SCIEPublish

Article

The Thermal Impact of Various Pavement Materials on Outdoor Temperature in a Temperate Four-Season Climate: A Case Study of Arak City, Iran

Masoumeh Atifehpour * and Roozbeh Arabi

Young Researchers and Elite Club, Khomein Branch, Islamic Azad University, Khomein 13485-38816, Iran; roozbeh.arabi7@gmail.com (R.A.)

* Corresponding author. E-mail: masoumeh.atifehpour7@gmail.com (M.A.)

Received: 26 July 2025; Accepted: 21 August 2025; Available online: 28 August 2025

ABSTRACT: Urban heat and oasis effects significantly alter urban microclimates due to anthropogenic heat emissions and the thermal properties of urban surfaces. This study aims to quantitatively assess the thermal effects of different pavement types on outdoor temperatures across seasonal extremes in a temperate four-season climate. Conducted in Arak city, Iran, on 22 July and 22 January 2023, this research investigates both warm and cold seasons to provide a comprehensive understanding of pavement influence on urban microclimates throughout the year. Using the ENVI-met 5.0.3 modeling software, an environmental meteorology tool for simulating urban microclimates, the thermal performance of commonly used asphalt pavement was compared with alternative materials such as basalt and light-colored concrete on Dr. Hesabi Street. Simulation results reveal that basalt and light-colored concrete pavements reduce summer cooling loads by up to 3.49 degrees Celsius (°C), enhancing pedestrian thermal comfort, but simultaneously increase winter heating demands by 1.04 °C. This balance presents an optimal scenario to minimize adverse climate effects across seasons. The findings offer valuable insights for sustainable urban planning, promoting resilient city design strategies that mitigate heat and oasis effects in diverse climates. This study contributes actionable recommendations for urban planners seeking to balance thermal performance in temperate climates with seasonal variability.

Keywords: Pavements; Cooling load; Heating load; Outdoor temperature; Pedestrian level; ENVI-met

1. Introduction

Human activities have increasingly impacted the environment in recent years, prominently contributing to climate change through anthropogenic heat emissions [1]. The consequences of these impacts manifest prominently in urban areas, where phenomena such as the urban heat island (UHI) and oasis effects cause significant temperature changes that vary by city and require tailored adaptation strategies [2]. Urban microclimates play a crucial role in shaping outdoor thermal comfort, which directly influences residents' health, energy use, and overall well-being by affecting temperature, air quality, and humidity levels [3,4]. For example, elevated temperatures increase the risks of heat-related illnesses during summer, while cold winters exacerbate heating demands and related health issues [5]. Furthermore, these microclimatic conditions substantially affect building energy consumption, as cooling and heating loads fluctuate with outdoor temperature variations [6].

This study focuses on a four-season climate, exemplified by Iran, where summers are hot and dry, and winters are cold. Managing thermal comfort in such climates requires addressing both extremes, which is critical for reducing energy consumption and mitigating health risks [7]. Arak, located centrally in Iran, exhibits typical seasonal variations with extreme temperature fluctuations, making it an ideal case study for testing urban microclimate moderation strategies. Although most previous research has concentrated on mitigating the UHI effect in summer, there is a significant research gap regarding the impact of surface materials on heating load during winter, which this study aims to address.

Outdoor temperature fluctuations greatly influence the energy required for indoor thermal comfort [8]. Consequently, altering outdoor microclimates to provide pleasant conditions for residents engaged in outdoor activities is essential for urban livability [9]. Urbanization intensifies these challenges in cities like Arak, where densely populated streets

https://doi.org/10.70322/ces.2025.10012

such as Dr. Hesabi Street experience pronounced temperature swings, worsening UHI in summer and extreme cold in winter. The prevalent use of materials incompatible with local climate exacerbates seasonal health problems and energy demands.

Addressing urban microclimate issues is vital for local comfort and broader urban sustainability goals, including public health improvements, economic savings, and environmental quality [3,10]. Innovative sustainable urban pavement materials—including permeable, reflective, and recycled pavements—have demonstrated benefits such as reducing surface temperatures, stormwater runoff, and enhancing durability [11]. For example, cool pavements can lower surface temperatures by up to 16°F compared to conventional asphalt [12], while phase change materials (PCMs) embedded in asphalt can regulate temperature fluctuations, mitigating UHI effects [13].

Therefore, regulating outdoor temperatures to improve pedestrian comfort and reduce energy demands is crucial for sustainable urban development [14,15]. This study analyzes and compares the effects of multiple ground cover materials on outdoor temperatures during warm summers and cold winters in Dr. Hesabi Street, Arak, focusing on energy consumption reduction, thermal comfort improvement, and environmental sustainability enhancement. Using ENVI-met 5.0.3 simulations, this study conducts a comparative evaluation of multiple surface materials under both summer and winter conditions to identify optimal solutions for four-season climates. A schematic summary of the research methodology and analytical workflow is provided to enhance clarity and facilitate a deeper understanding of the study's approach (Figure 1).

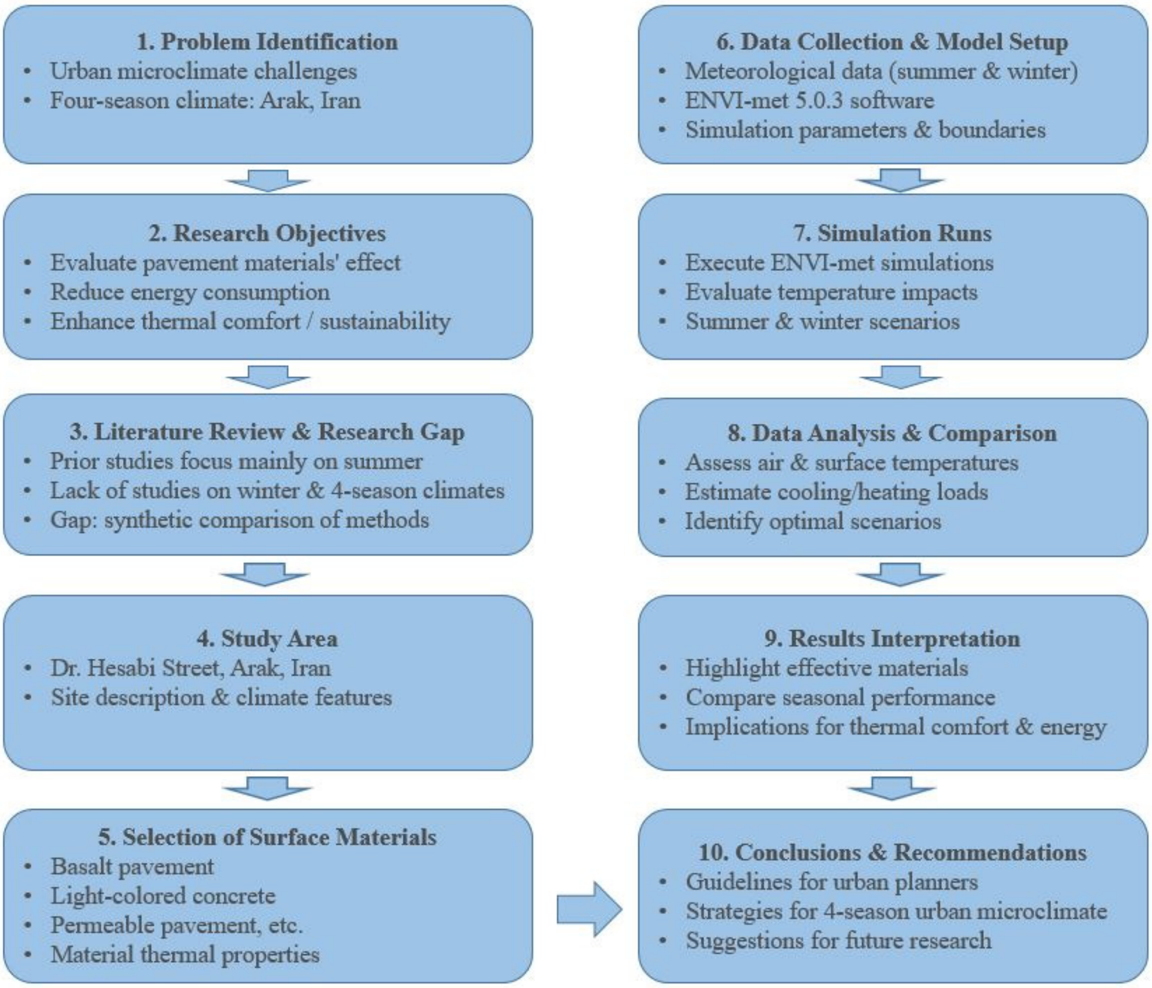


Figure 1. Research methodology and analytical workflow illustrating the assessment steps for pavement materials in Arak, Iran.

2. Research Background

Managing the environmental temperature balance in urban open spaces has recently become a key research focus, motivated by the need to mitigate UHI effects and improve outdoor thermal comfort. Various studies have highlighted effective strategies, often focusing on summer conditions, but with limited attention to cold seasons in regions with four-season climates. For example, Fiorillo et al. modeled street radiant temperatures in the Netherlands using ENVI-met software, underscoring the importance of microclimatic variables like humidity and wind speed for thermal comfort [16].

Several urban heat mitigation approaches including tree planting, green roofs, reflective surfaces, and increased permeability, have been studied in cities such as Vancouver and Mexicali, demonstrating effectiveness in reducing UHI intensity and improving air quality [17,18]. However, these tend to emphasize warmer seasons. Kappou et al. demonstrated significant surface temperature reductions from cool reflective materials during Athens summers, yet the seasonal balance remains inadequately addressed [19].

Research has identified that some green infrastructure benefits in summer may increase heating loads in winter [20], pointing to the complexity of dual-season urban climate management. For instance, evergreen plants reduce solar absorption in winter due to shading effects [21], impacting heating demands. Similarly, cool pavements can reduce air temperatures by up to 5 °C in summer, but their thermal behavior varies with material type and season [22,23].

Advanced materials, such as thermochromic asphalt, offer dynamic responses by altering reflectivity based on temperature extremes to mitigate ice formation in cold and reduce heat absorption in summer [24]. Permeable pavements generally maintain cooler temperatures in summer but may present challenges during freeze-thaw cycles [25].

Despite these advances, most studies concentrate on tropical or single-season climates, creating a significant knowledge gap regarding the comprehensive management of temperature extremes in four-season climates. Additionally, there is limited comparative analysis of simulation methods applied across seasons and materials. This study fills these gaps by evaluating multiple surface materials through ENVI-met modeling within a four-season context, enabling a synthetic comparison of their seasonal performances.

It should be noted that research on urban temperature management often neglects winter conditions, rendering findings less applicable to four-season climates such as Iran's. This underlines the unique contribution of our study in addressing environmental temperature balance for year-round comfort and energy efficiency in regions with pronounced climatic variation.

In summary, while sustainable materials and urban planning can mitigate UHI effects and improve thermal comfort, comprehensive strategies that consider both summer and winter conditions remain scarce. This research aims to provide such strategies, focusing on four-season climates and bridging the existing gaps in knowledge through a systematic simulation-based approach.

3. Urban Heat Island and Oasis Effect

3.1. Concept of Urban Heat Island and Oasis Effect

Earth is considered as an interconnected set consisting of elements such as water, soil, air, and biosphere with the interaction between them. However, the world is facing rapid urban sprawl [26].

Some believe that human stressors have created a unique situation that these factors may cause changes and transformations in the efficiency and foundation of the land system or a part of it [27].

Deforestation and change of land use of forests, construction of roads and development of residential land, and the physical dimensions of cities and requests for goods and resources by citizens have caused a reduction in the amount of global carbon deposition [28].

Heat islands refer to urban areas with a higher temperature than the average temperature, and oasis is an area with a lower temperature than the average temperature [29].

If the ways to deal with the heat island effect are managed, it can eventually lead to the creation of an oasis effect. In addition, the oasis effect is one of the comprehensive and sustainable methods known for cities in the future [30].

In general, there are three types of urban heat islands:

1. The thermal island of the urban boundary layer causes heat and increases the temperature of the atmosphere above the city compared to the surrounding suburbs.
2. The heat island above the urban crown means a significant increase in the air temperature in the space between the ground and the roof of the buildings.
3. The heat island of the city surface refers to the difference in the temperature of the ground surface in urban areas and rural areas [31].

One of the effects that is directly related to human intervention is the increase in temperature in urban areas compared to the countryside [32].

One of the main reasons for the emergence of the UHI is the use of materials incompatible with the environment in covering the street surface, such as asphalt with a dark color, which absorbs radiant energy, and the process of increasing the temperature of buildings and pollutants in the air. Urban heat is derived from anthropogenic heat, environmental pollution, waterproof surfaces, urban geometry and thermal characteristics in urban surfaces [3].

According to the statistical data analysis, changes in the climate pattern of the earth are happening, especially in urban areas. The effect of these changes in the climate, which is present in most of the characteristics of the human environment, causes the UHI to intensify. Intensification of the urban heat island, in addition to the effect it has on the ecosystem in which we live and the quality of the environment and mental and physical health, has adverse effects on the amount of cooling load and the emission of greenhouse gases and environmental pollutants [33].

3.2. Flooring Materials as One of the Factors of the Urban Heat Island Phenomenon

The results of experiments and simulations obtained by researchers regarding the effect of surface temperature on air temperature show that the rise of surface temperature is related to air temperature [34].

One of the most effective factors on the surface temperature and adjusting areas is the solar reflection coefficient and the radiative emission of solar radiation reaching the atmosphere of earth. A high percentage of the surface solar radiation with a low albedo is absorbed, a percentage of solar energy is absorbed by the earth and buildings, and some of it moves to the air and the atmosphere [35].

A large part of urban areas lacks vegetation and is covered with dark colored materials compared to the suburbs and rural areas. In fact, this difference has an impact on climatic patterns, energy consumption, and habitability in urban areas. Consequently, in urban areas, due to the use of dark-colored materials on the surfaces and the lack of vegetation cover, the outdoor air temperature increases and leads to creating of an UHI effect [36].

The development of using pavements due to the use of waterproof materials with high capacity on thermal energy storage increases the thermal mass, causes changes and transformations in the ground, and has a significant impact on the UHI [37].

The emergence of heat islands and the problems they cause can be attributed to the use of asphalt, which exacerbates the urban heat effect. In cities where the population has surpassed that of surrounding villages and countryside, higher air temperatures are common, leading to increased use of air conditioning systems and higher energy consumption during the summer season [38].

The network of urban streets is one of the most important and effective factors in absorbing more of the solar energy and converting it into heat. With the construction and development of the street network and the rapid physical development of urban areas, dealing with noise pollution is on the agenda of many road construction projects and operations. However, controlling the absorption of radiation emitted from the sun and the transfer of unfavorable heat to the environment has not been included in the programs of many projects [39].

4. Cool Pavement as a Technique to Achieve Outdoor Air Temperature Balance

Several solutions have been presented to control the increase in temperature of urban surfaces, and one of the methods used in this field is cool materials on the surfaces of urban streets. Cool materials are light-colored materials with a high albedo [40].

Cool pavement is among emerging materials and technologies. Compared to traditional pavements, these pavement materials and technologies reduce the surface temperature of pavements and produce less heat in the atmosphere [41].

By using various techniques and methods, cool pavements can reduce the negative effects of the UHI effect [42].

The process of absorption of solar thermal energy during the day by artificial surfaces and release of waves at night occurs by the albedo and emissivity of materials [43].

Albedo means the ratio between the energy reflected from the earth's surface and the radiation that reaches the earth's surface, which affects the temperature of the surface of the pavement, especially during the day, according to the color of the materials [44].

Emissivity refers to the ratio between the energy emitted by a surface and the energy emitted by a black surface, which affects the temperature of the surface, especially at the end of the day [45].

The thermal performance of road pavement surface in relation to solar radiation and thermal radiation is affected by albedo and emissivity, which are two determining components in this field [46].

An increase in albedo not only reduces the surface temperature of pavements and releases less heat into the atmosphere but also improves visibility at night and increases the durability and resistance of the pavement system [47].

Pavements generally consist of fine and coarse stone materials that are covered with a special glue. Increasing the albedo is possible by properly covering the surfaces or stone grains with a light color, a special glue, or a combination of the mentioned items [48].

4.1. All Kinds of Cool Pavements

4.1.1. Permeable Pavements

Materials with a dense structural feature and without open pores absorb the radiant heat of the sun and enter it inside. In fact, this type of material acts like a battery that stores thermal energy inside itself. At night, when the solar radiations are reduced, materials with a dense structural feature release their heat stored in depth into the atmosphere. Due to their porous structural feature, materials with permeability have a lower heat capacity and thermal conductivity compared to materials without open pores, and release heat equally [49].

Also, in permeable materials, with the increase in temperature due to the ability of water to pass through the empty space in the material, this water evaporates and leads to a decrease in the temperature of the material, and they get cooler [50].

4.1.2. Reflective Concrete Pavements

The surface albedo of pavements is directly related to the characteristics of materials that include a wide range. Colorful asphalt or concrete pavement can be known as pavement surface materials. New asphalts are not colored due to the enclosing of the aggregates by bitumen and their inability to reflect sunlight have a negligible amount of albedo. Bitumen will disappear over time, for a period of five to ten years. However, the newly constructed concrete pavement has a higher albedo than the asphalt pavement, and it gradually decreases over time [51].

4.1.3. Colored Paving Stones

In the late 1990s, a new solution was presented to improve the beautification of the urban landscape. The use of colored pavements in urban streets has been very common for citizens in order to improve aesthetics and functionality.

According to the definition provided by the Federal Highway Administration of the United States of America, colored pavement includes different types of pavements, which include different colored materials, colored asphalt, colored concrete, and is known as colored pavement and is placed on the road surface [52].

One of the effective measures is using light-colored coverings in the tunnel to improve drivers' visibility and reduce the cost of electricity used for lighting [53].

Spreading of colored stone materials is useful to improve the color of the asphalt covering and to improve the safety level due to the increase in the coefficient of friction of the pavement surface. Brightening the color of the pavement surface due to the use of bright colored materials, in addition to increasing the reflection coefficient of the solar radiation, leads to the filling of holes and empty spaces in the surfaces and reduces the permeability [54].

4.1.4. Increasing Thermal Capacity as a Technique in Materials Used in Cold Climates

Thermal capacity and thermal conductivity are factors for heat storage. By increasing thermal conductivity in materials, it is possible to transfer heat in the depth of the material. While by increasing thermal capacity materials with heat transfer and slow movement in their depth have the ability to store heat in themselves, and dividing the coefficient of these two characteristics is called the thermal diffusion coefficient. Materials with a high thermal diffusion coefficient tend to conduct heat to deeper layers. As a result, the temperature of the material remains unchanged for a longer period of time. The material with a low thermal diffusion coefficient causes the heat to reach only the surface layer of the material. As a result, it causes the heat to exhaust quickly from the object [55].

5. Methods and Materials

5.1. Research Hypothesis

This study hypothesizes that varying pavement materials significantly influence urban microclimate thermal conditions, reducing outdoor air temperatures and heating/cooling loads in a typical four-season temperate climate. Specifically, selecting and applying more reflective, permeable, or thermally adaptive pavement materials will effectively moderate thermal extremes during both summer and winter seasons in Dr. Hasabi Street, Arak.

5.2. Simulation with ENVI-Met Software 5.0.3

ENVI-met is a 3D microclimate simulation software based on computational fluid dynamics (CFD), designed for detailed urban environmental modeling [56]. It simulates atmospheric circulation, surface thermal fluxes, vegetation transpiration, soil thermal properties, and calculates thermal comfort indices such as PMV [57].

ENVI-met was chosen because it integrates complex interactions among urban materials, vegetation, and atmospheric processes with fine spatial resolution (1–10 m). This allows comprehensive analysis of pavement types on microclimate in both summer and winter. Alternative software models lack a similar combination of environmental interaction and 3D building modeling in a microclimate context.

While ENVI-met provides a powerful modeling framework, potential limitations include assumptions in turbulence modeling, simplified radiation models, and the inability to simulate long-term climate variability when only single days are simulated. Results should therefore be interpreted within these constraints.

5.3. Software Model Validation

To validate the model, air temperature and relative humidity data were collected with data loggers at three urban sites within Arak over one week in November 2023 (10:00 a.m.–3:00 p.m., at 1.1 m height) (Figure 2).

Measurement information			
precision	Manufacturing country	Product type	Measurement quantity
≥ 70% RH: ±(3%reading+3%RH < 70% RH: ±3%RH ±0.8°c	Taiwan	Lutron HT-3007SD	Temperature and humidity

Figure 2. Specifications of the data logger device and the location of meteorological data collection used for model input. The arrows labeled A, B, and C indicate the three selected measurement points, and the circle represents their corresponding locations.

Correlation coefficients between ENVI-met simulated values and observed data were calculated using Excel, showing a high degree of correlation. This confirms ENVI-met's suitability for urban microclimate simulation in this context (Figure 3).

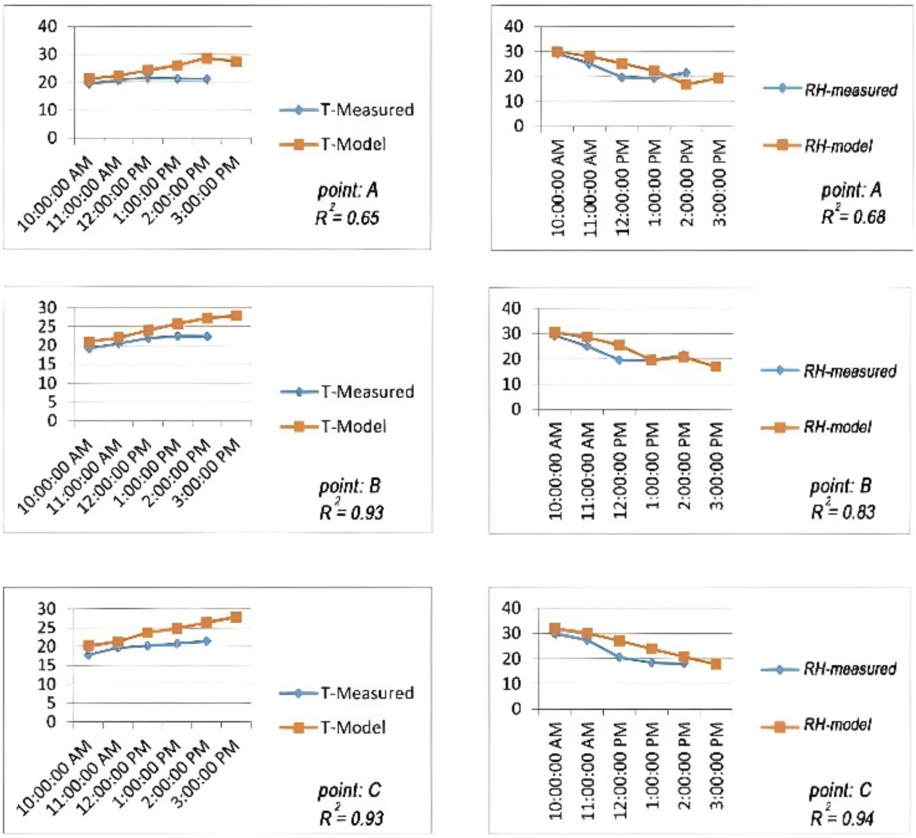


Figure 3. Correlation between temperature and humidity variables measured by the data logger and those calculated by ENVI-met software at the corresponding locations.

5.4. Case Study Selection Criteria and Rationale

Dr. Hasabi Street in Arak was deliberately selected as the case study site because it typifies a centrally located, densely urbanized corridor in a temperate four-season climate. This street experiences pronounced temperature extremes—hot, dry summers and cold winters—making it representative of microclimatic challenges faced by many similar mid-sized cities in Iran and comparable climate zones globally. The area's high pedestrian and vehicular traffic volume, combined with its mixture of residential and commercial buildings varying in height (3–15 m), produce complex urban heat phenomena intensified by prevalent use of dark, impermeable materials (asphalt and travertine).

Compared to peripheral or less dense urban areas, Dr. Hasabi Street distinctly reflects microclimate issues driven by urban morphology, material composition, and anthropogenic activity, thus making it an appropriate and relevant setting to evaluate pavement material interventions (Figure 4).

Figure 4. Geographic location map of Dr. Hasabi Street, where the case study is conducted. The circle indicates the specific area studied.

5.5. Model and Analysis of the Current Urban Context of Dr. Hasabi Street

The street is a one-way, 20-m-wide road paved with conventional asphalt, flanked by sidewalks surfaced with hard, dark, and impermeable materials (Figure 5).

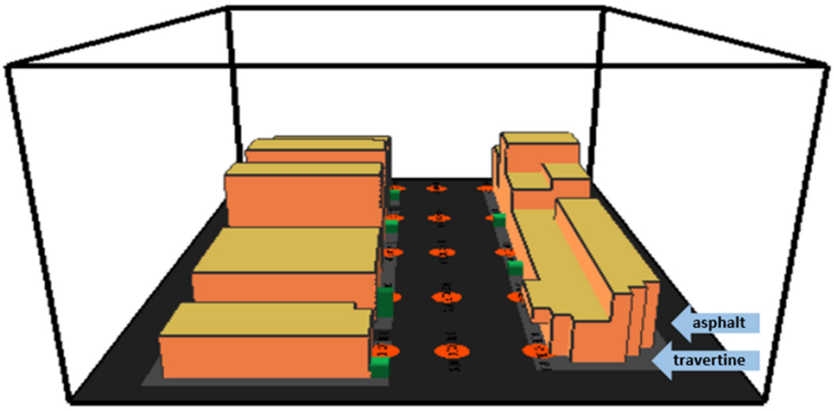


Figure 5. Current physical and environmental status of Dr. Hasabi Street, including the existing pavement and sidewalk materials.

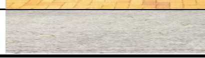
Trees are irregularly spaced without strategic planning, and buildings vary between 3 and 15 m. These conditions contribute to severe thermal stress during summer and winter (Figure 6).

Figure 6. Photograph illustrating another aspect or section of the current situation of Dr. Hasabi Street.

5.6. Simulation Scenarios of Material Change in Land Cover

Using ENVI-met 5.0.3, four distinct pavement material scenarios (Cases A–D) were simulated to evaluate their effect on outdoor air temperature during summer and winter (Table 1).

Table 1. Specifications of materials used for different pavement scenarios.

Material	Albedo	Emissivity	Heat Capacity	Material Image
Asphalt	0.2	0.9	0.92	
Asphalt with read coating	0.5	0.9	0.92	
Basalt brick	0.8	0.9	0.84	
Travertine stone	0.2	0.8	0.88	
Light concrete	0.8	0.9	0.88	
Brick(yellow stone)	0.5	0.9	0.84	
(concrete)used/dirty	0.3	0.9	0.88	

The simulations were performed on two representative days: 22 July 2023 (hot, dry summer), and 22 January 2023 (cold, wet winter), with simulation windows from 6:00 a.m. to 6:00 p.m. (Table 2).

Table 2. Input parameters set for ENVI-met simulations, including environmental and material characteristics.

Type	Input Parameters	Value
location	City	Arak
	Latitude	34.09 °N
	longtitude	49.70 °E
simulation	A day in the summer	22 July 2023
	A day in the winter	22 January 2023
	Time	11 h from 6:00 a.m. to 6:00 p.m.
buildings	Thermal conductivity	0.3
	Albedo of walls	0.4
	Buidings height	From 3 m to 15 m
road	Road width	20 m
	Road material	Asphalt
	Sidewalk material	Stone travertine
greening	Trees(hedge dense) 2 m–4 m	Albedo 0.2 Transmittance 0.3

The climatic conditions of the ENVI-met model simulation have been obtained from the closest meteorological station to the case study location. Then the results have been displayed using one of ENVI-met internal tools called Leonardo.

5.6.1. Case A

The first scenario is the current condition of the ground surface, where the road is covered with normal asphalt and the sidewalk is covered with travertine stone flooring, this case showed a minimum temperature of 35.71 °C and a maximum of 38.98 °C in summer, and a minimum temperature of 2.06 °C and a maximum of 4.78 °C in winter (Figures A1 and A2).

5.6.2. Case B

The second scenario, by changing the road material from normal asphalt to colored asphalt and the sidewalk from travertine to brick, caused a decrease in air temperature by 1.86–0.67 Celsius in summer and a decrease of 0.23–0.53 Celsius in winter (Figures A3 and A4).

5.6.3. Case C

The third scenario, by changing the road material to colored asphalt and the sidewalk to concrete, led to a decrease of 0.58–1.49 Celsius in summer and a decrease of 0.2–0.48 Celsius in winter (Figures A5 and A6).

5.6.4. Case D

The fourth scenario, as the best scenario, by changing the road material to basalt and the sidewalk to light-colored concrete, led to a decrease of 3.49–1.53 Celsius in summer and a decrease of 0.43–1.01 Celsius in winter (Figures A7 and A8).

Figures illustrating detailed temperature distributions and comparative analyses for each scenario (currently Figures A1–A8) have been moved to the Appendix to maintain clarity and narrative flow in the main body of the text. The Appendix contains comprehensive visualizations of summer and winter temperature variations for all four pavement scenarios.

Table 3 summarizes the quantitative evaluation of these scenarios and their impact on outdoor air temperatures in both seasons.

Table 3. Quantitative comparison of surface temperatures for four pavement scenarios during summer and winter seasons.

Case No.	Time	Road Material	Sidewalk Material	Summer Min Temp (°C)	Summer Max Temp (°C)	Summer Cooling *vs.* Case A (°C)	Winter Min Temp (°C)	Winter Max Temp (°C)	Winter Heating *vs.* Case A (°C)
A (current situation)	2:00 p.m.	Asphalt	Stone travertine	35.71	38.98	0.00	2.06	4.78	0.00
B	2:00 p.m.	Asphalt with red coating	Brick (yellow stones)	35.04	37.12	−0.67 to −1.86	1.83	4.25	−0.23 to −0.53
C	2:00 p.m.	Asphalt with red coating	Concrete pavement	35.13	37.49	−0.58 to −1.49	1.86	4.30	−0.20 to −0.48
D (best scenario)	2:00 p.m.	Basalt brick road	Light concrete pavement	34.18	35.49	−1.53 to −3.49	1.63	3.77	−0.43 to −1.01

These cases were designed based on material availability and applicability in Iran, focusing on their albedo, thermal properties, and permeability.

5.7. Limitations and Scope of the Simulation

This study acknowledges that simulating only two days—one representative summer day and one representative winter day—limits the temporal generalizability of the results. Variability in weather patterns and longer-term climatic trends are not captured. However, the selected days correspond to peak temperature periods intended to illustrate the maximum potential impact of pavement interventions.

The ENVI-met simulation was embedded within a rigorous scientific framework by controlling key environmental variables: only the pavement material type varied across scenarios, while urban geometry, meteorological inputs, and boundary conditions remained constant. Model validation against field-measured temperature and humidity data ensured the reliability and testability of simulation results beyond a simple computational exercise.

While limited to these two representative days, the simulation snapshots provide valuable insights into the maximal potential effects of pavement materials. Future research will expand temporal coverage through multi-day or seasonal simulations for a thorough understanding of long-term impacts. The statistical significance and robustness of observed temperature differences are addressed separately in Section 5.9, which presents preliminary significance testing results. Comprehensive statistical validation will be systematically pursued as part of ongoing research efforts.

5.8. Measurements and Results

Given the limited temporal scope of measurements and simulations to two representative days, the following results illustrate representative temperature variations among pavement scenarios within peak seasonal conditions. This process and its analysis demonstrate the significant impact of pavement materials in achieving environmental temperature balance for pedestrians (Figures 7–12).

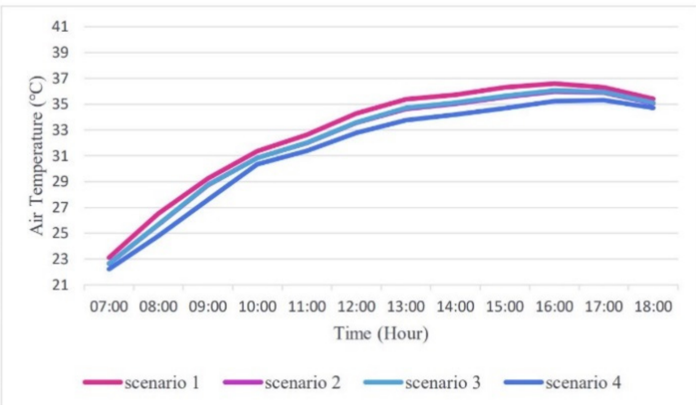


Figure 7. Comparison of the lowest air temperature among different pavement scenarios during summer.

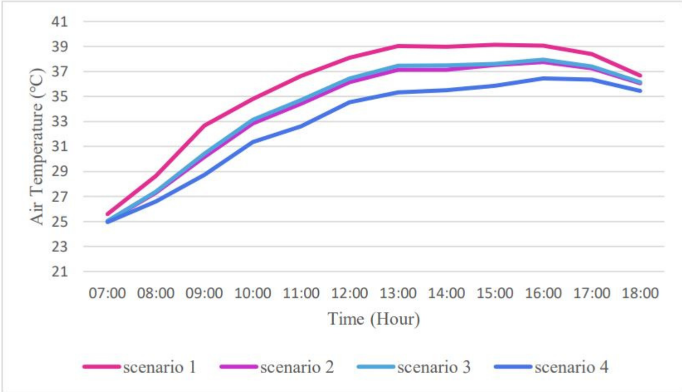


Figure 8. Comparison of the highest air temperature among different pavement scenarios during summer.

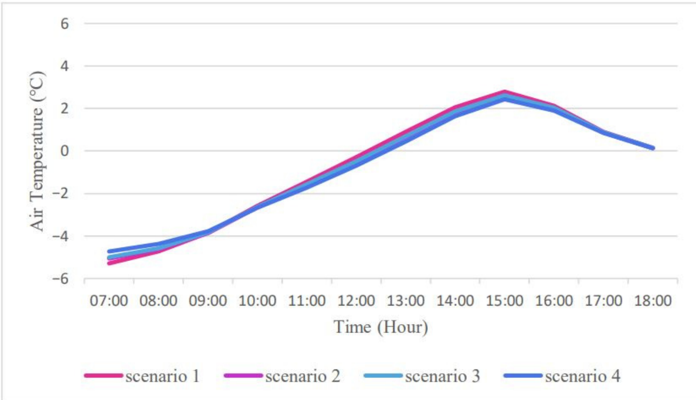


Figure 9. Comparison of the lowest air temperatures among different pavement scenarios during winter.

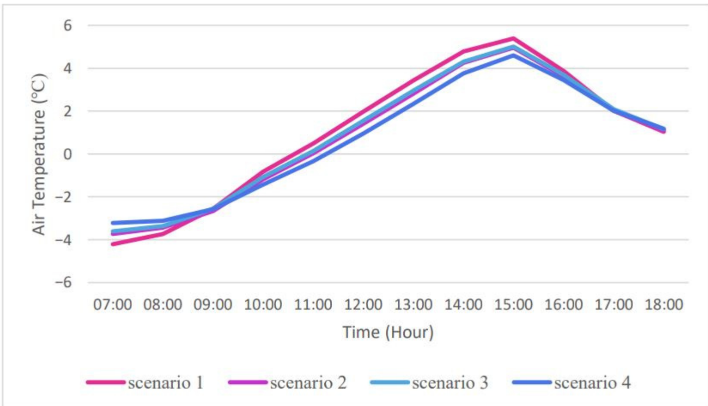


Figure 10. Comparison of the highest air temperature among different pavement scenarios during winter.

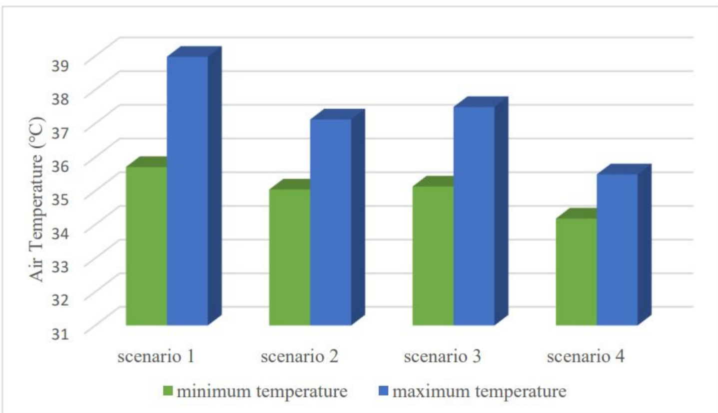


Figure 11. Comparison between the highest and lowest air temperatures for different pavement scenarios during summer.

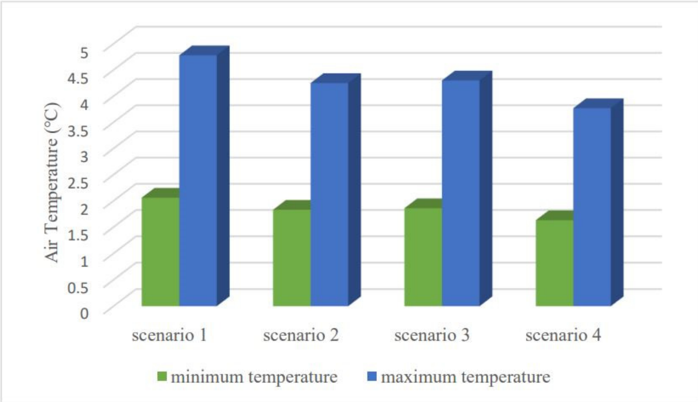


Figure 12. Comparison between the highest and lowest air temperatures for different pavement scenarios during winter.

5.9. Statistical Analysis of Temperature Differences

To enhance the robustness of the conclusions, basic statistical significance testing was conducted on the simulated outdoor air temperatures across the four pavement scenarios for both summer and winter representative days. Paired *t*-tests were applied comparing Scenario A (current condition) with each alternative pavement scenario (B, C, and D) using the spatially averaged minimum and maximum temperatures.

Results demonstrated statistically significant decreases in summer air temperatures for all modified pavement scenarios compared to the baseline (p-values < 0.05). Similarly, increases in winter air temperatures, indicating heating load effects, were statistically significant, especially for Scenario D, which showed the strongest thermal retention.

These analyses confirm that the observed temperature differences are statistically meaningful despite the limited temporal scope. Future research will extend these tests to multi-day and seasonal datasets to comprehensively validate the thermal impact of pavement materials.

6. Results

The UHI and urban oasis effects in Arak create considerable challenges for outdoor thermal comfort and energy demands. Four pavement material scenarios were evaluated for their impact on outdoor air temperature along Dr. Hasabi Street during both summer and winter.

The baseline (Scenario A), representing current conditions with ordinary asphalt roads and travertine sidewalks, exhibited maximum summer temperatures reaching 38.98 °C and winter lows near 2.06 °C (Figures A1 and A2). Replacing the road pavement with colored asphalt and sidewalks with brick (Scenario B) reduced cooling load by up to 1.86 °C in summer but increased winter heating load by 0.53 °C (Figures A3 and A4).

Scenario C combined colored asphalt roads with concrete sidewalks, decreasing summer cooling load by 1.49 °C but raising winter heating load by 0.48 °C (Figures A5 and A6). Scenario D, featuring basalt pavement and light-colored concrete sidewalks, achieved the greatest cooling load reduction of 3.49 °C in summer, with a 1.01 °C increase in winter heating load (Figures A7 and A8).

These quantitative results underscore the substantial influence of pavement materials on urban thermal conditions and affirm their critical role in regulating urban temperature dynamics.

7. Discussion

The results align with prior studies showing that dark surfaces, such as traditional asphalt, absorb significant solar radiation, intensifying the summer heat island effect [19,22]. Conversely, lighter-colored materials have higher albedo, reflecting more solar radiation, thus lowering surface and outdoor air temperatures.

Seasonal performance differences highlight the importance of selecting materials that balance summer cooling benefits with winter heating considerations. Basalt stone’s high heat capacity helps retain heat during colder months, increasing winter heating load while contributing positively to pedestrian thermal comfort [25]. Impermeable surfaces restrict evapotranspiration cooling, exacerbating UHI in summer. Therefore, selecting pavement materials based on permeability and albedo is essential for microclimate improvement.

Other factors likely influencing microclimatic interactions include urban spatial layout, shading from irregular tree distribution, and building heights ranging from 3 to 15 m. These aspects may affect simulation accuracy. Future research should integrate such complexities to capture a fuller picture of urban microclimate dynamics.

Uncertainties inherent in the ENVI-met modeling framework arise from assumptions in turbulence modeling, radiation schemes, and simplified vegetation and soil processes. While validated with strong correlations against empirical data (Section 5.3), these uncertainties affect absolute temperature predictions.

The study area represents a typical temperate four-season mid-sized city with a dense urban core. Similar results may not apply to cities with different climatic contexts or urban morphologies; hence, caution is advised when generalizing findings beyond Arak's geographic and climatic boundaries.

Table 4 shows guidance on adapting model parameters for application in different climatic zones, providing practical directions for broader applicability.

Table 4. Guidance on Adapting Model Parameters for Different Climatic Zones.

Climate Zone	Key Model Parameter Adjustments	Notes
Hot Arid	Increase surface reflectivity (albedo)	Emphasize cooling load reduction
Tropical Humid	Enhance evapotranspiration parameters	Account for higher humidity and rainfall
Cold Temperate	Adjust thermal inertia to account for longer heating seasons	Focus on winter heat retention strategies
Mediterranean	Balance summer cooling and mild winter heating parameters	Moderate seasonal variability

8. Recommendations for Urban Planning

Based on findings, targeted application of cool pavements within urban cores is recommended to enhance thermal comfort and energy savings. Basalt stone pavements on roads reduce summer cooling loads and retain heat in winter.

Light-colored concrete sidewalks increase sunlight reflection and surface cooling, beneficial in densely trafficked pedestrian zones. Implementation should prioritize dense, high-traffic corridors with minimal vegetation shading, where pavement thermal properties strongly influence the microclimate.

Combining pavement materials with urban greening and optimized shading infrastructure can amplify microclimatic benefits. Material selection should consider local availability and cost-effectiveness to ensure practical, sustainable urban development.

9. Conclusions

This study highlights the significant role of pavement materials in regulating outdoor temperatures in a temperate four-season city like Arak. The optimal combination of basalt pavement and light-colored concrete sidewalks reduced summer cooling loads by up to 3.49 °C, improving pedestrian comfort, while moderately increasing winter heating load by approximately 1.01 °C.

Findings are constrained by modeling assumptions and the specific urban context, necessitating further temporal expansion and testing across diverse settings to validate robustness. Urban planners can integrate cool pavements into designs to enhance energy efficiency, thermal comfort, and sustainable city development, especially where pronounced seasonal variability exists.

Future work should include detailed analyses of urban morphology, shading patterns, and longer-term climate fluctuations alongside experimental validation to refine these insights.

Appendix A

This appendix provides detailed temperature distribution maps and comparative analyses of the four pavement scenarios simulated by ENVI-met during summer and winter. These figures complement the main findings presented in the manuscript.

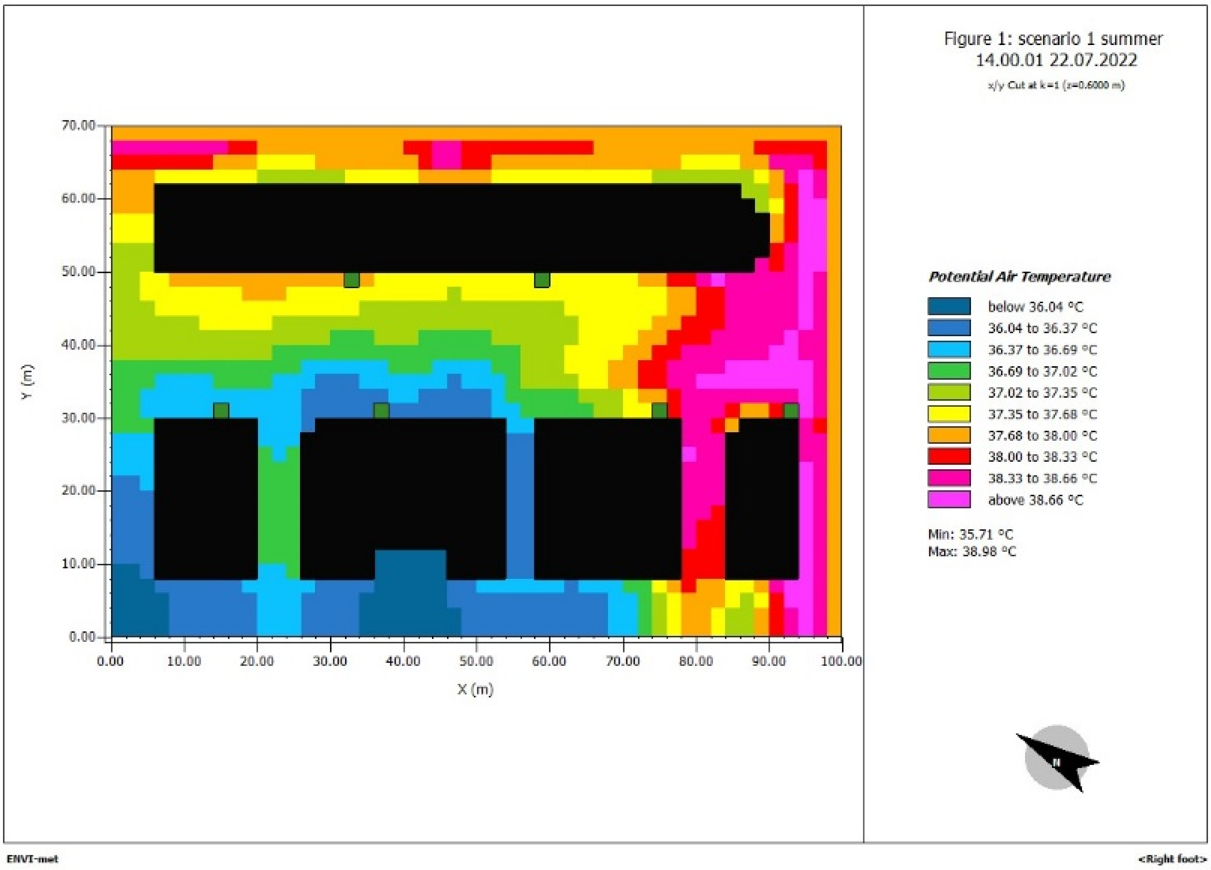


Figure A1. Analysis map of Case A (current pavement scenario) in summer produced by ENVI-met simulation, showing air temperature distribution (°C).

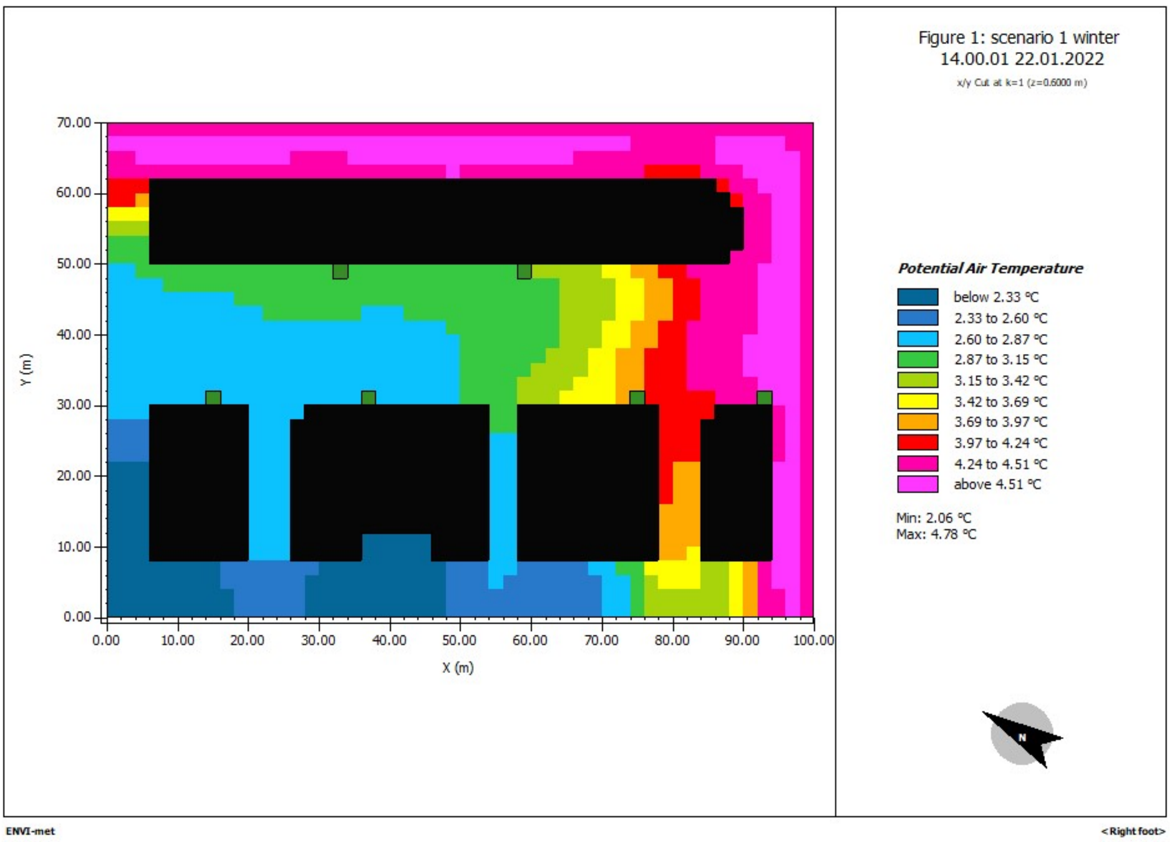


Figure A2. Analysis map of Case A (current pavement scenario) in winter produced by ENVI-met simulation, showing air temperature distribution (°C).

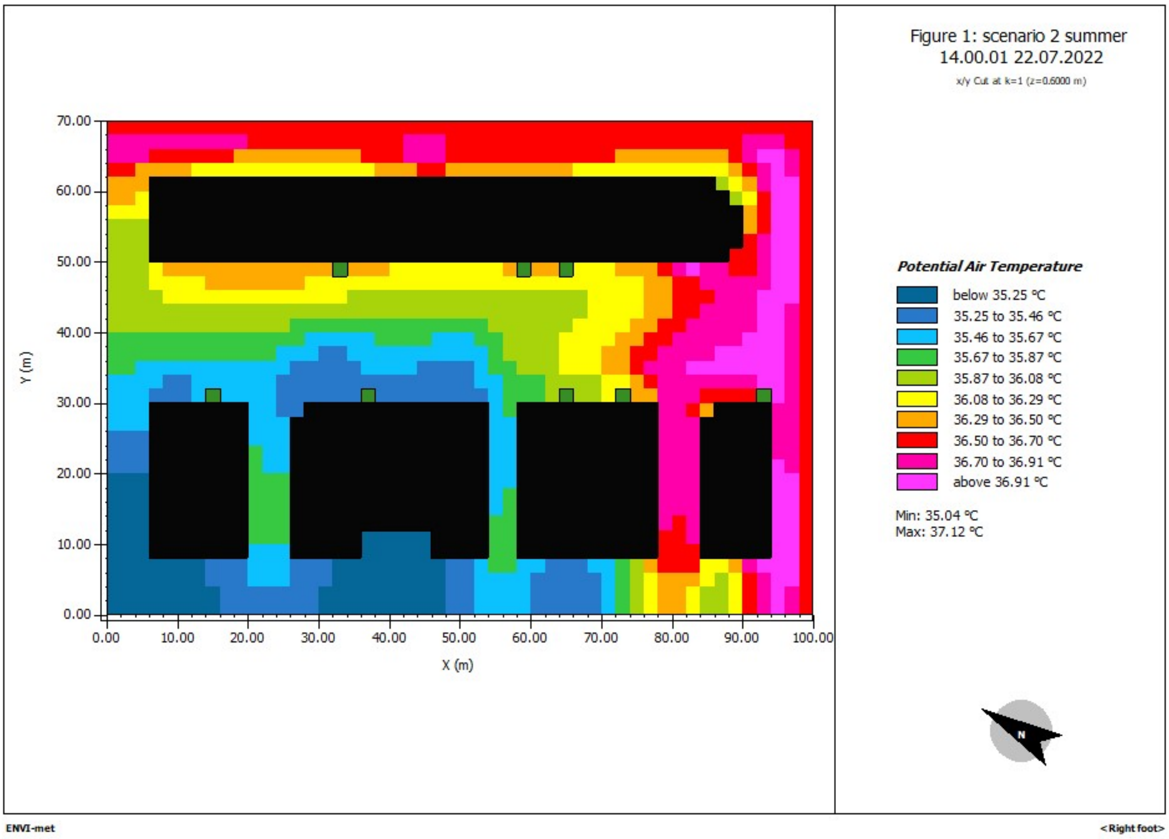


Figure A3. Analysis map of Case B (colored asphalt road and brick sidewalk) in summer produced by ENVI-met simulation, showing air temperature distribution (°C).

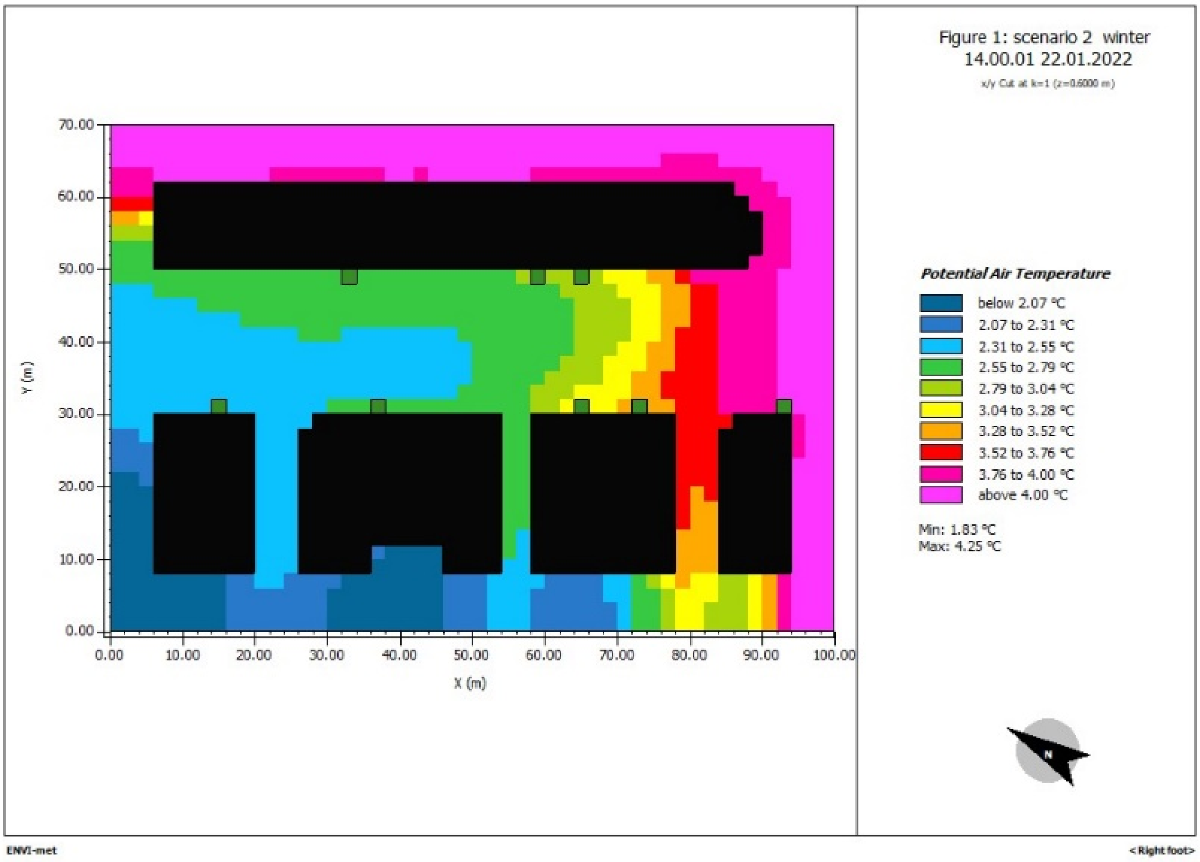


Figure A4. Analysis map of Case B in winter produced by ENVI-met simulation, showing air temperature distribution (°C).

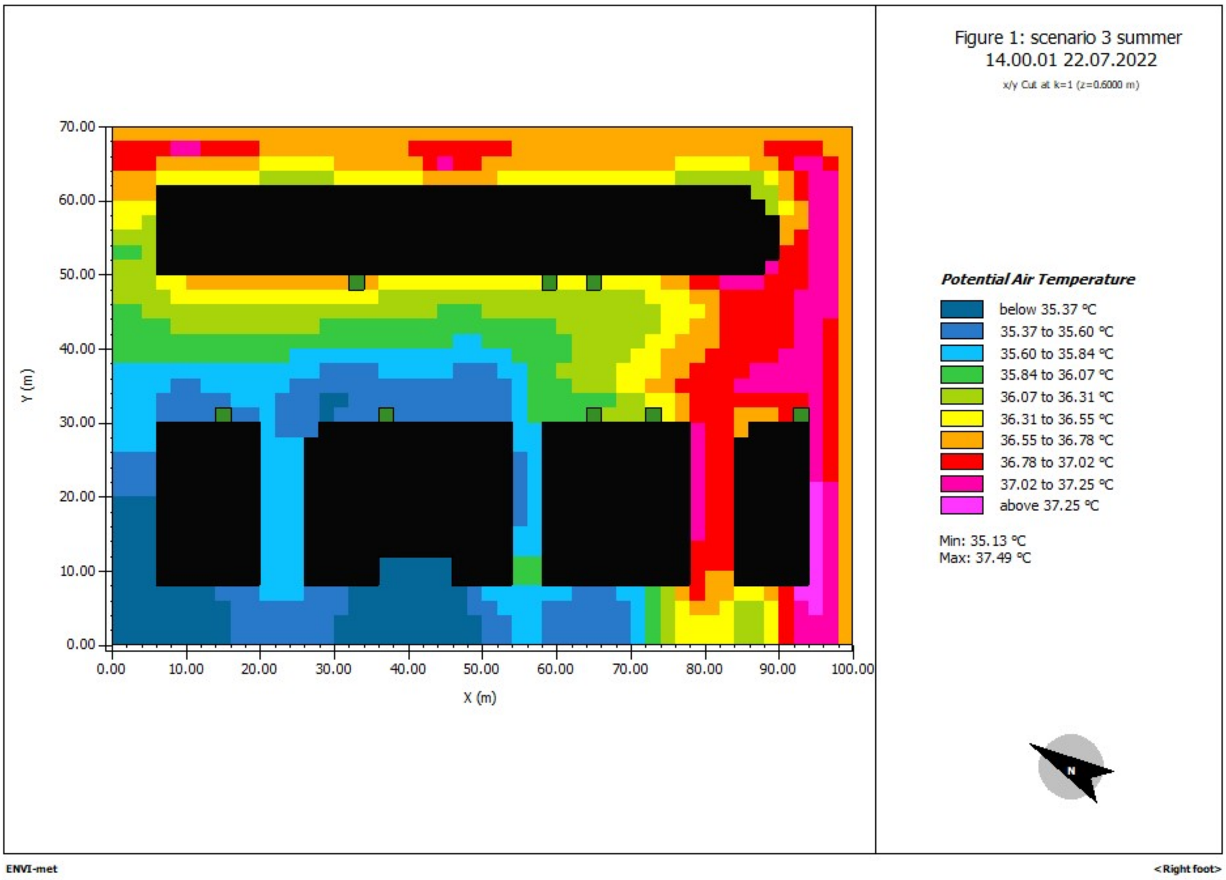


Figure A5. Analysis map of Case C (colored asphalt road and concrete sidewalk) in summer produced by ENVI-met simulation, showing air temperature distribution (°C).

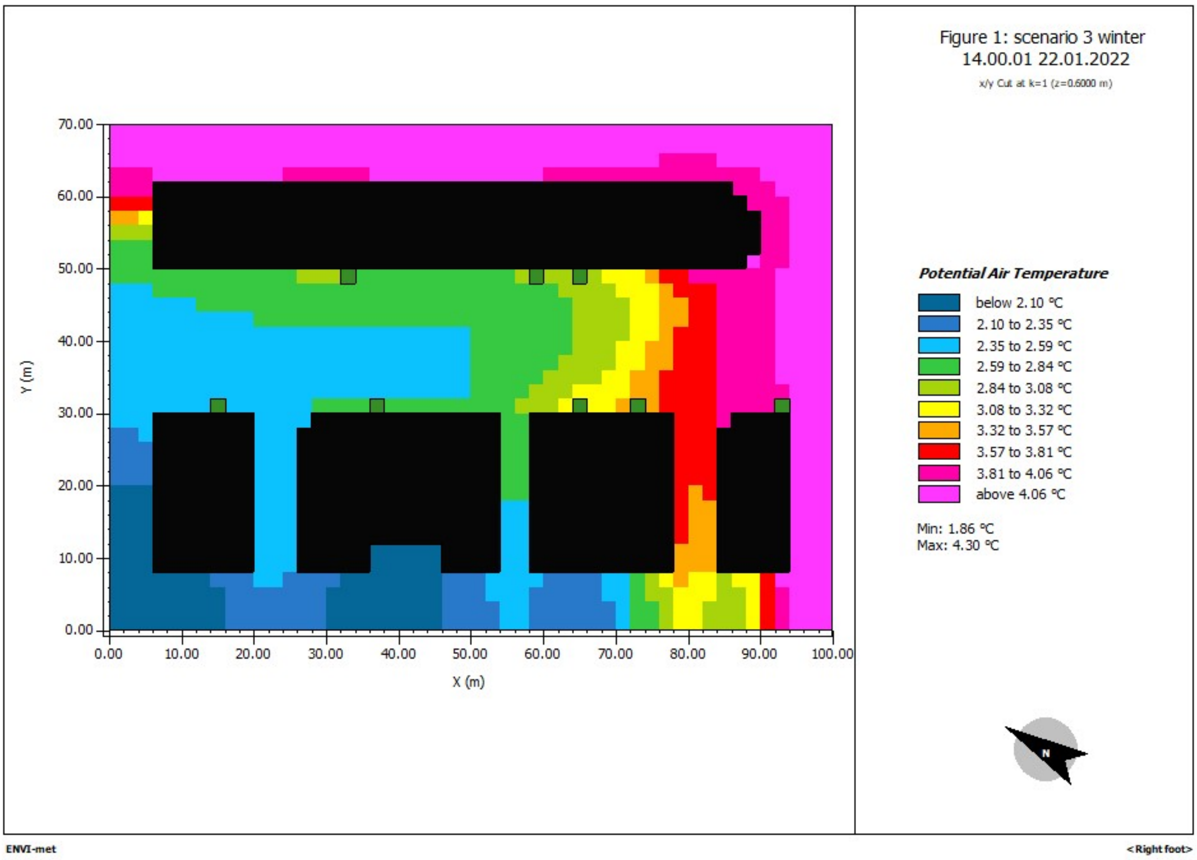


Figure A6. Analysis map of Case C in winter produced by ENVI-met simulation, showing air temperature distribution (°C).

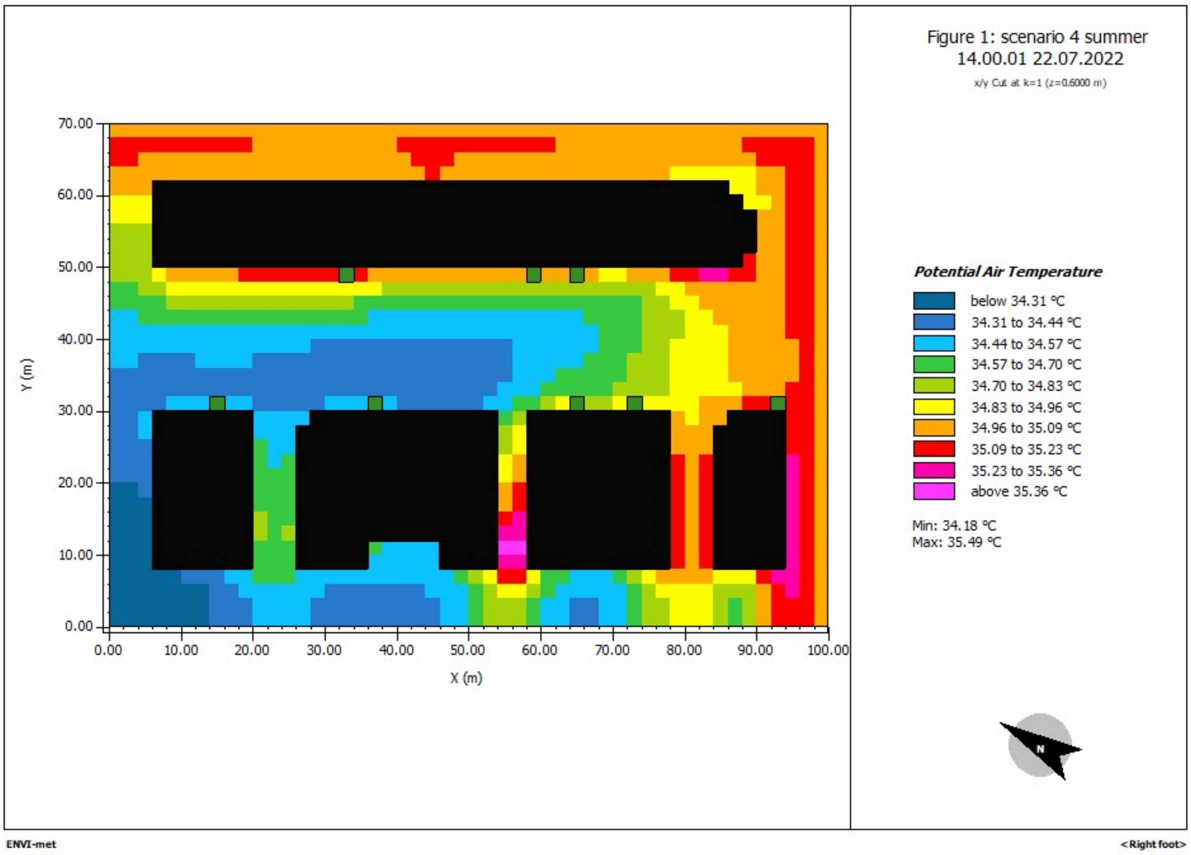


Figure A7. Analysis map of Case D (basalt road and light-colored concrete sidewalk), the best-performing scenario, in summer produced by ENVI-met simulation, showing air temperature distribution (°C).

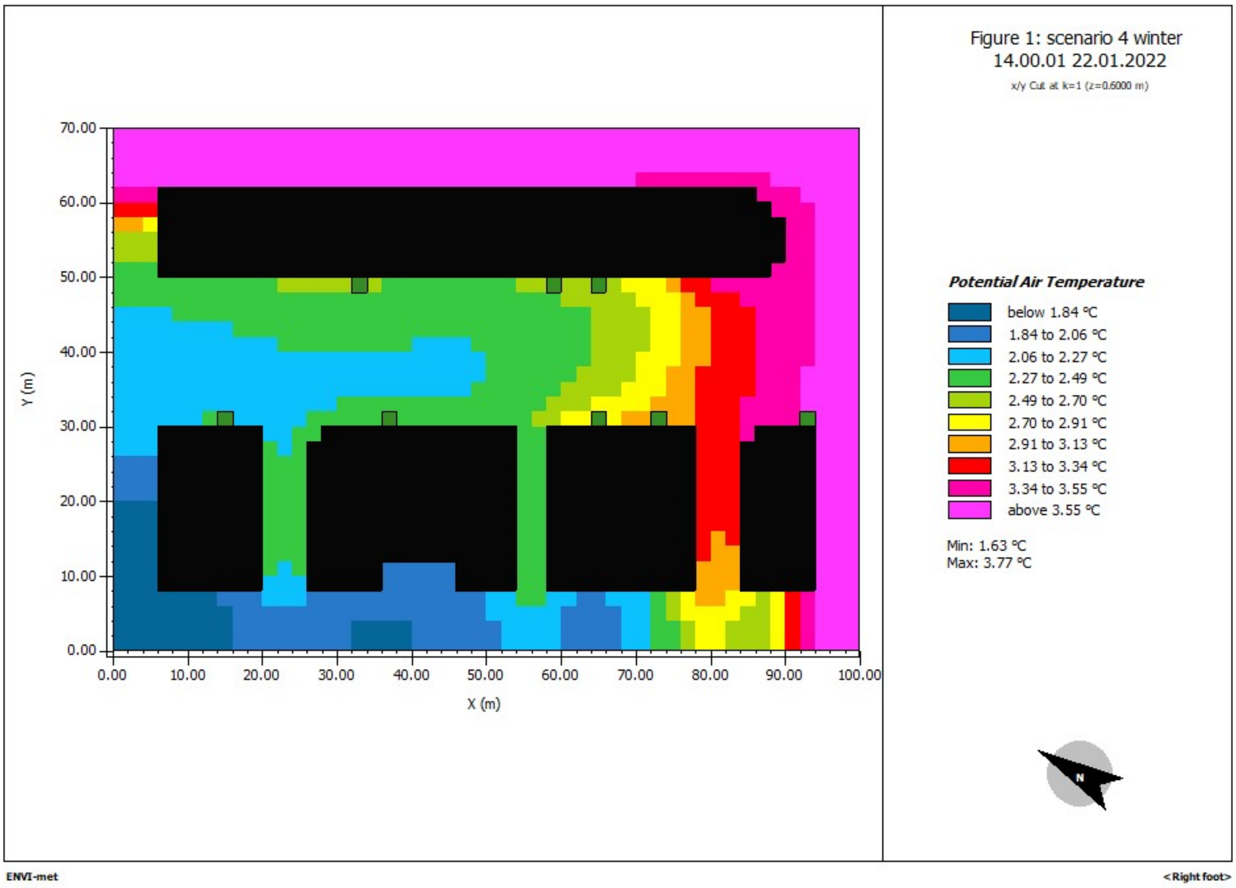


Figure A8. Analysis map of Case D in winter produced by ENVI-met simulation, showing air temperature distribution (°C).

Acknowledgments

The authors gratefully acknowledge the support and guidance received during this study.

Author Contributions

M.A. conceived and designed the study and drafted the manuscript; R.A. performed the data analysis and interpretation; both authors revised the manuscript critically for intellectual content; both authors approved the final version and agree to be accountable for all aspects of the work.

Ethics Statement

This study did not involve human participants or animals and therefore did not require ethical approval.

Informed Consent Statement

Not applicable. This study did not involve human participants.

Data Availability Statement

All data generated or analyzed during this study are included in this article.

Funding

No funding was received.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. Achouri H, Djaghrouri D, Benabbas M. Factors Affecting Microclimate and Thermal Comfort in Outdoor Spaces: a literature review. *J. Salut. Archit.* **2024**, *3*, 48–63.
2. Hassaballa A, Salih A. A Spatio-Temporal Analysis of Heat Island Intensity Influenced by the Substantial Urban Growth between 1990 and 2020: A Case Study of Al-Ahsa Oasis, Eastern Saudi Arabia. *Appl. Sci.* **2023**, *13*, 2755.
3. Irfeey AMM, Chau H, Sumaiya MMF, Wai CY, Muttil N, Jamei E. Sustainable mitigation strategies for urban heat island effects in urban areas. *Sustainability* **2023**, *15*, 10767.
4. Liu Z, Li J, Xi T. A Review of Thermal Comfort Evaluation and Improvement in Urban Outdoor Spaces. *Buildings* **2023**, *13*, 3050.
5. Joshi K, Khan A, Anand P, Sen J. Understanding the synergy between heat waves and the built environment: A three-decade systematic review informing policies for mitigating urban heat island in cities. *Sustain. Earth Rev.* **2024**, *7*, 25.
6. Ismail KA, Lino FA, Henríquez JR, Teggar M, Laouer A, Arici M, et al. Enhancement techniques for the reduction of heating and cooling loads in buildings: a review. *J. Energy Power Technol.* **2023**, *5*, 1–44.
7. Qiu J, Li X, Qian W. Optimizing the spatial pattern of the cold island to mitigate the urban heat island effect. *Ecol. Indic.* **2023**, *154*, 110550.
8. Lin Y, Huang T, Yang W, Hu X, Li C. A Review on the Impact of Outdoor Environment on Indoor Thermal Environment. *Buildings* **2023**, *13*, 2600.
9. Huang H, Li Y, Zhao Y, Zhai W. Analysis of the impact of urban summer high temperatures and outdoor activity duration on residents' emotional health: Taking hostility as an example. *Front. Public Health* **2022**, *10*, 955077.
10. Khalil HAEE, Ibrahim A, Elgendy N, Makhlouf N. Enhancing livability in informal areas: a participatory approach to improve urban microclimate in outdoor spaces. *Sustainability* **2022**, *14*, 6395.
11. Styer J, Tunstall L, Landis A, Grenfell J. Innovations in pavement design and engineering: A 2023 sustainability review. *Heliyon* **2024**, *10*, e33602.
12. Giorio M, Paparella R. Climate Mitigation Strategies: The Use of Cool Pavements. *Sustainability* **2023**, *15*, 7641.
13. Jin J, Chen H, Liu S, Xiao M, Liu L. Study on preparation and properties of phase change modified asphalt for the functional pavement. *Constr. Build. Mater.* **2024**, *439*, 137248.
14. Ozarisoy B. Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation. *J. Clean. Prod.* **2022**, *330*, 129675.
15. Wu H, Jin R, Liu M, Nie Z, Zhao H, Yao L, et al. Investigating the potential of street trees in mitigating pedestrian thermal stress during heatwaves conditions: An empirical study in Guangzhou. *Build. Environ.* **2024**, *265*, 111955.

16. Fiorillo E, Brilli L, Carotenuto F, Cremonini L, Gioli B, Giordano T, et al. Diurnal outdoor thermal comfort mapping through envi-met simulations, remotely sensed and in situ measurements. *Atmosphere* **2023**, *14*, 641.
17. Hu T. Greening the Grey: Nature-Based Solutions for Urban Heat Island Effect in the City of Vancouver 2024. Available online: https://lfs-mlws-2020.sites.olt.ubc.ca/files/2024/09/hutasso_170896_34307007_Tasso_Hu_MLWS_2024-1.pdf (accessed on 26 August 2025).
18. Ramos-Palacios CR, Banda-Escalante ME, Barba-Romo CF, Cisneros-Vidales AA, Rodríguez-Herrera JG. Effective green cover and equipment–infrastructure attributes of public green spaces in a Mexican metropolitan area. *Front. Sustain. Cities* **2024**, *6*, 1470693.
19. Kappou S, Souliotis M, Papaefthimiou S, Panaras G, Paravantis JA, Michalena E, et al. Cool pavements: State of the art and new technologies. *Sustainability* **2022**, *14*, 5159.
20. Qadourah JA. Energy efficiency evaluation of green roofs as a passive strategy in the mediterranean climate. *Results Eng.* **2024**, *23*, 102519.
21. Chen X, Li Z, Wang Z, Li J, Zhou Y. The Impact of Different Types of Trees on Annual Thermal Comfort in Hot Summer and Cold Winter Areas. *Forests* **2024**, *15*, 1880.
22. Gong X, Liu Q, Lv Y, Chen S, Wu S, Ying H. A systematic review on the strategies of reducing asphalt pavement temperature. *Case Stud. Constr. Mater.* **2023**, *18*, e01852.
23. Liu T, Xu P, Zhang T, Shen Y, Tao Y, Qi F, et al. Effects of cloud and tree shading on surface temperature of different pavement materials for urban sidewalks. *Int. J. Biometeorol.* **2025**, *69*, 605–619.
24. da Rocha Segundo IG, Margalho ÉM, Lima ODS, Jr., Pinheiro CGDS, de Freitas EF, Carneiro JASO. Smart asphalt mixtures: A bibliometric analysis of the research trends. *Coatings* **2023**, *13*, 1396.
25. ELNABAWI MH, HAMZA N, AHMED T. Exploring the Impact of Pavement Materials on Surface and Air Temperatures in Arid Climates. Passive and Low Energy Architecture PLEA 2024. 2024. Available online: https://www.researchgate.net/profile/Mohamed-Mahgoub-13/publication/382763355_PLEA_2024_WROCLAW_Rethinking_Resilience_Exploring_the_Impact_of_Pavement_Materials_on_Surface_andAir_Temperatures_in_Arid_Climates/links/66abaf148f7e1236bc2e815c/PLEA-2024-WROCLAW-Rethinking-Resilience-Exploring-the-Impact-of-Pavement-Materials-on-Surface-andAir-Temperatures-in-Arid-Climates.pdf (accessed on 26 August 2025).
26. Alkinani AS, Al-Hussaini ZIH, Alzaidi MMK. Cities' urban resilience in the face of urban sprawl challenges. *Acta Sci. Pol. Adm. Locorum* **2022**, *21*, 295–319.
27. Li L, Fu M, Zhu Y, Kang H, Wen H. The current situation and trend of land ecological security evaluation from the perspective of global change. *Ecol. Indic.* **2024**, *167*, 112608.
28. Li Y, Brando PM, Morton DC, Lawrence DM, Yang H, Randerson JT. Deforestation-induced climate change reduces carbon storage in remaining tropical forests. *Nat. Commun.* **2022**, *13*, 1964.
29. Wu W, Chen R. Finding Oasis Cold Island Footprints Based on a Logistic Model—A Case Study in the Ejina Oasis. *Remote Sens.* **2024**, *16*, 2895.
30. Gao K, Haddad S, Paolini R, Feng J, Altheeb M, Mogirah AA, et al. The use of green infrastructure and irrigation in the mitigation of urban heat in a desert city. In *Building Simulation*; Tsinghua University Press: Beijing, China, 2024.
31. Shao L, Liao W, Li P, Luo M, Xiong X, Liu X. Drivers of global surface urban heat islands: Surface property, climate background, and 2D/3D urban morphologies. *Build. Environ.* **2023**, *242*, 110581.
32. Ballester J, Quijal-Zamorano M, Méndez Turrubiates RF, Pegenaute F, Herrmann FR, Robine JM, et al. Heat-related mortality in Europe during the summer of 2022. *Nat. Med.* **2023**, *29*, 1857–1866.
33. Nayak S, Vinod A, Prasad AK. Spatial characteristics and temporal trend of urban heat island effect over major cities in India using long-term space-based MODIS land surface temperature observations (2000–2023). *Appl. Sci.* **2023**, *13*, 13323.
34. Wang R, Lu J, Gentine P, Chen H. Global pattern of soil temperature exceeding air temperature and its linkages with surface energy fluxes. *Environ. Res. Lett.* **2024**, *19*, 104029.
35. Ghufran M, Musarat MA, Alaloul WS, Irfan M. Effect of high-albedo crops and buildings on climate change. In *Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 231–250.
36. Ringstedt A. The Effects of Vertical Greenery on the Climate in Scandinavian Cities: A Scoping Review. 2024. Available online: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1910709&dswid=-1566 (accessed on 26 August 2025).
37. Chen H, Song F. Study on the Application of Environmentally Friendly Materials in the Construction of Sponge Cities in China and Their Impact on Rainwater Runoff. *J. Prog. Eng. Phys. Sci.* **2024**, *3*, 56–64.
38. Alotaibi AM, Makhdoom TK, Alquaity AB. Pathways Toward Improving the Energy Efficiency of Residential Air-Conditioning Systems in Saudi Arabia. *J. Sol. Energy Eng.* **2024**, *146*, 051010.
39. Aljashaami BA, Ali BM, Salih SA, Alwan NT, Majeed MH, Ali OM, et al. Recent improvements to heating, ventilation, and cooling technologies for buildings based on renewable energy to achieve zero-energy buildings: A systematic review. *Results Eng.* **2024**, *23*, 102769.
40. Basyouni YA, Mahmoud H. Affordable green materials for developed cool roof applications: A review. *Renew. Sustain. Energy*

Rev. **2024**, *202*, 114722.
41. de Azevedo Correia CM, Amorim CND, Santamouris M. Use of passive cooling techniques and super cool materials to minimize cooling energy and improve thermal comfort in Brazilian schools. *Energy Build.* **2024**, *312*, 114125.
42. Cheshmehzangi A, He BJ, Sharifi A, Matzarakis A. Climate Change, Cities, and the Importance of Cooling Strategies, Practices, and Policies. In *Climate Change and Cooling Cities*; Springer: Singapore, 2023; pp. 2–19.
43. Ahmadizadeh O, Vakilinezhad R. Evaluating the effect of urban surfaces albedo on the microclimate and outdoor thermal comfort in hot climate. *Int. J. Environ. Stud.* **2024**, *82*, 1074–1098.
44. Zhang X, Jiao Z, Zhao C, Qu Y, Liu Q, Zhang H, et al. Review of land surface albedo: variance characteristics, climate effect and management strategy. *Remote Sens.* **2022**, *14*, 1382.
45. Zhang H, Wang C, Wang Y, Wang S, Chen G, Zou Y, et al. Ca-Mn co-doping $LaCrO_3$ coating with high emissivity and good mechanical property for enhancing high-temperature radiant heat dissipation. *J. Eur. Ceram. Soc.* **2022**, *42*, 7288–7299.
46. Li J, Dong K, Zhang T, Tseng D, Fang C, Guo R, et al. Printable, emissivity-adaptive and albedo-optimized covering for year-round energy saving. *Joule* **2023**, *7*, 2552–2567.
47. Ghenai C, Rejeb O, Sinclair T, Almarzouqi N, Alhanaee N, Rossi F. Evaluation and thermal performance of cool pavement under desert weather conditions: Surface albedo enhancement and carbon emissions offset. *Case Stud. Constr. Mater.* **2023**, *18*, e01940.
48. Gryszpanowicz P, Sobik-Szołtysek J, Grabowski P, Janiszewski P, Kacprzak M. Chemical modifications of old natural stone pavements surface for safety reuse–Risk mitigation. *Constr. Build. Mater.* **2024**, *411*, 134300.
49. Zhou Y, Cheng Z, Zheng X, Wang T, Wu X, Yu X, et al. A Holistic Exploration of Porous Asphalt Mixtures: From Durability and Permeability to Low-Temperature and Functional Properties. *Heliyon* **2024**, *11*, e41437.
50. Seifeddine K, Amziane S, Toussaint E. Experimental investigation of physical characteristics to improve the cooling effect of permeable pavements. *Constr. Build. Mater.* **2022**, *345*, 128342.
51. Riaz A, Yasir N, Badin G, Mahmood Y. Innovative Pavement Solutions: A Comprehensive Review from Conventional Asphalt to Sustainable Colored Alternatives. *Infrastructures* **2024**, *9*, 186.
52. Eric Swenson P, PTOE PM. The Case for Color: Standardizing Red and Green Pavement Treatments for Exclusive Lanes. Institute of Transportation Engineers. *ITE J.* **2023**, *93*, 35–41.
53. Yang M, Ding H, Liao J, Li K, Chen J. Study of the Physiological Characteristics of Drivers Facing Apparent Changes in Highway Tunnel Structures. *Tunn. Undergr. Space Technol.* **2024**, *154*, 106050.
54. Boujelbene M, Boukholda I, Guesmi T, Amara MB, Khalilpoor N. Solar reflection and effect of roof surfaces material characteristics in heat island mitigation: toward green building and urban sustainability in Ha'il, Saudi Arabia. *Int. J. Low-Carbon Technol.* **2023**, *18*, 1039–1047.
55. Nilimaa J, Zhaka V. An overview of smart materials and technologies for concrete construction in cold weather. *Eng* **2023**, *4*, 1550–1580.
56. Prataviera E, De Carli M. A review on outdoor urban environment modelling. *J.Phys. : Conf. Ser.* **2024**, *2893*, 012024.
57. Barnstorf P, Alves FB, do Vale CP. Reflexions on an ENVI-met operation-methodology case study. *U. Porto J. Eng.* **2023**, *9*, 16–99.