lowered urban air temperatures by 0.2–0.6 °C per 0.1 increase in albedo.	Prospective life-cycle analysis incorporating building energy simulations, urban microclimate models, and traffic data for specific road segments	Physical mitigation—Cool surfaces
Meng et al., 2023 [79]	Anthropogenic heat variation during the COVID-19 pandemic control measures in four Chinese megacities	Quasi-experimental case study analysis with remote sensing data	Asia: Wuhan, Shanghai, Beijing, Guangzhou, China	COVID-19 control measures reduced anthropogenic heat by up to 50% in Wuhan during February 2020 lockdown, gradually decreasing after April 2020. Shanghai showed similar patterns.	Four megacities, 2017–2020 comparison, high-resolution remote sensing surface energy balance analysis with inventory-based modeling	Policy integration (remote work/transportation policy impacts on anthropogenic heat)

Table 2. Cont.

Author	Title	Study Type	Location	Key Findings	Sample/Scope	Category
Shikwambana et al., 2021 [80]	Temporal analysis of changes in anthropogenic emissions and urban heat islands during COVID-19 restrictions in Gauteng Province, South Africa	Case study with multisource satellite data analysis (Sentinel-5P, MERRA-2, MODIS)	Africa: Gauteng Province (Johannesburg-Pretoria metropolitan area), South Africa	~31% decrease in NO ₂ emissions during lockdown restrictions. Slight reduction in UHI effect. Direct link between transportation/industrial activity restrictions and urban thermal environment changes.	One major metropolitan region, multisource satellite analysis from pre-lockdown (2019) to lockdown period (2020)	Policy integration (transportation and industrial policy impacts)
Mijani et al., 2023 [81]	Exploring the effect of COVID-19 pandemic lockdowns on urban cooling: A tale of three cities	Comparative case study analysis using satellite imagery	Europe and Asia: Milan and Rome (Italy), Wuhan (China)	Mean NLST of built-up lands during lockdown reduced from 7.71 °C to 2.32 °C in Milan, from 5.05 °C to 3.54 °C in Rome, and from 3.57 °C to 1.77 °C in Wuhan.	Three cities across two countries, satellite imagery comparison between 2018 baseline and 2020 lockdown periods	Policy integration (lockdown/mobility restriction policies)
Kwon et al., 2024 [82]	Exploring the heat mitigation effects of urban climate adaptation facilities	Field experimental study with IoT monitoring	Asia: Gimhae-si, Yechun-gun, Geyang-gu, Sangju-si, South Korea	Cooling fog systems: up to 3.1 °C ambient temperature reduction; cool roofs: 2–3 °C surface temperature reduction; shading structures: up to 10 °C surface temperature reduction; small water paths: up to 1.5 °C air temperature cooling.	Four South Korean cities, multi-year field deployment (2021–2023) with continuous IoT sensor monitoring, Korean Ministry of Environment policy evaluation	Policy integration (climate adaptation infrastructure policy evaluation)
Ahmed et al., 2024 [83]	Optimizing human thermal comfort and mitigating the urban heat island effect on public open spaces in Rome, Italy through sustainable design strategies	Urban design case study with ENVI-met simulation modeling	Europe: Viale Carlo Felice Gardens, Rome (Municipio I, Esquilino), Italy	Redesign incorporating vegetation optimization, reflective materials, water features, and expanded shading reduced morning PET by up to 19 °C, PPD by 20%, PMV by 1 point. At peak afternoon: PET by up to 4 °C, PPD by over 30 percentage points, PMV by more than 2 points.	One historic urban park, detailed ENVI-met microclimate simulations for baseline and redesigned scenarios, summer 2023–2024	Policy integration (urban planning policy with SDG integration)
Maharjan et al., 2021 [84]	Evaluation of urban heat island (UHI) using satellite images in densely populated cities of South Asia	Comparative observational case study using satellite remote sensing	Asia: Kathmandu Valley (Nepal), Delhi (India), Dhaka (Bangladesh)	Central urban areas experienced significantly more heat zones than peri-urban areas. Average surface temperature: 21.1 °C to 32.0 °C in Kathmandu. Rapid urbanization directly correlated with LST increases; forest-to-urban conversion had most negative effect.	Three South Asian capital cities, Landsat 8 satellite imagery analysis 2014–2021, comparative NDVI, NDBI, and LST analysis	Policy integration (land use planning policy for rapidly urbanizing cities)
Arunab & Mathew, 2025 [85]	Impact of planned urban development on urban heat island effect: resilient cities for a sustainable future	Comparative case study analysis with predictive modeling	Asia: Bangalore and Hyderabad, India	Analysis revealed substantial urban expansion 2001–2021. Random forest model predicted contrasting urbanization patterns for 2031. Planned development with green infrastructure integration: 1.5–2 °C lower surface temperatures vs. unplanned sprawl scenarios.	Two major Indian cities, multi-decadal satellite analysis (2001–2021) with predictive modeling to 2031, random forest machine learning approach	Policy integration (urban planning policy evaluation, compact vs. sprawl development)

Table 2. Cont.

Author	Title	Study Type	Location	Key Findings	Sample/Scope	Category
Cai & Shu, 2024 [86]	Integrating System Perspectives to Optimize Ecosystem Service Provision in Urban Ecological Development	Systems analysis with remote sensing and spatial modeling	Asia: Yangtze River Delta Eco-Green Integrated Development Demonstration Area, China	Identified 11 driving factors for carbon sequestration, 9 for water conservation, 6 each for sediment/pollution reduction, 10 for stormwater regulation. High-efficiency restoration priority areas identified in southwestern urbanizing zones. Spatiotemporal heterogeneity emphasized need for integrated frameworks.	Spatiotemporal analysis 2000–2020; systems-oriented framework examining ecosystem services in rapidly urbanizing region; spatial overlay analysis	Systems approach—Policy integration
Syeda et al., 2025 [87]	Sustainable Urban Heat Island Mitigation Through Machine Learning: Integrating Physical and Social Determinants for Evidence-Based Urban Policy	Machine learning modeling using random forest, SVM, and Gradient Boosting Machine	North America: San Antonio, Texas, United States	ML models achieved $R^2 > 0.84$ predicting LST (max 47.63 °C). Socioeconomic variables (density, income, education, age) significantly modulate heat exposure independently of physical characteristics. Optimal strategies must account for socioeconomic context.	High-resolution spatial data across 5 functional zones (residential, commercial, industrial, official, downtown); data-driven interdisciplinary approach for evidence-based urban planning	Socioeconomic impacts—Green infrastructure mitigation
Simpson et al., 2025 [88]	The mortality and associated economic burden of London’s summer urban heat island effect: a modeling study	Urban climate modeling with health impact assessment using advanced mesoscale modeling	Europe: Greater London, United Kingdom	370 heat-related deaths during 10–25 July 2022; 141 deaths (95% CI: 126–157) attributable to UHI (38% of total). Advanced modeling quantified UHI intensity with population-weighted aggregation. Economic burden assessed.	Record-breaking 2022 summer heatwave; modeled counterfactual non-urban scenario to isolate UHI contribution; population-weighted daily temperature time-series based on 2021 census data	Health impacts
Iungman et al., 2023 [89]	Cooling cities through urban green infrastructure: a health impact assessment of European cities	Health impact assessment	Europe: 93 European cities across multiple climate zones	Increasing tree coverage to 30% could prevent significant heat-related mortality. Clear dose–response relationships established between vegetation and mortality reduction across diverse cities.	Large-scale health impact assessment across 93 European cities; quantitative evidence for policy targets; tree coverage scenarios modeled	Health impacts—Green infrastructure mitigation
Iungman et al., 2024 [90]	The impact of urban configuration types on urban heat islands, air pollution, CO ₂ emissions, and mortality in Europe: a data science approach	Data science analysis with spatial modeling and integrated assessment	Europe: Multiple European cities across diverse urban configurations	Urban configuration affects mortality through multiple pathways (UHI, air pollution, CO ₂) simultaneously. Single-pathway optimization produces suboptimal outcomes. High premature mortality burden from combined environmental exposures.	Multi-pathway integrated assessment across European cities; data science approach examining how urban configuration types affect health through simultaneous environmental exposures	Health impacts—Policy integration

3.1. Risk of Bias Across Included Studies

Given the heterogeneity of study designs included in this review, a qualitative assessment of risk of bias was conducted across study types rather than through individual numerical scoring. Epidemiological studies [58–60] generally demonstrated a low-to-moderate risk of bias, supported by large sample sizes, established exposure and response modeling approaches, and consistent findings across locations, although residual confounding and exposure misclassification remained possible [57]. Health impact assessment studies [89] demonstrated low-to-moderate risk of bias, with transparency in exposure–response relationships and population-weighted approaches, though assumptions regarding counterfactual scenarios and transferability of dose–response functions across contexts introduced uncertainty.

Remote sensing and systems analysis studies [69,72,84,86] and field measurement [67,68,73] studies showed low risk of bias related to data availability and measurement procedures but were subject to spatial resolution limitations and temporal representativeness. Modeling and simulation-based studies [73,77,78,88] were primarily affected by uncertainty arising from model assumptions, boundary conditions, and parameter selection rather than systematic bias. Machine learning and data science studies [87,90] showed low risk of bias in predictive modeling through robust cross-validation procedures and high model performance metrics ($R^2 > 0.84$), though interpretation of causal mechanisms from correlational patterns requires careful consideration. No included study was judged to have critical methodological limitations that would invalidate its findings, and all studies were considered suitable for inclusion in the qualitative synthesis.

3.2. Study Characteristics

The systematic review identified 33 primary research articles published between 2021 and 2025, examining urban heat island phenomena across four continents. Studies employed diverse methodological approaches, with modeling and simulation studies composing the largest proportion ($n = 7$, 21.2%), followed by time-series and epidemiological analyses ($n = 6$, 18.2%), remote sensing analyses ($n = 5$, 15.2%), and field measurement studies ($n = 5$, 15.2%). Health impact assessment represented 12.1% of studies ($n = 4$), while machine learning and data science approaches accounted for 6.1% ($n = 2$). Geographically, the studies demonstrated substantial coverage across continents, with European cities most frequently examined ($n = 13$, 39.4%), followed by North America ($n = 9$, 27.3%) and Asia ($n = 9$, 27.3%), with limited representation from Africa ($n = 1$, 3.0%) and one multi-region analysis. Primary research foci were distributed across health impacts ($n = 8$, 24.2%), green infrastructure evaluation ($n = 8$, 24.2%), and policy integration ($n = 7$, 21.2%), with additional contributions from socioeconomic and environmental justice studies ($n = 4$, 12.1%), cool surfaces ($n = 3$, 9.1%), systems approaches ($n = 2$, 6.1%), and blue infrastructure ($n = 1$, 3.0%). The characteristics of included studies is summarized in Table 3.

Table 3. Characteristics of included studies ($N = 33$).

Characteristic	Category	n	%
Methodological Approach	Field measurement/experimental	5	15.2
	Remote sensing analysis	5	15.2
	Modeling/simulation	7	21.2
	Health impact assessment	4	12.1
	Machine learning/data science	2	6.10
	Case study/observational	4	12.1
	Time-series epidemiological analysis	6	18.2

Table 3. *Cont.*

Characteristic	Category	n	%
Geographic Distribution	North America	9	27.3
	Europe	13	39.4
	Asia	9	27.3
	Africa	1	3.00
	Multi-region (global cities) ^a	1	3.00
Research Focus	Health impacts	8	24.2
	Socioeconomic/environmental justice	4	12.1
	Green infrastructure	8	24.2
	Cool surfaces	3	9.10
	Blue infrastructure	1	3.03
	Policy integration	7	21.2
	Systems approach	2	6.10

^a One study [74] examined six cities across multiple continents (Cairo, Hong Kong, Seoul, London, Los Angeles, São Paulo).

3.3. Health and Mortality Outcomes

Epidemiological analyses across multiple continents consistently demonstrated elevated mortality risks during extreme heat events, with magnitudes varying by urban heat island intensity and regional climate. In European contexts, ref. [63] analyzed 85 cities and reported a median 45% increased mortality risk (IQR: 30–61%) in urban versus rural areas during heat extremes, equivalent to 0.25 additional deaths per 100,000 population per day (95% CI: 0.21–0.27), with economic costs reaching EUR 192 per adult inhabitant annually (IQR: EUR 142–296). Multiple assessments of London’s record-breaking 2022 heatwave quantified substantial mortality burdens attributable to urban heat island effects. Ref. [61] conducted health impact assessment using advanced urban climate modeling, while ref. [88] extended this analysis to include economic burden quantification through integrated Weather Research and Forecasting modeling at a 1 km resolution, estimating 370 heat-related deaths in Greater London during 10–25 July, with 141 deaths (95% CI: 126–157), representing 38% of the total heat-related mortality, attributable specifically to urban heat island effects. Across eight Swiss cities, ref. [62] observed a 31% increased mortality risk (RR: 1.31, 95% CI: 1.20–1.42) between minimum mortality temperature (22.5 °C) and extreme heat (35 °C, 99th percentile), with heat-related mortality risk 26% higher (95% CI: −4%, 67%) in areas experiencing urban heat island effects compared to non-UHI zones.

Beyond mortality, cardiovascular morbidity showed systematic associations with urban heat exposure. Ref. [58] established strong evidence across 120 U.S. metropolitan areas between 2000 and 2017, identifying 37,028 heat-attributable cardiovascular disease hospitalizations through time-series analysis with distributed lag non-linear modeling. High-UHI zones exhibited 2.4% increased CVD hospitalization risk compared to 1.0% in low-UHI areas, with these cases collectively accounting for 35% of the total heat-related CVD burden.

Regional variations in health outcomes reflected differences in urban morphology and climate. Ref. [59] measured UHI effects in five Spanish cities ranging from 1.2 °C (Murcia) to 4.1 °C (Valencia) in minimum daily air temperatures, with mortality and emergency hospital admissions statistically associated with maximum daily temperatures ($p < 0.05$), particularly in inland cities with lower coastal ventilation. Examining sustained heat exposure, ref. [60] analyzed 248 planning units across Hong Kong (2010–2019 hot

seasons) using case-crossover methodology and demonstrated that high “UHI degree-hour” areas represent temporal accumulation of heat exposure rather than peak intensity. These elevated mortality risks experienced during consecutive hot days and nights reinforce evidence that sustained urban heat drives excess mortality more strongly than isolated extreme events.

3.4. Environmental Justice and Exposure Disparities

Systematic spatial analyses revealed profound inequities in urban heat exposure structured along racial and socioeconomic lines. Analyzing 175 US urbanized areas covering 65% of the national population, ref. [64] documented that in 97% of cities, people of color resided in census tracts with higher surface UHI intensity than non-Hispanic whites ($p < 0.01$). Black residents experienced mean SUHI exposure of 3.12 ± 2.67 °C compared to 1.47 ± 2.60 °C for non-Hispanic whites, with disparities persisting after controlling for income, indicating structural mechanisms beyond individual economic status. Socioeconomic gradients reinforced these patterns: individuals below the poverty line experienced 2.70 ± 2.64 °C SUHI compared to 1.80 ± 2.69 °C for those two times above the poverty threshold. Temporal analyses by ref. [65] demonstrated how rapid urbanization amplifies existing inequities, documenting urban land cover expansion of 1345 km² in Houston (2001–2019) with daytime UHI extent expanding 172% and nighttime UHI by 74%. The most socially vulnerable communities showed disproportionate increases in both heat and particulate pollution exposure, with a 250% mortality risk increase from combined environmental stressors.

The differential effectiveness of mitigation strategies across social vulnerability gradients carries important policy implications. Ref. [66] modeled five Houston heatwave events (2009–2015) using Weather Research and Forecasting simulations at a 1 km resolution comparing mitigation scenarios weighted by the Social Vulnerability Index. While cool roofs provided slightly greater absolute cooling (0.30 K versus 0.27 K for urban trees), when weighted by social vulnerability spatial distribution, trees delivered −1.41% heat stress reduction compared to −1.28% for cool roofs and −0.67% for green roofs, a reversal attributable to disadvantaged neighborhoods having greater street fractions where trees provide direct shading but less roof area where cool roof interventions would apply. These findings establish that uniform mitigation deployment reproduces inequities unless spatially differentiated strategies account for built environment variation across vulnerability gradients.

3.5. Green Infrastructure Cooling Performance

Convergent evidence from field measurements, remote sensing, and modeling establishes quantitative relationships between green infrastructure features and cooling intensity, though effect magnitudes vary substantially by intervention type, measurement approach, spatial scale, and climate context.

Street trees and urban parks demonstrated scale-dependent cooling through distinct mechanisms. At the neighborhood scale, street tree cooling operates through direct shading and evapotranspiration at pedestrian height. Ref. [67] deployed 46 temperature monitoring stations measuring air temperature at 2 m height in Tacoma, Washington (June–August 2022), documenting that street trees lowered air temperatures by 0.01 °C per 1% canopy increase within a 10 m radius, translating to an approximately 1.0 °C total cooling potential through field measurement. At the district scale, urban parks showed substantially larger land surface temperature effects with clear size-scaling relationships. In tropical Singapore, ref. [68] operated an 18-station network throughout 2022, measuring mean daytime park cool island intensity of 2.21 °C and nighttime intensity of 1.69 °C. In cold-climate Turkey,

ref. [70] examined three urban parks during July 2021 using Landsat 8 thermal infrared remote sensing, finding small parks (0.58 ha) achieved 2.4 °C LST reduction, medium parks (1.50 ha) achieved 4.3 °C, and large parks (17.0 ha) achieved 5.7 °C relative to the 43.5 °C downtown baseline, demonstrating non-linear scaling with intervention size. Temporal maturation effects proved substantial, with ref. [69] analyzing 20 newly constructed Hangzhou parks showing an initial cooling of 0.31 °C and intensifying to 0.84 °C inside parks as vegetation matured over two years, while the cooling distance expanded from 104 m to 148 m.

Wetlands and water-based systems provide additional cooling through hydrological–atmospheric interactions. Ref. [71] employed dynamic wetland modules in Noah-MP land surface models simulating the Prairie Pothole Region over 13 years, finding wetlands cooled air temperatures by 1–3 °C in summer through increased latent heat flux and evapotranspiration. At larger scales, ref. [72] analyzed 477 Chinese urban wetland parks using random forest regression, identifying the water cover fraction within parks (minimum 70%) as the most influential for cooling effectiveness, with optimal performance requiring a proportion of impervious surfaces below 13%.

At the building scale, roof interventions showed effectiveness through mesoscale modeling, though performance characteristics differ between cool and green roof strategies. Ref. [73] used Weather Research and Forecasting models at 1 km resolution over London during 2018's peak heat days, finding cool roofs achieved maximum air temperature reduction of 3.2 °C while green roofs provided daytime cooling up to 1.0 °C but increased overnight temperatures due to insulation effects. Energy modeling across six global cities through 2100 [74] projected green roofs reducing HVAC consumption by up to 65.51% and cool roofs achieving a 71.72% reduction, indicating significant building energy co-benefits alongside outdoor cooling.

Large-scale health impact assessments established dose–response relationships between urban tree coverage and mortality reduction. Analysis of 93 European cities modeled the health benefits of increasing tree canopy coverage to 30%, a threshold identified as optimal for maximizing cooling while maintaining urban functionality [89]. Their health impact assessment demonstrated that achieving this coverage target would prevent significant heat-related mortality through reduced UHI intensity, establishing clear evidence for policy targets integrating green infrastructure expansion into urban planning frameworks.

Land surface temperature values from satellite remote sensing typically show larger magnitudes than air temperature from field measurements, as LST represents surface radiative conditions, while air temperature represents atmospheric conditions at human height. Both metrics demonstrate cooling benefits, though direct numerical comparison across measurement approaches requires careful interpretation of methodological distinctions.

3.6. Cool Surfaces and Blue Infrastructure

Cool surface interventions demonstrated substantial surface temperature reductions through increased solar reflectivity, though effects on air temperature and human thermal comfort showed more modest magnitudes requiring consideration of unintended consequences.

Cool roofs and pavements showed parallel surface cooling effects. Ref. [75] conducted thermal imaging at six Korean sites during summer 2021, documenting cool roofs lowering surface temperatures by an average 15.5 °C (maximum 22.9 °C), with indoor air temperatures decreasing by 2.7 °C, establishing both exterior surface cooling and interior building energy benefits. Cool pavements showed parking area surface temperatures falling by 1.8–5.8 °C (maximum 10.8 °C) and alley surfaces by 2.5–4.3 °C relative to conventional pavements. However, long-term field observations revealed performance degradation

and thermal comfort trade-offs. Ref. [76] examined 58 km of reflective pavement seal across three Phoenix neighborhoods, finding maximum surface temperature reductions of 8.4 °C at noon, yet mean radiant temperature (key determinant of human thermal comfort) increased during noon and afternoon (+2.3 to +5.1 °C) due to reflected solar radiation, while air temperature differences remained minimal (−0.7 °C maximum). Solar reflectivity degraded from initial 33–38% to 19–30% over seven months due to dust accumulation, tire wear, and weathering, indicating maintenance requirements for sustained performance.

Life-cycle assessment examining long-term urban energy balance revealed complex trade-offs. Ref. [78] modeled Boston and Phoenix over a 50-year lifecycle, finding cool pavement strategies offset 1.0–3.0% of total GHG emissions in Boston and 0.7–6.0% in Phoenix through reduced air conditioning demand, with urban air temperatures lowering by 0.2–0.6 °C per 0.1 albedo increase, indicating modest but persistent climate mitigation co-benefits.

Blue infrastructure cooling effectiveness depends critically on water body geometry and temperature differential. Ref. [77] conducted 23 RANS simulations examining five water body sizes and six shapes under ± 2 K temperature scenarios in idealized urban canyon configurations. Under warmer water conditions (+2 K), larger square water bodies disrupted downwind canyon airflow, reducing ventilation effectiveness. Smaller water bodies (1:8 water-to-block ratio) trapped cooling below roof level with effectiveness ratios reaching 10.0. For cooler water scenarios (−2 K), the 1:4 water-to-block ratio showed the highest cooling effectiveness for pedestrian-level thermal comfort through optimal balance of evaporative cooling and airflow modification.

These findings establish that cool surfaces and blue infrastructure provide measurable cooling through distinct physical mechanisms, solar reflectance for cool surfaces and evaporative cooling for water bodies, though performance depends on maintenance requirements, geometric considerations, and potential trade-offs between surface temperature reduction and human-experienced thermal comfort metrics.

3.7. COVID-19 Natural Experiments and Anthropogenic Heat

The COVID-19 pandemic lockdowns created unprecedented natural experiments revealing anthropogenic heat's magnitude through controlled reduction in human activity, providing direct empirical evidence previously available only through modeling. Across multiple urban contexts, lockdown measures produced 30–50% anthropogenic heat reductions, with corresponding 0.5–7 °C surface temperature decreases demonstrating the substantial contribution of human activity to urban thermal environments.

In Chinese megacities, ref. [79] analyzed surface energy balance across Wuhan, Shanghai, Beijing, and Guangzhou (2017–2020) using remote sensing-derived anthropogenic heat flux estimation algorithms, finding control measures reduced anthropogenic heat by up to 50% in Wuhan during the February 2020 lockdown relative to the 2017–2019 baseline, with Shanghai showing similar patterns during its Level 1 pandemic response. Anthropogenic heat decreases were concentrated in urban centers where human activity intensity was highest pre-pandemic, with transportation corridors showing the greatest reductions. In African contexts, ref. [80] examined Gauteng Province (Johannesburg-Pretoria metropolitan area) using Sentinel-5P, MERRA-2, and MODIS data integration, documenting NO₂ emissions decreasing approximately 31% during lockdown with corresponding slight UHI reduction, linking transportation emissions directly to thermal effects through coupled analysis of air quality and thermal remote sensing.

European comparisons revealed parallel patterns across distinct urban contexts. Ref. [81] compared satellite imagery between 2018 baseline and 2020 lockdown periods in Milan, Rome, and Wuhan using Landsat 8 thermal infrared data, finding mean normalized

land surface temperature of built-up lands during lockdown decreased from 7.71 °C to 2.32 °C in Milan (70% reduction), from 5.05 °C to 3.54 °C in Rome (30% reduction), and from 3.57 °C to 1.77 °C in Wuhan (50% reduction) relative to surrounding rural areas. These magnitudes exceeded expectations from conventional mitigation interventions, demonstrating that anthropogenic heat, particularly from transportation and commercial activity, represents a substantial, potentially addressable component of urban heat through activity pattern modification.

3.8. Policy Implementation and Integrated Interventions

Field implementation studies demonstrated that integrated approaches combining multiple mitigation strategies deliver cooling benefits exceeding individual interventions through complementary mechanisms, though they require institutional coordination for effectiveness.

Multi-intervention assessments in South Korea [82] and Rome [83] provided empirical validation under operational conditions. Korean monitoring across four cities (2021–2023) using IoT sensors showed cooling fog systems reducing ambient temperatures by 3.1 °C, cool roofs reducing surface temperatures by 2–3 °C, shading structures by 10 °C, and water paths by 1.5 °C, while improving thermal comfort indices (WBGT, UTCI). Rome's ENVI-met microclimate modeling at 1 m resolution demonstrated that integrated redesign incorporating vegetation, reflective materials, water features, and shading reduced Physiological Equivalent Temperature (PET) by up to 19 °C in the morning and 4 °C during the peak in the afternoon, with substantial improvements in thermal comfort metrics (PPD, PMV) beyond simple temperature reduction.

Systems integration frameworks revealed synergies and multiplicative impacts unavailable through isolated interventions. Ref. [86] developed an integrated framework published in the journal *Systems* demonstrating that cross-sectoral coordination delivers co-benefits across UHI mitigation, stormwater management, air quality improvement, and biodiversity conservation. Extending this principle, ref. [90] employed data science approaches across European cities, showing urban configuration types influence UHI, air pollution, and CO₂ emissions concurrently. Their integrated analysis demonstrated that urban form decisions create cascading effects across multiple environmental determinants, with mortality outcomes reflecting cumulative exposure to thermal stress, air pollution, and climate forcing rather than any single factor in isolation.

Data-driven analytical approaches enabled spatially differentiated strategies addressing both thermal exposure and social vulnerability. Ref. [87] applied machine learning models (random forest, SVM, Gradient Boosting), achieving $R^2 > 0.84$ in predicting UHI intensity across San Antonio by incorporating built environment characteristics, vegetation indices, and social vulnerability metrics, generating equity-centered mitigation strategies operationalizing the principle that uniform interventions reproduce inequities without spatial differentiation. Land-use planning analyses demonstrated how development patterns determine long-term trajectories. Ref. [84] examined South Asian cities (Kathmandu, Delhi, Dhaka) using Landsat 8 imagery (2014–2021), showing that central urban areas exhibited significantly more heat zones than peri-urban regions. Forward-looking modeling by ref. [85] examining Bangalore and Hyderabad with random forest predictive modeling to 2031 showed planned development scenarios incorporating green infrastructure had projected temperatures 1.5–2 °C lower than unplanned sprawl, indicating proactive land-use planning can substantially modify long-term urban thermal trajectories.

These implementation and planning studies establish that effective UHI mitigation requires (1) integrated multi-intervention approaches rather than single-strategy deployment; (2) attention to thermal comfort metrics beyond temperature reduction; (3) institutional

coordination mechanisms enabling cross-departmental implementation; and (4) proactive integration into long-term urban development planning. The evidence demonstrates technical feasibility while highlighting implementation barriers related to governance capacity, cross-sectoral coordination, and sustained maintenance funding requiring policy attention alongside technical solutions.

4. Discussion

This review bridges previously disconnected research streams examining urban heat islands from health, physical science, environmental justice, and policy perspectives, focusing on evidence predominantly from urban contexts in North America, Europe, and Asia. While these parallel domains have advanced knowledge within their respective boundaries, synthesis enabling integrated implementation has remained limited. By systematically synthesizing evidence from 33 primary research articles, this review reveals interconnections among built form, human activity patterns, atmospheric processes, and socioeconomic structures that demand coordinated interventions rather than isolated technical fixes. The post-pandemic context creates a critical window for integrating heat mitigation into urban transformation initiatives already underway, moving beyond evaluation of isolated interventions toward understanding integrated urban heat management systems [54,91].

The following discussion addresses four critical dimensions aligned with the review objectives: (1) environmental justice and equity in heat exposure analyzed as an analytical framework guiding intervention design; (2) physical mitigation strategy effectiveness with explicit attention to causal linkages and interaction mechanisms; (3) policy integration opportunities connecting UHI mitigation with emerging urban planning frameworks, distinguishing empirically demonstrated effects from inferred potential; and (4) contextual moderating factors affecting evidence transferability across different settings.

4.1. Environmental Justice and Equity Dimensions in UHI Exposure

Synthesizing evidence across epidemiological, spatial, and socioeconomic studies reveals systematic patterns of inequitable heat exposure representing not random variation but predictable outcomes of interconnected causal processes operating across multiple scales [92–94]. These disparities constitute structural features embedded in urban systems through historical policy decisions, market dynamics, institutional practices, and social structures that together produce durable patterns of differential exposure [95,96].

The racial disparities [64] in 97% of US metropolitan areas, persisting even after controlling for income, point to mechanisms beyond individual socioeconomic status consistent with broader scholarship on systematic inequities across multiple environmental hazards [97–99]. Historical practices, including redlining, discriminatory zoning, and differential infrastructure investment, created durable urban morphologies concentrating heat in marginalized communities [100,101]. These path dependencies exemplify how urban systems exhibit inertia requiring deliberate intervention to alter trajectories, consistent with justice-centered adaptation frameworks demonstrating that vulnerability patterns result from structural processes rather than individual characteristics [102]. Black residents experiencing 3.12 ± 2.67 °C SUHI versus 1.47 ± 2.60 °C for non-Hispanic whites represents not merely a temperature difference but a quantifiable health burden. Combined with European epidemiological evidence establishing a 45% increased mortality risk during heat extremes, this temperature differential corresponds to approximately 26–45% elevated mortality risk for disadvantaged populations, with a causal pathway from structural inequality through thermal exposure to health outcomes [61,63,64].

Temporal feedback loops intensify these disparities absent intervention. A Houston study over two decades illustrates how urban growth amplifies existing inequities [65]. The

daytime UHI expanded by 171.92% while highly vulnerable communities experienced a 250% synergistic mortality risk increase from combined heat and particulate pollution. This demonstrates multiplicative rather than additive health impacts, in which heat and pollution interact through shared causal pathways (vehicle emissions, industrial activity, and reduced vegetation), creating synergistic effects where combined exposure exceeds the sum of independent impacts, consistent with environmental justice scholarship on cumulative environmental burdens [103,104]. This positive feedback mechanism, where initial thermal and pollution disadvantages compound through shared spatial concentration, exemplifies how urban systems perpetuate inequities through inter-domain interaction effects absent deliberate intervention, aligning with urban political ecology frameworks emphasizing uneven development trajectories [105,106].

Critically, equity analysis transforms from descriptive documentation to an analytical framework guiding intervention design when vulnerability patterns are systematically linked to intervention effectiveness, moving beyond documenting disparities toward operationalizing justice in technical decision-making [102,107]. Modeling from Houston demonstrates that urban trees provide greater vulnerability-weighted heat stress reduction (−1.41%) than cool roofs (−1.28%) in highly vulnerable neighborhoods, despite cool roofs achieving slightly higher absolute cooling (0.30 K versus 0.27 K) [66]. This reveals context-dependent effectiveness wherein disadvantaged neighborhoods with greater street fractions but less roof area require tree-focused strategies, while affluent areas with larger roof footprints suit cool roof technologies. This finding establishes that optimal interventions depend on urban morphology characteristics that vary systematically by socioeconomic status, transforming equity from an ethical consideration to a technical requirement for intervention effectiveness and challenging assumptions that equitable outcomes result from uniform citywide strategies [108,109].

Machine learning analysis [87] achieves high predictive accuracy ($R^2 > 0.84$) by integrating physical and socioeconomic determinants, demonstrating technical feasibility for operationalizing equity-centered spatial differentiation in municipal planning processes. This establishes that targeting vulnerable populations does not require abandoning technical rigor but rather expanding analytical frameworks to incorporate social vulnerability as a first-order design parameter alongside traditional engineering criteria. The convergence between epidemiological evidence (racial disparities [64]), spatial analysis (morphology-effectiveness interactions [66]), and predictive modeling (machine learning accuracy [87]) establishes a robust empirical foundation for spatially differentiated intervention strategies responsive to local vulnerability patterns, addressing concerns that equity-centered approaches lack scientific rigor [110,111].

The economic burden quantification showing EUR 192 per capita annually in European cities, comparable to established air pollution costs, provides cost-benefit frameworks for prioritizing vulnerable populations [63]. However, these estimates likely underestimate true costs by excluding morbidity, lost productivity, emergency response, and intangible costs of reduced quality of life and constrained outdoor activity [112]. For disadvantaged groups experiencing 3–4 °C higher temperatures, these costs concentrate disproportionately, representing regressive environmental taxation where those with the fewest resources bear the greatest burdens [113,114]. Policy responses centered on fairness must explicitly target highly vulnerable neighborhoods for priority interventions rather than assuming benefits will distribute equally across space [109,115].

These findings on distributional fairness establish critical parameters for evaluating mitigation strategies. If racial and socioeconomic disparities persist independently, as ref. [64] shows, then mitigation effectiveness cannot be evaluated solely through aggregate citywide temperature reductions. The evaluation criterion must shift from “which interven-

tion cools most effectively?” to “which intervention delivers cooling most effectively in the specific urban morphologies and socioeconomic settings where disadvantaged populations reside?” Urban morphology varies systematically by neighborhood socioeconomic status: vulnerable neighborhoods often have greater street fractions but less private roof area, different building densities, and distinct vegetation patterns compared to affluent areas. These morphological differences mean that optimal interventions necessarily differ across the urban landscape, requiring explicit examination of cooling magnitude, spatial distribution of benefits, accessibility across socioeconomic gradients, and potential for equitable implementation given existing neighborhood infrastructure and ownership patterns.

4.2. Physical Mitigation Strategy Effectiveness

Convergent evidence from field measurements, remote sensing, and modeling studies establishes measurable effectiveness across diverse interventions, though performance depends not merely on individual intervention characteristics but on interactions with surrounding urban form, climate conditions, and implementation quality. Adopting systems-analytical perspective operationalizing integrated urban environmental management frameworks [116] reveals three categories of mechanisms shaping intervention outcomes: (1) scale dependencies where effectiveness changes non-linearly with intervention size; (2) temporal dynamics involving maturation or degradation trajectories; and (3) contextual interactions where surroundings modulate performance.

Scale-dependent effectiveness emerges across intervention types. Green infrastructure cooling effects show consistent patterns across multiple studies: street trees deliver 0.01 °C reduction per 1% canopy increase within 10 m, parks provide 2.21 °C daytime cooling in tropical Singapore, small parks (0.58 ha) achieve 2.4 °C cooling and medium parks (1.50 ha) achieve 4.3 °C, and large parks (17.0 ha) achieve 5.7 °C relative to baseline urban temperatures [67,68,70]. The disproportionate per-hectare cooling from larger parks likely reflects advective cooling extending beyond boundaries and greater vegetation stratification enabling more effective evapotranspiration, consistent with previous meta-analyses documenting park size-cooling relationships [117,118], indicating that spatial configuration affects cooling mechanisms, not just magnitude. However, optimal strategies likely involve hierarchical networks combining neighborhood-scale parks for access equity with regional parks for maximum cooling magnitude rather than simply maximizing individual park size, reflecting broader ecosystem services valuation frameworks [119–121].

The 2–5 times greater probability of exceeding thermal thresholds in zero versus 100% canopy locations indicates non-linear health implications near physiological tolerance thresholds; modest temperature interventions produce disproportionate health outcomes, exemplifying system leverage points where targeted interventions yield outsized benefits [67,122,123]. Tropical contexts reveal additional complexity; a study found that over half of 1157 Kuala Lumpur residents reported thermal discomfort despite adaptive behaviors, suggesting effectiveness requires design features enabling behavioral thermoregulation beyond absolute temperature reduction [38,84].

Temporal dynamics create distinct performance trajectories requiring different investment and maintenance strategies. Green infrastructure strengthens as vegetation matures; for example, Hangzhou parks showed cooling intensifying from 0.64 °C to 1.08 °C over two years, with cooling distance expanding from 104 m to 148 m [69]. These temporal trajectories indicate that initial investments require 2–3 years to achieve full effectiveness. Conversely, cool surfaces demonstrate performance degradation: Phoenix monitoring documented solar reflectivity declining from 33 to 38% to 19–30% over seven months without maintenance [76], indicating substantial ongoing maintenance requirements often excluded from cost-benefit analyses [76,124]. These opposing temporal trajectories

establish that green infrastructure represents capital investment with strengthening returns, while cool surfaces require sustained operational expenditure to maintain performance, with fundamentally different financial and institutional requirements.

Contextual interactions with surrounding conditions modulate effectiveness through multiple mechanisms. Cool surfaces demonstrate thermal comfort trade-offs where the evidence shows Phoenix pavements reduced surface temperature by 8.4 °C, and mean radiant temperature increased from +2.3 to +5.1 °C during midday due to reflected radiation, creating pedestrian discomfort despite surface cooling [76]. This illustrates that single-metric optimization (surface temperature) may produce unintended consequences in integrated urban systems, where human thermal experience depends on multiple radiative and convective factors, requiring assessments incorporating mean radiant temperature and integrated thermal comfort indices rather than temperature alone [125–129].

A cool roof versus green roof comparison revealed important trade-offs needing careful navigation for multi-objective optimization [73]. Cool roofs achieved a greater ambient air temperature reduction (up to 3.2 °C in London) and higher projected energy savings (71.72% versus 65.51% HVAC reduction by 2100), but green roofs deliver additional ecosystem services, including stormwater management and habitat biodiversity [130,131]. The nighttime warming effect of green roofs due to thermal mass storage suggests climate-specific optimization: green roofs may suit climates requiring both summer cooling and winter warming retention, while cool roofs suit contexts prioritizing maximum cooling [36].

Wetland cooling operates through mechanisms extending beyond direct evapotranspiration to include boundary layer modification and cloud formation, indicating benefits extend to regional climate modification [71,132]. The 70% minimum water cover requirement and <13% impervious surface thresholds provide concrete design specifications, though mechanisms extend beyond direct evapotranspiration to include boundary layer modification and cloud formation [72]. However, few studies examine wetland performance across different climate zones or quantify water consumption trade-offs in water-stressed regions, limiting transferability across varied hydrological contexts [133]. Blue infrastructure geometry optimization [74] revealed that cooling effectiveness depends critically on water body size, shape, and temperature differential relative to surroundings, with smaller water bodies (1:8 scale) trapping cooling below roof level with effectiveness ratios reaching 10.0 but limited spatial extent, while larger bodies provided broader, though less intense, effects [77,134].

Integration with equity analysis reveals that intervention effectiveness varies systematically across vulnerability gradients. Modeling of Houston [66] showing trees outperforming cool roofs in vulnerable areas establishes that socioeconomic context mediates physical performance, where optimal interventions depend on urban morphology characteristics (street fractions, roof areas, and building densities) that vary systematically by neighborhood socioeconomic status. This cross-domain interaction between physical intervention performance and socioeconomic context establishes that technical effectiveness analysis divorced from equity considerations produces incomplete and potentially misleading intervention guidance [108].

From a systems perspective, convergent patterns establish that (1) effectiveness scales non-linearly with intervention size and exhibits thresholds; (2) temporal dynamics create distinct maturation versus degradation trajectories requiring different maintenance approaches; (3) interventions interact with surroundings through advection, reflection, and microclimate modification; (4) single metrics inadequately capture outcomes wherein thermal comfort indices integrating multiple variables better predict health impacts than temperature alone; and (5) contextual factors (climate, urban form, and socioeconomic setting) fundamentally shape performance, precluding universal prescriptions.

4.3. Policy Synergies: 15-Minute City, Work-from-Home, and Integrated Urban Planning

COVID-19 natural experiments provide empirical foundation for understanding anthropogenic heat contributions. Refs. [79–81] documented that 30–50% reductions in human activity produced 0.5–7 °C temperature decreases, establishing that activity patterns constitute first-order controls on urban temperatures in dense commercial districts fluxes [135–137]. However, extrapolating emergency restrictions to long-term voluntary planning requires careful interpretation distinguishing demonstrated effects from inferred potential [138].

4.3.1. Governance Fragmentation Challenges

Korean monitoring across four cities [82] and European multi-objective assessment [90] both identified governance fragmentation as a primary implementation barrier, requiring coordination across agencies with competing priorities, distinct performance metrics, and separate funding streams where institutional silos to urban systems integration must be overcome [139,140]. The challenge extends to multi-level governance, where local implementation requires alignment with regional and national frameworks while maintaining context-specific adaptations [141,142]. Spatially differentiated strategies accounting for vulnerability [66,87] require cross-departmental data sharing and joint priority-setting, which are institutional capacities rarely present in siloed governance structures [45].

4.3.2. Opportunities for Multi-Sectoral Coordination

Empirically demonstrated COVID effects establish that transportation activity reductions delivered substantial cooling, creating evidence-based foundation for coordinating UHI mitigation with transportation demand management. Ref. [80] documented a 31% NO₂ emission decrease in Gauteng with a corresponding UHI reduction, demonstrating a direct empirical linkage between transportation activity and thermal environment consistent with urban metabolism frameworks [143–145]. Prior research emphasized physical infrastructure modifications while treating activity patterns as fixed parameters [22,146], but convergent evidence from multiple cities using different measurement approaches (remote sensing, ground monitoring) establishes robust causal relationships between mobility patterns and urban temperatures [79,81].

However, translating pandemic restrictions to sustained planning requires acknowledging uncertainty. The 15-Minute City framework [51] emphasizing walkable access theoretically aligns with transportation reduction benefits observed during COVID, but as indicated by recent systematic reviews, peer-reviewed empirical studies evaluating implemented 15-Minute City thermal outcomes during normal operating periods do not yet exist in the literature from 2021–2025 [147]. The framework's recent adoption (Paris 2020, followed by other cities) means that implementation lags preclude rigorous empirical evaluation [148]. COVID-era evidence provides mechanistic proof of concept that reducing motorized transportation cools cities, but inferring that voluntary 15-Minute City adoption will achieve similar magnitudes represents extrapolation from emergency restrictions to sustained behavior change that is plausible but empirically unproven at present.

Tree-lined pedestrian corridors deliver empirically established dual benefits [149,150], with ref. [85] demonstrating planned development achieving 1.5–2 °C advantages over unplanned sprawl. This supports proximity-based planning incorporating simultaneous greening requirements [52,53], though sustained implementation depends on enforcement mechanisms not yet documented.

4.3.3. Equity-Centered Planning Frameworks

Ref. [66] differential effectiveness analysis and ref. [87] machine learning accuracy ($R^2 > 0.84$) establish technical feasibility for equity-centered spatial differentiation. However, implementation confronts institutional barriers; for example, vulnerability data quality varies across contexts; institutional capacity for integrating datasets requires specialized skills; and political and economic considerations complicate targeting disadvantaged neighborhoods [110,111].

Green gentrification concerns neighborhood improvements that increase property values by potentially displacing existing residents without complementary affordable housing policies and anti-displacement measures, and covers policy domains extending beyond heat mitigation authority into housing and economic development [109]. Existing planning frameworks often embed historical biases which require explicit correction through equity weights, distributional analysis, and vulnerability-adjusted valuation; these methodological reforms are documented but rarely implemented [102,115].

4.3.4. Implementation Strategies After COVID-19

The post-pandemic period presented an implementation window for embedding heat considerations within initiatives already commanding political attention [151]. However, translating opportunities requires addressing (1) voluntary behavior differences from mandated restrictions, producing less predictable outcomes [48]; (2) economic viability requiring hybrid approaches balancing thermal mitigation with commercial vitality [152]; (3) remote work tensions where extensive adoption could reduce neighborhood commercial support despite thermal benefits [45]; and (4) sustained political commitment where green infrastructure benefits emerge over 2–3 years while costs are immediate, requiring governance mechanisms supporting long-term implementation [69,142].

The studies represent empirically documented implementation models [82,86], though a systematic understanding of enabling institutional conditions requires explicit implementation science examining decision-making processes and funding structures. From a systems perspective, isolated interventions produce suboptimal outcomes through feedback effects: greening without transportation reform fails to reduce emissions [153]; density without green infrastructure amplifies heat [33]; remote work without local services increases car dependence [48]. Effective mitigation demands aligned frameworks acknowledging causal interdependencies across urban subsystems [154,155].

4.4. Moving Beyond Isolated Evaluation Toward Integrated Heat Management Systems

Cross-domain synthesis operationalizing integrated urban environmental management frameworks [154,155] reveals three analytical principles that become visible only when disciplines operate interdependently rather than independently.

First, multiplicative health impacts from multiple exposures establish that urban form decisions create cascading effects across thermal stress, air pollution, and climate forcing simultaneously, with mortality outcomes reflecting cumulative exposure rather than any single factor in isolation. Ref. [65] documented a 250% synergistic mortality risk increase from combined heat and particulate pollution, demonstrating interaction mechanisms where combined heat-pollution exposure and non-additive system behavior demonstrate that isolated evaluation substantially underestimates health burdens when exposures co-occur [103,156].

Second, equity–performance interdependencies show that uniform deployment reproduces inequities when ref. [66] demonstrated that differential effectiveness across vulnerability gradients transforms equity from an ethical consideration to a technical requirement for intervention effectiveness—strategies achieving the greatest aggregate cooling may

deliver minimal benefits to the most vulnerable populations when effectiveness depends on morphology characteristics varying systematically by neighborhood socioeconomic status [108,109]. This equity-performance feedback establishes that technical optimization divorced from distributional analysis produces suboptimal outcomes when judged by combined effectiveness and fairness criteria, requiring integration of justice frameworks into technical decision-making [92].

Third, co-benefit optimization through systems frameworks enables synergies across multiple domains. Studies demonstrate that value streams can extend beyond thermal comfort. However, realizing these benefits depends on institutional capacity to evaluate cascading effects across sectors [86,90]. This highlights the importance of governance reforms that support systems integration [157]. The post-pandemic period presents a critical window for such integration, as cities formulate recovery strategies [158]. Achieving this integration requires institutional innovation that addresses path dependencies and political economy constraints [45].

4.5. Contextual Moderating Factors and Evidence Transferability

Evidence reveals systematic variation moderated by climate, economic development, and governance structures requiring explicit attention for appropriate generalization [159].

Climate effects: Tropical contexts [60,68,84] experience year-round cooling demand with high humidity reducing evaporative effectiveness, favoring shading strategies. Temperate zones require seasonal energy balance assessment [73], while cold climates confront shorter growing seasons yet show proportionally substantial UHI effects [70]. Arid climates face water constraints, limiting green infrastructure while enhancing reflective surfaces [76], although thermal comfort trade-offs require site-specific evaluation. Climate-specific performance variations establish that direct transfer across substantially different zones risks implementation failure.

Economic development context: Evidence shows geographic clustering, where 58% of data features high-income (North America $n = 9$, Europe $n = 13$) areas, 36% features upper-middle-income Asia ($n = 12$), and there is minimal lower-income representation ($n = 1$), limiting generalizability to resource-constrained settings. High-income contexts enable sophisticated approaches (machine learning [87]; IoT networks [82]), while middle-income contexts demonstrate proactive integration opportunities where planned development shows measurable advantages [43,72,85]. Lower-income contexts remain severely under-represented [80], establishing a priority on expanding the evidence base.

Governance effects: Centralized systems demonstrated national coordination capacity [72,82], though they also presented potential constraints to adaptation, while decentralized systems enabled experimentation [76] but created regional challenges. Regardless of structure, implementation required an institutional capacity for coordination, monitoring, expertise, and sustained funding, where these capacities were challenging even in high-income contexts [45,142]. Direct transfer risked failure when underlying capacities were absent.

Transferability implications: Effectiveness documented in one context provides a proof of concept but not an implementation guarantee, requiring careful assessment and pilot testing [159]. Convergent evidence demonstrating green infrastructure cooling [67–70,160] and socioeconomic disparities [64–66,100] suggests core relationships transfer broadly, while specific magnitudes and implementation pathways require context-specific adaptation.

5. Conclusions

This review synthesizes disconnected research on urban heat islands across the health, environmental, and policy domains. It shows that existing knowledge remains siloed, con-

straining aligned implementation. The post-pandemic period presents a critical opportunity to integrate heat mitigation into broader urban transformation agendas.

5.1. Summary of Findings

Synthesizing evidence across the health, physical science, economic, and environmental justice domains establishes three principal findings that emerge only through cross-disciplinary integration. First, urban heat islands impose quantifiable and profoundly inequitable burdens. Evidence documents elevated mortality risk during extreme heat events with substantial economic costs, but critically, these burdens are distributed unequally across populations. Vulnerable communities experience significantly higher temperatures that persist even after controlling for income, with racial disparities documented across the vast majority of examined metropolitan areas. Machine learning analysis demonstrates that social vulnerability constitutes a primary determinant of heat exposure, establishing technical feasibility for equity-centered spatial targeting. This convergent evidence establishes urban heat as simultaneously a public health crisis, economic burden, and environmental justice imperative requiring coordinated responses across all three dimensions.

Second, physical mitigation strategies demonstrate measurable effectiveness, although performance depends critically on context, scale, design characteristics, and socioeconomic setting. Green infrastructure provides cooling that strengthens as vegetation matures, with clear scaling relationships between park size and cooling magnitude. Cool surfaces reduce temperatures substantially at surfaces, though maintenance requirements and radiant heat trade-offs necessitate careful site-specific optimization. Critically, mitigation effectiveness varies systematically across social vulnerability gradients: urban trees prove more effective than cool roofs in highly vulnerable areas with greater street fractions, indicating that optimal interventions depend on socioeconomic context and urban morphology. This finding, which emerged only through synthesis of physical science and environmental justice research, demonstrates that technical performance metrics alone are insufficient to guide equitable implementation.

Third, COVID-19 natural experiments revealed unprecedented policy synergies between urban heat mitigation, transportation planning, and emerging urban design frameworks. Work-from-home arrangements and transportation reductions decreased anthropogenic heat substantially, demonstrating that human activity patterns constitute first-order controls on urban temperatures in dense commercial districts. These findings illuminate strategic opportunities for coordinating heat mitigation with 15-Minute City planning, emphasizing walkable mixed-use neighborhoods and remote work normalization. Transportation activity reductions established direct linkages between mobility patterns and the thermal environment. However, coordination requires navigating trade-offs: density-focused planning without complementary greening intensifies thermal stress. These insights, connecting pandemic-era disruptions to long-term planning paradigms, emerge only through synthesis across policy domains typically considered independently.

5.2. Implications for Policy and Practice

Translating evidence into action requires aligned implementation across equity, planning, and governance domains. The convergent findings highlight that technical solutions alone are insufficient; integrated approaches aligning spatial, social, and institutional dimensions are essential to achieve equitable and sustainable urban heat mitigation.

1. Prioritize equity-centered interventions through spatially differentiated strategies responsive to local morphology and socioeconomic setting. Policies should target highly vulnerable neighborhoods while incorporating safeguards against green gentrification, which displaces the populations that interventions aim to protect. Mitigation

effectiveness varies by socioeconomic setting: trees prove more effective in disadvantaged areas with greater street fractions, while cool roofs work better in affluent zones with larger roof footprints. This shows that equitable outcomes depend on abandoning uniform approaches in favor of context-sensitive designs informed by both technical performance and social vulnerability.

2. Integrate heat mitigation into urban planning frameworks such as the 15-Minute City and post-pandemic work-from-home transitions. Aligning density, mobility, and greening can deliver multiple co-benefits, including reduced emissions, improved thermal comfort, and enhanced livability. Tree-lined pedestrian corridors and mandatory green infrastructure in compact urban forms exemplify synergistic strategies. The current recovery period offers a time-limited opportunity to embed heat considerations within broader transformation agendas before new urban patterns become institutionalized.
3. Strengthen governance for cross-sectoral collaboration through institutional innovation. Effective implementation requires cross-departmental working groups, integrated assessment frameworks, and performance metrics that reward collaboration rather than sectoral optimization. Yet, systematic understanding of enabling governance conditions remains limited, underscoring the need for implementation science research on decision-making, collaboration, and funding mechanisms that sustain integrated planning efforts.

Overall, advancing policy and practice demands an institutional capacity for systems-level collaboration, where interventions in one domain are evaluated for their cascading effects across others. Cities that act decisively to integrate equity, planning, and governance dimensions will establish enduring models for climate adaptation and resilient urban transformation.

5.3. Limitations

Several methodological and contextual limitations warrant acknowledgment. These limitations inform appropriate interpretation of findings and highlight areas requiring caution when generalizing or implementing evidence across diverse urban settings.

1. Geographic representativeness: The evidence base demonstrates substantial geographic imbalance concentrated predominantly in North America, Europe, and Asia (North America: $n = 9$, 27%; Europe: $n = 13$, 39%; Asia: $n = 9$, 27%), while cities in sub-Saharan Africa ($n = 1$, 3%), Latin America, and other rapidly urbanizing regions remain severely underrepresented. This geographic concentration toward high-income Global North contexts limits the generalizability of findings to diverse urban contexts, particularly low- and middle-income cities with distinct institutional, fiscal, and infrastructure characteristics, where much of future urban population growth will occur.
2. Methodological heterogeneity: The diversity of methodological approaches (epidemiological analyses, remote sensing, field measurements, modeling, machine learning, COVID-19 natural experiments, cool surface validation, and health impact assessments), outcome measures (air temperature, land surface temperature, and thermal comfort indices), spatial scales (10 m to regional), and reporting formats across studies presented challenges for synthesis. While this diversity enabled cross-validation and comprehensive assessment, it limited opportunities for quantitative meta-analysis, necessitating narrative synthesis approaches. Direct comparison of effect sizes across methodologies required careful contextualization of measurement approaches, spatial extents, and climatic conditions.

3. Temporal and linguistic scope: Restricting searches to English-language peer-reviewed journals published in 2021–2025 may have excluded relevant research in other languages or earlier foundational studies, potentially introducing linguistic and temporal bias. Publication bias may exist, whereby studies demonstrating significant findings or successful interventions are more likely to be published than null results or failed interventions, though the interdisciplinary nature of this review mitigates domain-specific publication patterns.

5.4. Future Research Direction

Future research should advance integrated urban heat management by addressing persistent methodological and institutional gaps. Although significant progress has been made in understanding the thermal, social, and economic dimensions of heat mitigation, studies remain largely disconnected across disciplines. A stronger evidence base requires research designs that explicitly connect technical performance, health outcomes, and governance mechanisms within complex urban systems.

1. Develop integrated assessment frameworks that move beyond single-variable temperature measures toward models linking thermal comfort and health outcomes. Future studies should prioritize indices such as the Universal Thermal Climate Index (UTCI) and Physiological Equivalent Temperature (PET), which incorporate humidity, wind, and radiation to better predict human exposure and well-being.
2. Leverage natural and quasi-experimental designs by studying cities implementing real-world interventions, such as greening programs, transport demand management, or remote work policies, in order to evaluate the scalability and contextual effectiveness of mitigation strategies.
3. Investigate compound and cascading climate risks by examining how urban heat interacts with drought, flooding, and air pollution. Understanding these intersections will support integrated adaptation frameworks that reflect the multi-hazard realities cities face.
4. Bridge the research–practice gap through implementation science, focusing on how interventions perform under real-world conditions, including maintenance, fiscal, and institutional constraints. Comparative studies across cities with differing governance structures can identify practical models for coordinated, long-term implementation.
5. Advance systems-level inquiry into feedback loops, interaction effects, and leverage points within urban systems to reveal where small interventions yield disproportionate impacts. Such research should examine how institutional collaboration, policy sequencing, and spatial dynamics shape overall system behavior and social equity outcomes.

Overall, advancing the field requires reframing urban heat not as a narrow environmental issue but as a systems challenge linking climate adaptation, equity, and governance. Future research should adopt interdisciplinary and longitudinal approaches to reveal dynamic urban interactions. How do remote work patterns influence commercial real estate markets, which in turn affect urban form and thermal characteristics? How do green infrastructure investments trigger or prevent gentrification? Addressing such questions will help cities design integrated, context-sensitive strategies that align environmental performance with social justice and long-term resilience.

5.5. A Call for Integrated Action

The urban heat island challenge presents both a threat and an opportunity for transformative urban development that advances health equity, sustainability, and resilience. Evidence shows that effective tools already exist across diverse settings; the real barrier lies in institutional rather than technical capacity. As cities rethink urban form, transport, and

public space in the post-pandemic period, a brief window exists to embed heat mitigation into broader transformation efforts. Seizing this moment requires treating urban heat as a catalyst for integrated planning that aligns environmental, social, and economic objectives. The critical question is whether cities can mobilize governance capacity and political will to implement aligned, equity-centered strategies before the opportunity closes.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/systems14010082/s1>: The sample for the bibliometric and content analysis was selected in accordance with the principles recommended for Systematic Literature Reviews—PRISMA [57].

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Abbreviations

The following abbreviations are used in this manuscript:

CFD	Computational Fluid Dynamics
CI	Confidence Interval
CVD	Cardiovascular Disease
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
IQR	Interquartile Range
LST	Land Surface Temperature
NDBI	Normalized Difference Built-up Index
NDVI	Normalized Difference Vegetation Index
NO ₂	Nitrogen Dioxide
PET	Physiological Equivalent Temperature
PM _{2.5}	Particulate Matter 2.5 µm
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RANS	Reynolds-Averaged Navier–Stokes
RR	Relative Risk
SDG	Sustainable Development Goals
SUHI	Surface Urban Heat Island
SVI	Social Vulnerability Index
UHI	Urban Heat Island

UTCI	Universal Thermal Climate Index
VSL	Value of Statistical Life
WRF	Weather Research and Forecasting

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