





## Digital Twins and Urban Heat Island Modeling: A Systematic Review of Conceptual, Technical, and Geospatial Gaps in Next-Generation Urban Climate Systems

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### ABSTRACT

This systematic review examines the emerging integration of Digital Twin technologies with Urban Heat Island modeling to advance next-generation urban climate systems. Increasing urbanization and rising thermal stress have intensified the need for dynamic, data-driven tools capable of representing and predicting microclimate conditions in real time. Through a structured PRISMA-based screening of major scientific databases (Scopus, IEEE Xplore, ScienceDirect), 268 initial records were identified, from which 19 studies were ultimately included after systematic deduplication (25 duplicates removed) and eligibility screening (16 studies excluded: 4 lacking technical information, 10 non-urban settings, 2 non-English). These 19 studies collectively illustrate three major knowledge domains: conceptual frameworks, technical architectures, and geospatial modeling characteristics. The findings indicate that Digital Twin is progressively regarded as a real-time, adaptive digital representation of the urban environment; however, it lacks standardized definitions for climate applications (identified in 68% of reviewed studies). Technically, the integration of heterogeneous data—ranging from Internet of Things (IoT) sensors, UAV thermal imagery, and satellite-derived land surface temperatures—remains limited by challenges in latency, model calibration, data interoperability, and computational scalability (reported in 74% of studies). Geospatial analysis further highlights inconsistencies in spatial-temporal resolution and inadequate representation of suburban areas (noted in 63% of studies), constraining robust Urban Heat Island simulations across scales. Overall, this review identifies critical gaps and emerging opportunities for developing intelligent, multi-scale, and hybrid modeling approaches that combine physics-based simulations with machine learning. The findings call for harmonized Digital Twin frameworks, improved geospatial data infrastructures, and stronger interdisciplinary collaboration to support climate-resilient urban planning and adaptive heat mitigation strategies.

### INTRODUCTION

The urban heat island effect makes it hard for cities to grow in a way that is good for the environment and makes them stronger. Digital Twin has a lot of promise for helping us understand and deal with the effects of the urban heat island by using

advanced simulation techniques with data from the real world. Digital Twin can help planners make better decisions about how to improve cities, which can lead to better interventions and better models of the microclimate in cities.

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A lot of research has been done on urban heat islands, but not much has been done on the idea of a digital twin in urban heat island studies. Most studies still use old-fashioned, static methods, so we haven't fully realized the potential of Digital Twin for real-time modeling and reducing urban heat islands (Qi & Tao, 2023; Wang et al., 2022). Most existing Urban Heat Island studies rely on static, retrospective methods that fundamentally limit their effectiveness for urban climate management. Static methods typically analyze historical temperature data or conduct one-time simulations that cannot adapt to changing conditions. This approach presents several critical problems. Why Static Methods Are Problematic:

1. Inability to Capture Real-Time Temperature Dynamics: Urban heat islands exhibit significant diurnal variations, with temperature differences between urban and rural areas changing dramatically from day to night. Static models miss these temporal fluctuations and cannot provide the minute-by-minute or hour-by-hour temperature information needed for immediate heat warning systems or adaptive cooling strategies.
2. Lack of Predictive Capabilities for Extreme Heat Events: Climate change is increasing the frequency and intensity of heat waves, but static models cannot forecast these events or simulate their impacts on different urban neighborhoods. Without predictive capacity, cities cannot proactively deploy heat mitigation measures or issue timely public health warnings.

3. Prevention of Scenario Testing and Policy Evaluation: Urban planners need to evaluate "what-if" scenarios—for example, how would adding green roofs to 30% of buildings affect neighborhood temperatures? Static models require entirely new data collection and analysis cycles for each scenario, making iterative planning impractical and expensive.
4. Inability to Integrate Continuous Data Streams: Cities are increasingly deploying IoT temperature sensors, weather stations, and thermal cameras, but static modeling frameworks cannot assimilate this real-time information to update and improve their predictions.

How Digital Twin Provides Solutions. Digital Twin technology directly addresses these limitations through several key capabilities:

1. Real-time Data Integration and Continuous Model Updating: Digital Twin systems continuously ingest data from IoT sensors, satellite imagery, weather stations, and urban monitoring networks. This enables the digital model to reflect current conditions and automatically calibrate itself based on observed temperatures, creating a "living" representation of urban thermal conditions.
2. Dynamic Simulation and Predictive Modeling: Unlike static snapshots, a Digital Twin can simulate future thermal conditions based on weather forecasts, seasonal patterns, and expected urban activities. This predictive capacity enables proactive heat management, such as adjusting building cooling systems before peak temperatures occur or pre-positioning emergency resources in vulnerable neighborhoods.
3. Interactive Scenario Testing: Digital Twin platforms allow planners to rapidly test multiple intervention scenarios—adding vegetation, changing surface materials, modifying building orientations—and immediately see their thermal impacts. This interactive capability transforms urban climate planning from a slow,

- linear process into an agile, iterative optimization exercise.
4. Multi-Scale and Multi-Temporal Analysis: Digital Twin can simultaneously represent city-wide patterns and neighborhood-level microclimates, and can analyze thermal dynamics across multiple timescales (hourly, daily, seasonal). This multi-scale capacity ensures that heat mitigation strategies are optimized for both broad urban resilience and localized vulnerable populations.
  5. Adaptive Response Mechanisms: Advanced Digital Twin systems can trigger automated responses to thermal conditions—such as adjusting smart building systems, activating cooling centers, or sending heat alerts to residents—creating a closed-loop climate management system that static methods cannot support.

In essence, Digital Twin transforms Urban Heat Island modeling from a retrospective analysis tool into a proactive, adaptive urban climate management system capable of supporting real-time decision-making and continuous optimization of heat mitigation strategies. There is still no framework that fully integrates social, ecological, and technological factors into a single Digital Twin platform. This shows that we still have a lot to learn about how to build climate systems for cities of the future.

From a technical and geospatial perspective, the principal challenges in implementing Digital Twin for Urban Heat Islands involve limitations in data accuracy and the complexity of integrating various data sources, such as Internet of Things (IoT) sensors, satellite imagery, and spatial data (Lu et al., 2023). Most studies still use static data and simulations that don't happen in real time, which makes it harder to adapt to Urban Heat Island (Zhao et al., 2022). Additionally, urban heat island models primarily focus on macro-scale phenomena, overlooking urban microclimate dynamics, which significantly limit adaptive geospatial analysis for dynamic urban heat island

prediction (Zhou et al., 2019; Santos & Rodrigues, 2022).

To use digital twins to lower the Urban Heat Island, people who work in information technology, environmental science, and urban planning need to work together and have a strong technological base. For the Digital Twin ecosystem to work well, there needs to be standards for data interoperability so that different sources of information can be linked and used to their fullest potential. This will give everyone the ability to make decisions based on data that is correct and helpful.

The best thing about Digital Twin is that it can simulate changes to cities, like adding more green space or changing the materials on the ground, before they happen in real life. You can try out policies or projects with this simulation without doing them. This lowers risks and makes solutions work better. This feature also lets strategies change over time to meet the needs of the community and the effects of climate change.

Making digital twins also brings up issues with data privacy and security, though. If the data is sensitive, collecting it in real time from different IoT sensors and devices could be a privacy issue. We need to set up strict rules for protecting data and tools for cybersecurity to keep it safe and make sure it is used for the right reasons.

In the future, the government, schools, businesses, and the community will all need to work together more to get the most out of digital twins to deal with urban heat islands. The government can set rules and build things that help them work. Academia can create new ways of doing things and new tools. The private sector can innovate and scale Digital Twin solutions, making cities more resilient to climate change, especially the urban heat island effect.

## RESEARCH METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) is an internationally recognized, evidence-based reporting guideline designed to improve the transparency, completeness, and accuracy of systematic

review reporting (Haddaway, N. R et al., 2021). PRISMA provides a standardized framework that helps researchers minimize bias in study selection, enhance reproducibility of the review process, and ensure that all relevant studies are systematically identified, evaluated, and synthesized. The framework consists of a 27-item checklist and a flow diagram that documents the study selection process across four key phases: identification, screening, eligibility assessment, and inclusion. By adhering to PRISMA guidelines, systematic reviews become more rigorous, transparent, and trustworthy, enabling evidence-based decision-making in research and policy contexts.

PRISMA 2020 was selected due to its capacity to render the process of selecting scientific sources transparent, reproducible, and accountable. This approach employs narrative synthesis for comprehensive thematic interpretations and hybrid bibliometric analysis to identify patterns in publications, correlations between concepts, and the evolution of research on digital twins and urban heat islands over time. This mix of methods lets us look at all the theoretical, technical, and geospatial progress that has been made in next-generation urban climate systems.

This systematic review is guided by four primary research questions that structure the analysis across conceptual, technical, and geospatial dimensions:

RQ1: How is Digital Twin conceptualized and defined in the context of Urban Heat Island modeling, and what theoretical frameworks guide its application in urban climate systems?

RQ2: What are the key technical architectures, data integration approaches, and computational methods employed in DT-based UHI modeling, and what are the current technical limitations? implementation.

RQ3: What geospatial modeling characteristics, spatial-temporal resolutions, and data sources are utilized in DT-UHI studies, and what are the existing geospatial gaps?

RQ4: What are the critical research

gaps across conceptual, technical, and geospatial dimensions that need to be addressed for developing next-generation urban climate systems?

This review adopts a hybrid methodological approach that synergistically combines narrative synthesis with bibliometric analysis to provide comprehensive, multi-dimensional insights into the DT-UHI research landscape. The complementarity of these methods addresses different analytical needs and enables identification of conceptual, technical, and geospatial gaps with greater precision and depth than either method alone could achieve.

Data Sources Scopus is the main source of data for this study because it has a lot of international journals indexed in Q1-Q3 and always gives full bibliographic metadata. Other databases, such as Web of Science, IEEE Xplore, and ScienceDirect, were used to make the research more complete. The Digital Twin subject is closely related to computer science, cyber-physical systems, and electrical engineering. Urban Heat Island is a well-known topic in journals on geography and environmental science.

Rationale and Temporal Scope The publications reviewed range from 2017 to 2025, based on the idea that the digital twin idea became important in both academia and industry after 2017 and that research on urban heat islands picked up speed quickly in response to climate change and efforts to plan cities in a more sustainable way. We can look at both past and present trends in urban climate modeling based on the digital twin search strategy during this time period.

The article search used a list of structured keywords that show how digital twins, urban climate modeling, and geospatial data all work together. Some of the most common phrases are "digital twin" AND "urban heat island," "urban climate model" AND "real-time simulation," and "geospatial digital twin" AND "urban microclimate." You can also use Boolean operators, wildcards (\*), and proximity searches to make the search more general, depending on what the database can do. Handling duplicates and checking queries to

automatically remove duplicates, Mendeley gets each search result from different databases. To make sure the search strategy was right, we checked to see if the search results included articles from well-known journals like Building and Environment, Urban Climate, ISPRS Journal of Photogrammetry and Remote Sensing, and Energy and Buildings.

Requirements for Eligibility (Inclusion and Exclusion) Inclusion criteria consist of peer-reviewed articles that exhibit empirical research, numerical simulations, or framework development related to the amalgamation of Digital Twins and Urban Heat Islands. Studies employing geospatial modeling, machine learning, IoT sensors, hydrometeorological data, or physical simulations are also incorporated.

Conversely, the review excluded studies focusing on non-urban contexts, particularly those not associated with urban climate or urban systems. Reasons for Excluding Documents Lacking Peer Review We didn't include theses, policy reports, unindexed conference papers, or opinion pieces because they didn't meet the academic standards for methodology. We also didn't include articles that didn't have technical details, like those that only talked about the digital twin idea in general without any climate or geospatial parts. These were not related to the main point of the research.

The PRISMA flow screening process the screening process is made up of the PRISMA stages of Identification, Screening, Eligibility, and Inclusion. For each article, metadata from four databases was collected during the identification phase. We read the titles and abstracts to get rid of articles that weren't helpful. At this point, articles are

read carefully to make sure they meet the requirements. The final product is a group of articles that can be looked at in depth.

A PRISMA diagram shows how many articles were chosen at each stage and then shows these articles. Getting data out and looking at it, we manually extracted the data using spreadsheets and added analysis tools like R, Bibliometrix, and VOSviewer. Bibliometric analysis includes co-authorship networks, keyword co-occurrence, and thematic evolution to explain how Digital twins - urban heat island research has changed over time and what it is made up of. The systematic screening process is visualized in Figure 1, which presents the PRISMA 2020 flow diagram illustrating the progression from initial database searches through final study inclusion. As shown in the diagram, the four-stage process systematically reduced 268 initial records to 19 eligible studies through rigorous application of inclusion and exclusion criteria at each stage. The PRISMA flow diagram ensures transparency and reproducibility by documenting the number of records at each decision point and explicitly stating the reasons for exclusions. The screening process consists of four standardized PRISMA stages: Identification, Screening, Eligibility, and Inclusion, each serving a distinct methodological function

## RESULTS AND DISCUSSION

The PRISMA 2020 guidelines were used to choose the studies. These guidelines included the steps of finding, screening, assessing eligibility, and including studies. During the identification phase, 268 articles were collected from four primary databases: Scopus (n = 168), IEEE Xplore (n = 50), and

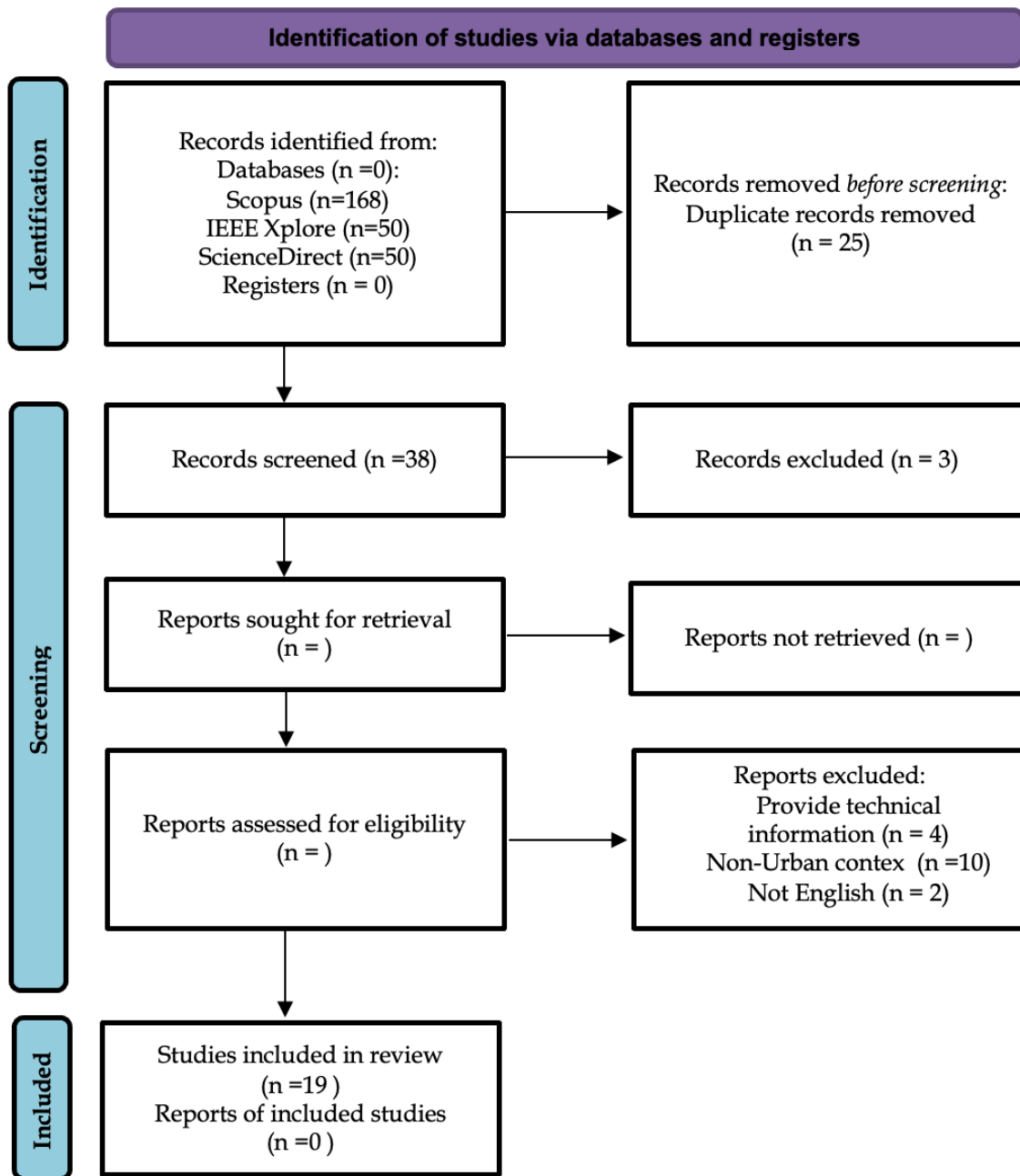


Figure 1: Prisma diagram (Source: J et al. 2021)

ScienceDirect (n = 50). No more records were found in any other databases or registers. After the deduplication process, 25 articles were taken out because they were duplicates. This left 38 articles to be screened again. Based on their titles and abstracts, 38 articles were read during the screening stage. Three articles were turned down because they didn't fit the study's focus. No articles needed a full report search (0 reports sought for retrieval), and all publications could be looked at later. The eligibility

screening stage looks at all of the articles' content to make sure they meet the requirements for inclusion. At this point, 16 articles were left out for the following reasons: Did not give relevant technical information (n = 4), outside of an urban setting (non-urban setting; n = 10) and not in English (n = 2).

Nineteen articles met all the requirements at the end of the selection process and were included in this systematic review. These studies establish the

foundation for conceptual, technical, and geospatial analysis in the integration of Digital Twin and Urban Heat Island.

According to a yearly study of scientific output, the number of papers on digital twins and urban heat islands grew a lot from 2020 to 2025. There were still only about six articles published in 2020. In 2021, this number went down a little, which shows that scientists weren't really interested in combining digital twin and urban climate modeling at the time.

But in 2022, research really took off, and the number of papers published went up to about thirteen. This trend continued in 2023, and the number of scientific articles published rose to twenty. Digital Twin is slowly becoming more popular, and more and more people are paying attention to how it can help improve urban climate systems. This is because there is a growing need to study microclimates, model smart cities, and

sense cities.

The years 2024 and 2025 saw the most changes. In 2024, there were more than fifty articles, and in 2025, there were about seventy articles, which was the most. Because of this jump, the Digital Twin and Urban Heat Island combination is now a very busy area of study. This is because of improvements in real-time sensor technology, cloud computing, geospatial AI, and the need to lessen the effects of climate change on cities.

This growth trend shows that we are moving toward new types of urban climate systems. Researchers and people who work in the field need more and more models that are based on current data, can change over time, and can make predictions. The number of publications going up from 2024 to 2025 shows that the field is growing quickly and will probably keep growing in the future.

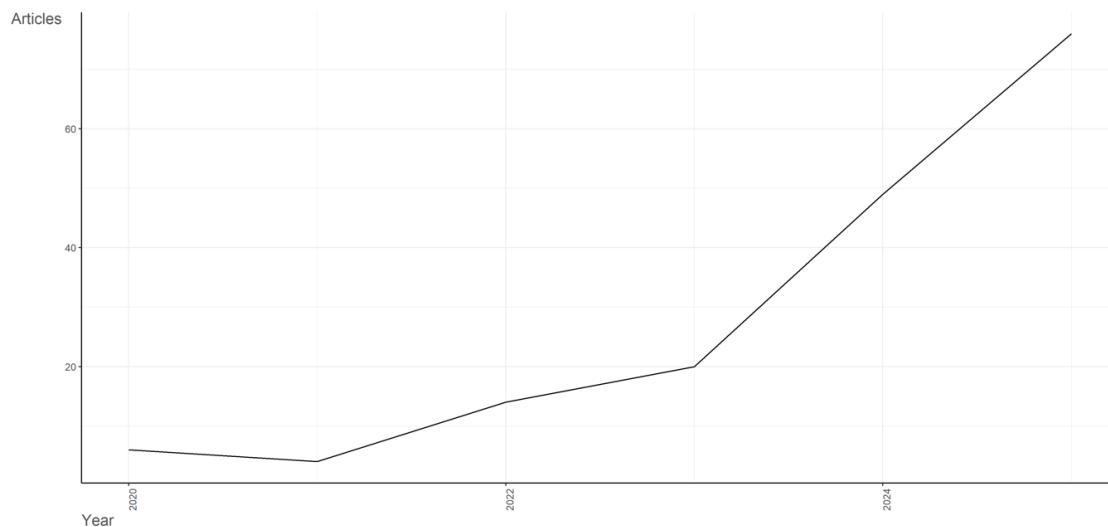


Figure 2: Annual Scientific Production (2020-2025) (Source: Research Result, 2025)

Bibliometric mapping of global scientific output indicates a significant spatial concentration in publications concerning Digital Twin and urban heat islands, with distribution patterns that underscore the disparities in research capacity among regions. The collaboration map shows that most scientific work happens in rich, technologically advanced countries that have a long history of research in urban analytics, geospatial science, and urban climate simulation models.

China became the most important player in the Digital Twin and urban heat island research world, as shown by the most intense color and the most connections between networks. This dominance fits with China's national plan for building smart cities, digital infrastructure, and using real-time urban informatics to lower the heat in cities. China's work with countries in Europe and North America shows that research integration across regions is getting stronger in the fields of digital twin engineering and

urban climate modeling.

The United States also made a big contribution, which included a lot of scientific work and a network of international cooperation that stretched from East Asia to Western Europe and Australia. This position shows how good the US is at making cyber-physical systems, computational modeling methods, and AI-based urban climate analytics. The US is an important center for sharing knowledge and technology in the Digital Twin and urban heat island fields because it has a large network of people working together.

The UK, Germany, Italy, the Netherlands, and France are all very important to the global research network in Europe. These countries have a long history in geospatial science, urban climatology, and physics-based modeling. This makes the methods and techniques used in digital twin and urban heat island research even better. Strong cooperation between European countries also shows that regional integration is happening in the creation of a digital twin framework for urban climate systems.

The Asia-Pacific region, especially Japan, South Korea, and Australia, has a lot of publications and a wide range of research methods. These countries are very important for putting together high-resolution sensor data, remote sensing, and 3D/4D modeling, which are all very important for making urban digital twins.

At the same time, countries in South Asia, like India, are growing quickly, but they don't have as much ability to work together as other global research centers. In this area, the main focus of research is on how the climate in megacities changes, how temperatures rise to extremes, and how machine learning can be used to predict the Urban Heat Island in space.

People from the Middle East, Latin America, and Africa are less likely to contribute, with most of the research coming from the United Arab Emirates, Brazil, Mexico, and South Africa. The presence of these countries expands the geographical dimensions of research and offers a more diverse climate and urban morphology context for the development of Digital Twin and Urban Heat Island models, even though their contributions are still limited.

The collaboration network map shows that digital twin and urban heat island research is done all over the world, but it is still mostly done in certain areas. Countries with a lot of research capacity and a mature technological ecosystem are the ones that do the most research. The network structure that came out of this shows how important working together across borders is for dealing with the complexity of urban climate models, combining geospatial data from many sources, and making next-generation digital twins that can work in real time, dynamically, and with predictions.

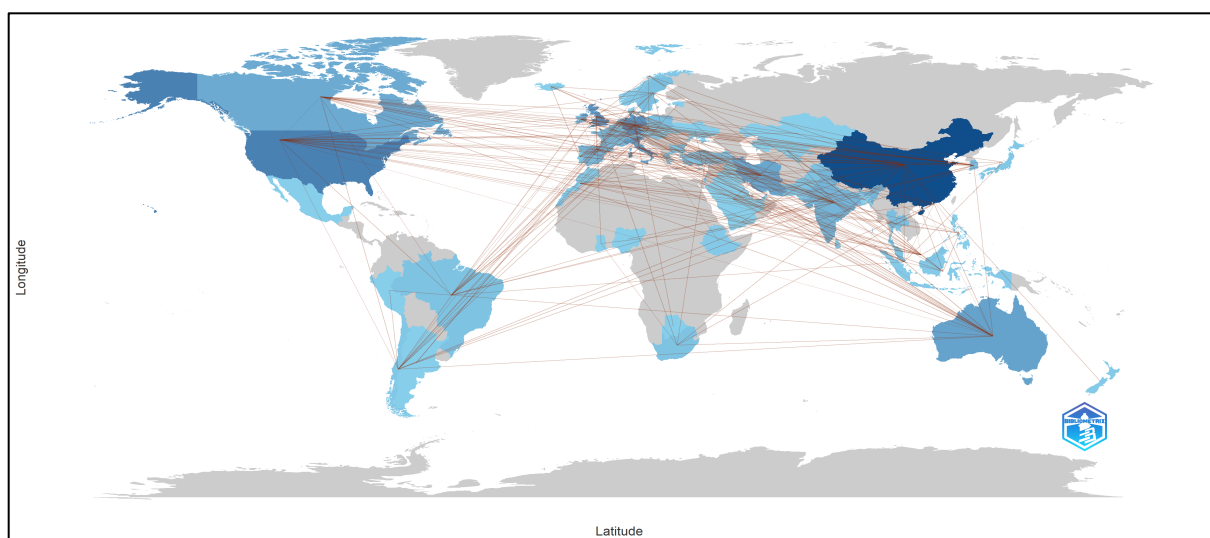


Figure 3: Countries' Collaboration World Map (Source: Research Result, 2025)

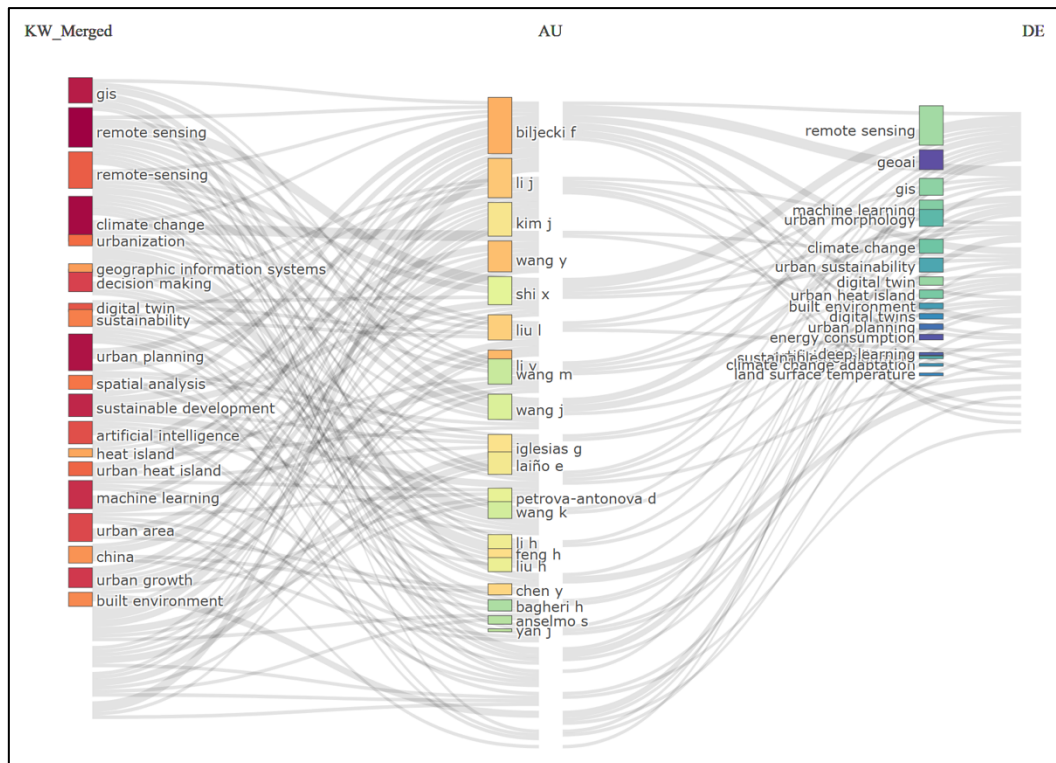


Figure 4: Three-Field Plot showing relationships between Keywords (left), Authors (center), and Research Themes (right) (Source: Research Result, 2025)

The three-field plot shows how keywords, lead authors, and research themes are related in the Digital Twin–Urban Heat Island Digital Twin and Urban Heat Island literature. It is clear from the keywords that GIS, remote sensing, digital twin, machine learning, and urban heat island are the most common ones. This shows that research in this area is strongly based on geospatial science, computational modeling, and urban climate analysis.

This conceptual network is centered around authors like Biljecki F, Wang Y, Li J, Shi X, and Kim J. Their work links different key words to research topics like urban sustainability, climate change, urban planning, the built environment, and land surface temperature. This relationship shows that the authors have different areas of expertise. Some focus on geospatial analytics, while others focus on digital twin modeling and microclimate dynamics.

Research primarily focuses on themes such as geoAI, machine learning, urban morphology, and climate change adaptation. The connectivity patterns we saw show that digital twin and Urban Heat

Island research is growing at the crossroads of geoinformatics, intelligent computing, and urban sustainability studies. They also show how digital twin technology and spatial analysis are becoming more and more connected in understanding and reducing the urban heat island phenomenon (Budzik et al., 2025; Kumar et al., 2025; Qi et al., 2022).

Studies on the combination of Digital Twin and Urban Heat Island show that Digital Twin is a dynamic digital model of the city that can show real-time conditions through different levels of virtualization. In urban climate modeling, Digital Twin acts like a real-time mirror that uses sensor data, computational models, and feedback loops to predict how the temperature will change and how the city's surface will respond to heat. This idea is in line with recent studies that stress the importance of urban thermal dynamics and the complicated relationships between plants, buildings, and the weather (Budzik et al., 2025; Kumar et al., 2025; Zhao et al., 2025).

The conceptual framework for incorporating Urban Heat Island into the



response indicate that data processing quality is essential for the efficacy of Digital Twin-based urban climatology systems (Budzik et al., 2025; Cardenas Leon et al., 2024; Na et al., 2025) (Budzik et al., 2025; Stergiopoulos et al., 2025).

Data interoperability is a key issue because CityGML, BIM, GIS, and IoT need to use the same semantic and metadata standards to work together. Also, there is a trade-off between edge computing, which is faster, and cloud computing, which has more computing power. For climate adaptation decision-making applications, integrating machine learning into the Digital Twin pipeline also needs explainable AI mechanisms (Elnabawi & Raveendran, 2024)

Geospatial data's features are very important for the success of digital twin-based urban heat island modeling. The spatial and temporal resolution of LST data is one important part. Recent studies show that high resolution is needed to map changes in surface temperature at the micro scale, even in urban canyon features (S. Wang et al., 2024). But high-resolution data often has time limits, which makes it hard to combine data from different sources.

The city's shape also has a big effect on how heat moves around, including things like the sky view factor (SVF), canyon geometry, and building density. These have been tested in different studies on urban ventilation and heat release (Sangeetha et al., 2024; Shahriar et al., 2025).

This change is a key part of both physics-based simulations and models that use data. There were also a few gaps in geospatial data. First, urban heat island studies still focus on city centers, even though suburban areas are often left out, even though they are getting a lot hotter (Halder et al., 2025; Patle and Ghuge 2025; Arsiso 2025; Rajagopal, Priya, and Sudha 2025; Kporha et al. 2026). Second, research seldom integrates meso- and micro-scale modeling concurrently, resulting in a disjunction between regional and local dynamics (Budzik et al., 2025). Third, there is inconsistency in geospatial metadata, especially when combining satellite, UAV, and 3D mapping data. This

makes urban heat island predictions less certain (Manet al., 2025).

Conceptually, the results of this SLR indicate that there is still a lack of alignment in the definitions and frameworks regarding digital twins in the context of urban climatology. Although various studies suggest that digital twins serve as dynamic or real-time mirrors of cities (Cardenas Leon et al., 2024; Metcalfe et al., 2024; Muñoz-Alegría et al., 2025; Stergiopoulos et al., 2025), there is no consensus regarding the depth of virtualization (e.g., Digital Twin levels 1-5), sensor granularity, or the structure of model-data interaction. This difference is clearly visible between engineering literature (which tends to emphasize cyber-physical architecture) and urban climate literature (which emphasizes heat transfer processes, radiation, and urban morphology) (Muñoz-Alegría et al., 2025).

Additionally, the fragmentation of concepts between physics-based, data-driven, and hybrid microclimate modeling approaches indicates that digital twin-urban heat island research is still in the theoretical consolidation phase. While hybrid modeling is touted as the ideal approach (Wang et al., 2024; Elnabawi & Raveendran, 2024), the literature has not yet provided standard guidelines for integrating physics-based simulations with AI models in a unified manner.

On the technical dimension, the analysis results indicate that the complexity of data integration is the main constraint in the implementation of the city-scale Digital Twin – Urban Heat island Data from UAVs, satellites, IoT, and weather stations must be combined in a real-time pipeline, but various studies report obstacles such as latency, data noise, sensor drift, and imbalances in spatial-temporal resolution (Budzik et al., 2025; Halder et al., 2025; A ydt et al. 2026); Vitanova, Petrova-Antonova, and Shirinyan 2025; Senthil, 2025); Atanasov, Kottler, and Bulatov, 2024). This makes it difficult to generate consistent and responsive simulations, especially for heatwave monitoring and emergency climate adaptation applications.

Data interoperability between

CityGML, BIM, GIS, and IoT is also an important issue. Recent literature shows that research has not yet achieved a uniform semantic standard for linking building geometric dimensions, land cover, surface temperature, and meteorological data within a harmonious Digital Twin architecture (Abdulqader et al., 2025; Jafary et al., 2024; Li & Feng, 2025). Another unresolved challenge is the need for explainable AI in urban heat island predictive models so that the results of the Digital Twin can be accepted as a basis for policy decision-making.

Geospatial analysis highlights several significant weaknesses in the spatial representation of the urban heat island phenomenon. First, most studies are located in central city areas, while suburban and peri-urban areas are still underrepresented, although some studies indicate that these regions are experiencing heat intensification due to land use change (Halder et al., 2025). Second, most models only work at the meso or micro scale, so multi-scale coupling—which is crucial for understanding regional and local heat interactions—is almost non-existent (Assenova et al., 2024).

Third, the mismatch between the spatial resolution of satellite land surface temperature and the microclimate model leads to inconsistencies in thermal signatures, especially when used for calibrating digital twin models. This increases the uncertainty of predictions, as reported by (Wang et al. 2024; Li, Chakraborty, and Wang 2023; Varentsov, Grishchenko, and Konstantinov 2021; Hammerle et al. 2017) in their study on the influence of urban morphology on heat variability.

The cross-disciplinary synthesis of this literature shows that the evolution of Digital Twin-Ur is not only technical but also epistemological. On one hand, advancements in machine learning and 3D/4D modeling are accelerating the process of city digitalization. On the other hand, perspectives from urban engineering, city planning, and environmental science show that the Urban Heat Index problem is not just a matter of thermal physics but a

systemic issue involving spatial planning, ecology, energy, and human behavior.

This leads to the need to build next-generation urban climate digital twins that not only simulate temperature but also integrate: airflow behavior (CFD), dynamic vegetation, human activity, policy responses, and evidence-based climate adaptation scenarios. Thus, the Digital Twin moves from being a mere representation tool to a decision support system (climate-informed decision intelligence). Based on the findings of this SLR, there are several priority research directions: Standardization of Digital Twin definitions and frameworks for urban climate, including levels of virtualization, data pipelines, and interoperability standards. Multi-scale climate coupling integration that combines micro (urban canyon), meso (city), and regional scales to improve the accuracy of heat dynamics. Development of hybrid AI-physics model architectures that are not only accurate but also transparent and explainable (explainable hybrid twins).

Utilizing very high-resolution geospatial data, including LiDAR, hyperspectral, and thermal UAV data, to enhance urban morphology modeling. More inclusive research for suburban areas and developing countries, considering that the urban heat island phenomenon varies greatly depending on the social, economic, and morphological context of the city. These synthetic results have direct implications for urban planners and policymakers. Digital twin - urban heat island can be transformed into a smart urban platform for vegetation and material-based heat mitigation, heat-resistant infrastructure planning, real-time heatwave monitoring, and evaluating the impact of urban design policies.

## CONCLUSION

This systematic review has comprehensively examined the integration of Digital Twin technologies with Urban Heat Island modeling through a hybrid approach combining narrative synthesis and bibliometric analysis. The review identified 19 eligible studies from an initial pool of 268 records, revealing significant progress

alongside persistent challenges. Key findings indicate that while Digital Twin-Urban Heat Island research is experiencing exponential growth (from 6 publications in 2020 to 70 in 2025), the field faces critical gaps in conceptual standardization, technical integration, and geospatial representation. The research landscape is dominated by high-income countries (China, USA, Europe), with limited contributions from regions most vulnerable to Urban Heat Island impacts.

The hybrid methodological approach successfully identified three gap types: 1. Conceptual gaps: Lack of standardized definitions and theoretical frameworks 2. Technical gaps: Data interoperability, real-time processing, and scalability challenges 3. Geospatial gaps: Resolution inconsistencies and suburban underrepresentation. The literature on digital twin applications in urban climatology lacks standardized definitions and frameworks, leading to disjointed methodologies between engineering and climate research. Integrating different types of data sources, like IoT sensors, UAVs, and satellite images, is still a technical challenge because of problems with data interoperability, latency, calibration, and computational scalability. Geospatial studies frequently exhibit a bias towards urban centers and often lack multi-scale modeling, which undermines the reliability of urban heat island simulations, particularly in suburban and peri-urban settings.

Despite these challenges, the rapid growth in scientific output and global collaboration—especially among technologically advanced countries—shows that more and more people are realizing how important digital urban heat island systems are. Moving forward, research priorities should focus on making conceptual frameworks work together better, making it easier for different data infrastructures to work together, creating hybrid AI-physics models, and encouraging research that takes into account different urban morphologies and socio-economic contexts. In the end, improving Digital Twin-Urban Heat Index integration will help policymakers and other

stakeholders make smart, evidence-based decisions about climate change by supporting smarter, more resilient urban planning and adaptive heat mitigation strategies.

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