Influence of pavements on the urban heat island phenomenon: A scientific evolution analysis

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Abstract

The growth of the population in cities and the increase in the use of construction materials caused the cities' internal temperature to increase, producing the effect known as urban heat island. For this reason, there is scientific interest in mitigation methods of adaptation to this effect in the construction area.

The main objective of this research is to analyse the scientific articles published from 1990 to 2019 that relate to pavements and the urban heat island phenomenon, using the SciMAT tool for bibliometric analysis to evaluate the general evolution of this area of science.

The analysis was carried out on 107 articles, and a clear evolution was found in the research methodologies of studies of pavements in urban heat island conditions. Until 2008, 73% used all type of field experiments. In 2019, this ratio had decreased to 36%, while investigations with laboratory experiments were the most prevalent, at 37% of all investigations. In recent years, interdisciplinary research has focused on the issues of mitigating the effects of urban heat islands together with improving the energy performance of dwellings.

Keywords

Urban heat island; pavement; bibliometric analysis; construction; SciMAT

1. Introduction

Currently, more than 50% of the world's population lives in cities. By 2050, this proportion will increase to two thirds, i.e. some 6.5 billion people. An effect produced by the growth of cities is the urban heat island (UHI), which is a phenomenon whereby ambient temperatures are significantly higher in cities than in rural areas due to the absorption and accumulation of heat in pavements and other physical interactions. This effect is accentuated because, in urban sectors, surfaces that were initially covered by vegetation are replaced by infrastructures such as streets, houses and buildings. Therefore, surfaces that were once permeable become waterproof and relatively dry, favouring an increase in ambient temperature [1].

On a hot summer's day, a natural soil exposed to solar radiation in rural areas remains close to air temperature, while roofs and pavements in a nearby urban area can reach up to 50°C more than the ambient temperature [2]. The concept of UHI began to be studied in the 1980s with the classic articles by Oke [3,4]. The tremendous thermal inertia and low albedo of concrete materials have the propensity to absorb and store solar radiation [5,6]. In cities, this effect increases because large tracts of the underlying surface are covered with different types of coatings and pavements. Therefore, after many studies of urban microclimatology, methods began to be developed for mitigating UHI.

In 2015, Qin published a review of the development of cool pavements for mitigation of UHI [7]. This publically available article provided the first general classification of cool pavement and methodologies to minimise the thermal effects of urban pavements. The main focus of this article was on reflective flooring, evaporative flooring and heat storage modifications of the flooring. Then, in 2017, an article was published by Mohajerani *et al.* [8], presenting tables of the main articles available and their contributions to the study of thermal conductivity of asphalt concrete from 1957 to 2015. This article is very similar to the structure of the research by Qin [7]. The effects of urban canyon change air velocity, due to narrow streets, building heights and recesses in an urban context. Green areas were also considered in mitigation of UHI. Recently, an article reviewing ecological road materials has been published [9]. In this article, permeable asphalt production materials were analysed, in addition to noise reduction flooring, low heat absorption materials, exhaust gas-decomposing pavements, pavement thaw (de-icing pavements), and pavement energy-use (energy harvesting pavements), among others. It can be seen that recent articles are considering new types of pavements with an environmental approach. In the modern world, pavements in the urban environment must be multifunctional, not only to mitigate UHI but, also, to be environmentally friendly and to improve other indicators of the quality of human life in cities.

To have an overview of the scientific evolution of a study area, several analyses were carried out using bibliometric methodologies. In recent years, these analytical methodologies have been used in various fields as diverse as education [10], sustainable building [11], computer science [12], business economics [13,14], medicine [15], thermodynamics [16], etc.

The main objective of this article was to analyse scientific articles published in WoS and SCOPUS databases in the last three decades that were related UHIs, pavements and mitigation methods for UHIs' thermal effects. This was done via manual and bibliometric analytical methods to evaluate the general evolution of this scientific field to identify main studies, authors and changes in methodologies from different time periods, geographical coverage of these studies, possible future lines of research and insights for the development of public policies in different decision-making organisations.

In order to accomplish this, we developed the following specific objectives:

i) retrieve scientific articles from the indexed databases for the area of study;

ii) manually analyse and classify the articles;

iii) analyse the articles employing a bibliometric tool;

iv) interpret scientific evolution through the results obtained previously.

2. Material and methods

2.1. Selection methods of the scientific literature

For the literature review, the Web of Science (WoS) and SCOPUS databases were used. For this, all indexed records that included the keyword fields or the words **"pavement"** and **"urban heat island"** were searched for in the respective database platforms.

The first search was carried out on WoS and SCOPUS, where 228 and 114 records were published, respectively. After review, only articles in journals were left for analysis and content control of the abstracts was performed as follows:

(i) only articles located in both databases (WoS and SCOPUS) were used;

(ii) articles from the following thematic areas were used: engineering, materials science, energy and environmental sciences;

(iii) articles related to the construction of buildings, roads, construction materials research, microclimatology, environmental effects and construction technologies were selected.

Once the content control was carried out, a list of 107 articles was formed, which are presented in both referential databases. The double use of referential databases is justified because SCOPUS accumulates more citations of each document, compared to WoS.

The literature sample was restricted to the period 1990-2019, which represented all of the scientific publications. Four discrete periods were established: 1990-2008, 2009-2014, 2015-2016, and 2017-2019. Each period had to have at least 10 items and comprise either the same or a greater number of articles than the previous period, in addition to having a maximum of publications per period. The number of articles in each period were 15, 27, 27 and 38, respectively, with period maximums of: 7 articles (2007), 8 articles (2012), 15 articles (2015) and 19 articles (2018).

The 107 selected articles were used to perform a manual analysis of the scientific literature. At the same time, a bibliometric computational tool (SciMAT v1.1.04) was used to identify the most relevant research topics, emerging themes, themes in decline and peripheral themes in the four periods studied. Next, the two phases in which the work is separated have been developed:

2.2. Systematic literature review

In the first phase, a manual analysis was performed, individually analysing each previously selected article from the research databases and then classifying them. The methodology used was as follows:

1. Geographic distribution of articles.
2. Main magazines, authors and most-cited articles.
3. Classification of articles to identify the following indicators:
    - (i) General type of article —it can be from a field experiment, controlled field experiment, laboratory experiment, numerical simulation, review article, etc.
    - (ii) Research objective focused on our research line —it can be pavements in general, concrete, roofs, concrete modifications, etc.
    - (iii) General purpose classification of the article —may be for UHI mitigation, effects other than soil and vegetation, microclimatology, etc.
    - (iv) If UHI mitigation articles were identified in step (iii), it is then necessary to identify more specific types of mitigation.
4. Analysis of the historical evolution of the most important and relevant articles in each period, derived from the data in the previous sections.

2.3. Bibliometric analysis

In the second phase, the objective was to analyse the 107 WoS and SCOPUS scientific journals for articles on pavements and UHIs over the last three decades (1990-2019). The co-occurrence of terms has been analysed through grouping techniques, performing science mapping for each period and performance analysis, to detect and visualise conceptual subdomains regarding concrete. Similarly, thematic evolution has been analysed, presenting the first science mapping of the complete set of "pavements" and "UHI", showing its structure, evolution and trends. Science mapping and performance analyses are considered to be the most relevant bibliometric resources [17].

Bibliometric mapping is focused on monitoring a scientific field and delimiting research areas by determining their cognitive and evolutionary structure, showing the structural and dynamic aspects of scientific research [17–20]. This type of analysis allows for the quantifying and measuring of the performance, quality and impact of the generated science mapping and its components [20]. In this investigation, the SciMAT v1.1.04 bibliometric tool has been used to construct science maps and strategic diagrams in order to analyse the temporal evolution of the main topics on technostress [21].

SciMAT enables us to be able to carry out bibliometric analysis of the content of articles based on science mapping [20]. This tool has been developed according to the methodology of Cobo *et al.* [22], based on the analysis of co-words [23] and the *h-index* [24]. The *h-index* of a researcher measures the quality of his research based on the number of his articles in scientific journals and the citations received [25]. The original definition of *h-index* was conducted by Hirsch [26] as “A scientist has index h if h of his or her Np papers have at least h citations each and the other ($Np-h$) papers have $\leq h$ citations each”.

In the same way, SciMAT allows the building of scientific maps from the analysis of occurrences of keywords that characterise each item. This allows monitoring of a scientific field, outlining the research areas so that we can understand their intellectual, social, conceptual and cognitive structure. Likewise, it allows analysis of its structural evolution, the construction of scientific maps and visualisation of the evolution of a scientific area [20]. The advantages of using SciMAT compared to other bibliometric tools (e.g. Bibexcel, CiteSpace, CoPalRed, IN-SPIRE, VantajaPoint, or VosViewer) have been described by Cobo *et al.* [22].

Besides this, thematic networks between keywords are established through this tool. SciMAT allows identification of the importance of each thematic network through the construction of strategic diagrams by thematic network analysis which measures centrality and density [27].

The centrality measures the degree of strength of the external links of the subject with other subjects. This measure allows us to interpret the importance of a topic in the global development of a research field. Density measures the internal cohesion of all links between the keywords that describe the topic and provides an idea of the level of development of that topic [22,25,28]. Through centrality and density, a research field can be represented in a strategic diagram. SciMAT allows us to characterise the importance of each thematic network within a scientific field. This characterisation can be represented as a set of topics divided into four categories and positioned in two-dimensional space. This space is called a strategic diagram [20], as seen in Fig. 1.

- Upper right quadrant: this represents those topics that are well developed and that are important for the construction of the scientific field. Since they represent a strong centrality and high density, they are also referred to as "motor themes" as they are essential to building the research area.
- Upper left quadrant: this corresponds to those topics that are highly developed internally but are isolated from the rest of the themes. These themes have marginal importance in the development of the scientific field. They are also called "highly developed and isolated themes". These topics have little relevance for the field, being specialised topics on the periphery of the area.
- Lower right quadrant: this area represents the essential topics that are important for the scientific field but are not well developed. They are called "basic and transversal themes" as it shows the relevant themes but with little development.

- Lower left quadrant: this area contains very few developed and marginal themes with a low density and centrality. They are also called "emerging or declining themes" as they include themes that lack development and relevance.

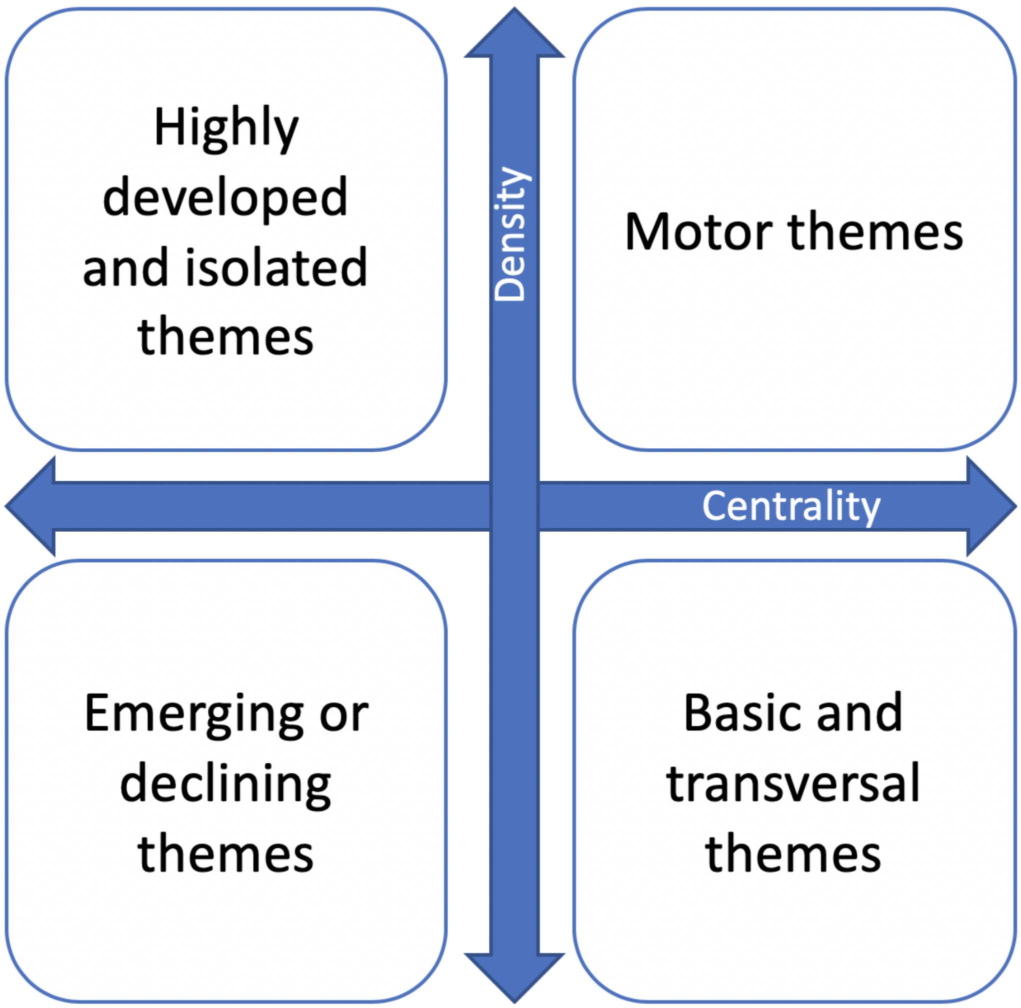

Fig. 1. Structure of the strategic diagram.

The main idea behind this analysis is to make a comparison between the results of the evaluation of manual themes and from SciMAT; identifying similar patterns of development in the scientific field.

3. Results

3.1. Systematic literature review

This study analyses the development of scientific articles relating to the terms **"pavement"** and **"urban heat island"**. Fig. 2 shows the number of articles versus publication year. The year 2018 was the peak with 19 articles published. Only a few articles were published in the 1990s however, from 2004 there has been a continuous growth in the number of articles published, regarding the topics of this study.

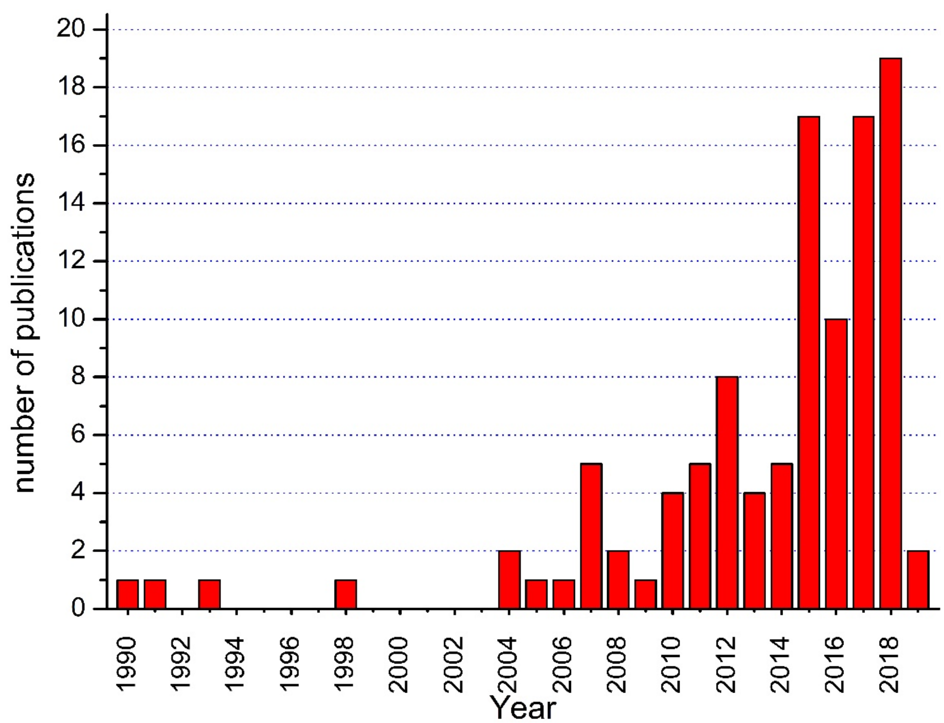

Fig. 2. Number of articles published related to UHI/pavement per year.

Fig. 3 shows the geographical distribution of published articles, using the origin country of the first author. Researchers from countries in the European Union (including the UK), US, and China, published 34%, 26%, and 23% of the total number of articles, respectively. In the southern hemisphere, only researchers from Australia and Brazil published articles on the subject of UHI/pavement.

Table 1 shows the main journals and their most relevant articles, including their Impact Factor (IF), calculated by the last Journal Citation Reports (2019). The journal with the highest proportion of articles is *Energy and Buildings* (14% of all published articles), followed by *Building and Environment* (7%), with the most cited article in the UHI/pavement topic (the article concerned the surface heat budget of concrete pavement compared to green roofs [29]).

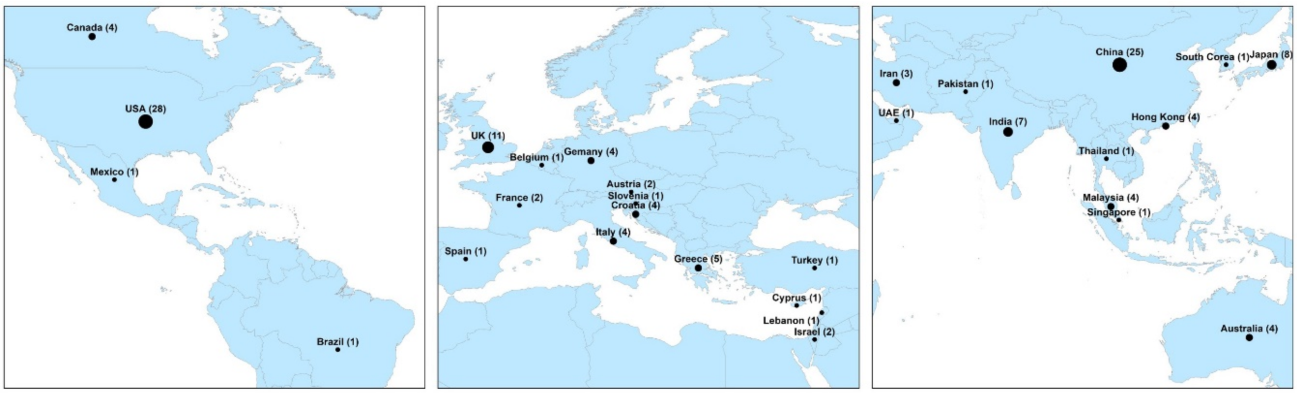

Fig. 3. Geographic distribution of published articles according to main author country of origin.

In general terms, all of the articles deal with the thermal effects of different types of flooring, radiation balance, surface heat budget, and possible modifications of concrete and other types of flooring with direct or indirect connections to mitigation of the UHI. Table 1 contains a summary of the most relevant articles in each journal.

Since 2016, the number of articles on different types of pavements, methodologies, environmental effects and UHI has increased in the Journal of Cleaner Production (one of the journals with the highest IF in the field). Examples of topics published in this journal are sustainable production of permeable concrete pavements [30], cool photocatalytic pavements [31], paving blocks that retain water to reduce runoff [32] and phase change materials (PCM) (which can be used to reduce UHI effects) [33]. Table 1 shows more detail for these articles. Additionally, the analysis shows that the articles published in ELSEVIER journals have a greater number of citations compared to other publishers.

Table. 1. Most important journals and most cited articles.

Journal name	Number of articles	Journal IF 2019	Name of the most cited article	Authors	Number of citations*	Main outcomes of the most cited article
Energy and Buildings	15	4.867	Reductions in air conditioning energy caused by a nearby park	Ca, Asaeda, & Abu [34]	178	Surface temperature in park 19 °C lower than on asphalt street and 15 °C lower than concrete surface temperature
Building and Environment	8	4.971	Surface heat budget on green roof and high reflection roof for mitigation of UHI	Hideki Takebayashi & Moriyama [29]	338	The tendencies of the sensible heat flux accord with the pitch relation of the surface temperature of the white paint, green and cement concrete surface.
Construction and Building Materials	6	4.419	Experimental study on the effects of fine sand addition on differentially compacted pervious concrete	Bonicelli, Giustozzi & Crispino [35]	35	The results suggested that adding 5%, per mass, of fine sand to permeable concrete improves mechanical and surface characteristics and reduces their drainage capacity
Journal of Cleaner Production	5	7.246	Aging albedo model for asphalt pavement surfaces	Sen & Roesler [36]	28	The albedo of a series of asphalt and concrete pavement test sections of different ages was measured. A non-linear model of albedo aging for asphalt pavements was developed
Transportation Research Record	4	1.029	Cyclic heat island impacts on traditional versus pervious concrete pavement systems	Haselbach, Boyer, Kevern & Schaefer [37]	63	Permeable concrete with low albedo can work like cool pavement
Solar Energy	4	4.608	On the development, optical properties and thermal performance of cool coloured coatings for the urban environment	Synnefa, Santamouris & Apostolakis [38]	326	Cool coating with near-infrared reflective pigments to mitigate UHI effect. It can be used for concrete walls and ceilings
Applied Sciences - Basel	3	2.474	Strength, permeability, and freeze-thaw durability of pervious concrete with different aggregate sizes, porosities, and water-binder ratios	Liu, Luo, Wei, & Yu [39]	11	A balance between permeability, mechanical strength, and freeze-thaw durability of porous concrete can help to mitigation of UHI thermal effect.
Road Materials and Pavement Design	3	2.582	Laboratory-simulated investigation on thermal behaviours of permeable concrete pavements	Wu, Sun, Liu & Yin [40]	8	Thermal behaviour of traditional and porous concrete pavements and their thermal impacts in the surrounding environment. The greater the porosity of the pavement material, led to greater the reduction in its temperature
Journal of Testing and Evaluation	3	0.877	Effect of phase-change materials on thermal and mechanical properties of asphalt mixtures	Chen, Wan & Lin [41]	20	Researchers recommend the use of PCM in asphalt mixtures to solve the pavement problem at high temperatures. They recommend a phase-change temperature of 50 vs. 45ºC and a latent heat of 100 J/g vs. 110 J/g.
Advances in Materials Science and Engineering	3	1.271	Study on surface heat budget of various pavements for UHI mitigation	Takebayashi & Moriyama [42]	31	Sensible heat flux for a concrete surface is 180 W/m^2 lower than asphalt. The reduction of 100 W/m^2 in sensible heat flux for water retention concrete and porous concrete surfaces compared to asphalt

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After the analysis of the main journals, the authors with three or more published articles were analysed as shown in Table 2. Qin of Guangxi University is the most productive author for the articles analysed in this research. Qin is lead author in four articles on the following topics: pavement energy balance [43], urban canyon albedo research [44] and a review of cool pavement classification and its possibilities for mitigating the UHI effect [7]. In addition, Qin presents other investigations with methodologies for mitigating the UHI effect; while these have not been found with the search formula in the materials and methods section, these investigations are considered essential studies in the area. In 2016, the author concluded that rewetting the pervious concrete surface can help keep this surface cool for 12–24 hours and help minimise the UHI's thermal effect in a dry, hot climate in summer [45]. In 2019, Qin presented the results of experimental work on the curing of cement pastes, where it was observed that those cured in a moist chamber had an albedo 0.01–0.10 higher than those cured in an indoor environment [46].

Similarly, researchers from the University of Illinois (Sen & Roesler) work in the area of rigid pavements, cool photocatalytic pavements and preservation of pavements in the context of UHI [31,47,48].

Table 2. Main authors cited in the analysis.

Main author	Institution corresponding to the last article published by the author	Number of publications	*h-index**	Most cited articles as author or co-author	Number of citations*
Qin	Guangxi University, Nanning, China	4	23	A review of the development of cool pavements to mitigate UHI effects [7]	197
Roesler	University of Illinois at Urbana-Champaign, Urbana, USA	3	24	Aging albedo model for asphalt pavement surfaces [36]	28
Sen	University of Illinois at Urbana-Champaign, Urbana, USA	4	4	Aging albedo model for asphalt pavement surfaces [36]	28
Liu	Jilin University, Changchun, China	3	9	Strength, permeability, and freeze-thaw durability of pervious concrete with different aggregate sizes, porosities, and water-binder ratios [39]	11
Luo	Jilin University, Changchun, China	3	4	Strength, permeability, and freeze-thaw durability of pervious concrete with different aggregate sizes, porosities, and water-binder ratios [39]	11
Jiang	Chang'an University, Xi'an, China	3	9	Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction functions [49]	26
Biligiri	Indian Institute of Technology Tirupati, Tirupati, India	3	17	Comprehensive laboratory evaluation of thermophysical properties of pavement materials: Effects on UHI [50]	11

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The classification of the general types of scientific articles found in the four periods studied is presented in Fig. 4 (Tables A.1 – A.9). From the first period (1990-2008) to the last period (2017-2019), the number of articles regarding field experiments and controlled field experiments was reduced but the number of articles with results derived from laboratory experiments increased. If the article is a comparison between an experiment and a numerical simulation, it has been considered as being experimental. In the last period of analysis (2017-2019), the percentage of "other" articles increased, e.g. those that span different scientific fields, investigations with satellite data, and unidentified articles.

Fig. 4. Classification by general type of article.

Based on the above, the focus of the analysis was on articles regarding field experiments and controlled field experiments. Tables A.1-A.4 present these types of articles for the four specific periods. Tables A.5-A.7 present articles based on laboratory–based studies. Table A.8 shows the articles of numerical simulations and Table A.9 shows articles on other types of studies.

3.1.1. First period (1990-2008)

The main characteristic of the first period (1990-2008) is the prevalence of articles on field experiments and controlled field experiments. The first article dates from 1990 [51], in which the authors conduct an UHI analysis of Tokyo. They found differences in the surface temperature of different types of pavements (building roofs, pavements, green areas and soil). Another article from Japan [34] shows research results for surface heat budget and diurnal variations in atmospheric temperature on asphalt pavements when compared to grass. In 2004, Ramier *et al.* presented the results of a surface water balance analysis of porous asphalt concrete. The authors determined that the total runoff loss was 84% for porous asphalt concrete, while this value was 30% for traditional asphalt pavement [52]. These results indicated that road hydrological behaviour contributes to the creation of a UHI due to thermal exchanges.

In the same year, Takahashi *et al.* published an article on the numerical simulation of atmospheric temperature, walls, and pavements in Kyoto. The authors used computational fluid dynamics for the analysis [53].

In the US, Mueller & Day published an article on the effect of asphalt and concrete pavements on the bio-productivity of plants. This study showed that, during fall/winter, oleander shrubs (*Nerium oleander* L.) in mesiscape (turf) areas produced 20% less biomass and 13% less leaf area, and they had 12% lower relative growth rates than other groundcover types (gravel, concrete and asphalt). By contrast, in spring/summer, oleanders in the mesiscape produced 11% more biomass and 16% more leaf area, and they had 3% higher growth rates than other groundcover types [54].

The analysis showed that, up until 2005, studies on general urban microclimatology and the environmental effects of pavements predominate. Since 2006, a group of researchers from Greece published an article on the use of reflective coating for buildings as a method of mitigating the effects of UHI. During a summer's day, the use of reflective coating can lower the surface temperature by up to 4°C and up to 2°C overnight, compared to conventional concrete [55]. In 2007, the same research team published an article on the use of cool coloured coating, fabricated with near-infrared reflective colour pigment [38]. These are some of the first articles directly related to the mitigation of the thermal effects of UHI.

In 2007, a group of researchers from Japan published an article on the analysis of surface heat budget and water balance for a controlled field experiment on a pavement with high albedo, concrete, and a vegetated surface; the main idea was to find better coverage to mitigate UHI. As a result, they demonstrated that sensible heat flux agreed with the pitch relation of the temperature of each surface that was studied [29].

In the US, high-reflection concrete production technology was developed using slag as a replacement for Portland Cement in a UHI mitigation measure. Additionally, this mixture can also be used in highways [56]. In 2008, UHI research conducted in Nanjing, China concluded that atmospheric temperature on concrete was between 0.2 and 2.9°C above the temperature of green areas [57].

Overall, it can be seen that, in the first period of analysis, the predominant work was on field experiments and controlled field experiments. Articles on urban climate in the late 1990s had certain weaknesses. On the other hand, from 2008 onwards, articles on possible solutions for UHI mitigation were published which considered improvements in roofs, building walls, and city pavements.

3.1.2. Second period (2009-2014)

The second period (2009-2014) is shorter than the first period but the scientific productivity increased. In 2009, Volder *et al.* published an article on the effects of permeable and non-permeable concrete on vegetation, soil water content, and surface temperature. Regarding temperature, the authors concluded that the soil type did not significantly affect the surface temperature [58].

In the article by Starke *et al.*, the authors concluded that permeable concrete is a feasible solution for mitigating UHI because of its good evaporation characteristics (16% higher than non-permeable concrete) [59].

In 2010, researchers published articles on the use of green roofs as a UHI mitigation method. A good example was published by Japanese researchers Sendo *et al*. They evaluated ornamental plant species on the flat rooftop of a four-story building located in Kobe and concluded that the vegetation reduced the rooftop temperature 6–8°C compared to a concrete rooftop during summer nights [60].

Conversely, a prototype of non-white, reflective-solar concrete roof tiles, and roof asphalt shingles, was created using a two-layer spray coating process. This was designed to maximise solar reflectance as each layer is painted with pigmented, thin, quick-drying latex based on acrylic or a mixture of polyvinylidene fluoride/acrylic. The first coating layer was a white, base layer of titanium dioxide that increases the solar reflectance of grey concrete from 0.18 to 0.79. The second layer is a "cool" upper layer with weak absorption in the near infrared (NIR) and/or strong NIR backscatter [61].

In 2011, Cao *et al.* used a heat-reflectance coating for road surfaces [62] and Haselbach *et al. used* concrete systems [37] as mitigation measures of the UHI. Additionally, Liu *et al.* developed numerical analysis for the estimation of thermal effects in soils under different types of pavements [63].

In 2012, the most cited article was on the effect of atmospheric and global temperature on concrete pavements [64]. In Japan, Takebayashi & Moriyana developed a complex, controlled field experiment and numerical simulations of the surface heat budget of different pavements to mitigate UHI [42]. The researchers tested four types of concrete and four types of asphalt, concluding that materials with water retention properties showed better characteristics for mitigating UHI.

Conversely, in 2012, Stempihar *et al.* conducted a numerical simulation of porous asphalt concrete and Portland Cement concrete pavements [65]. The article shows that UHI mitigation is complex and should include more factors (e.g. albedo, pavement structure, pavement thickness) to model the use of different types of pavement to mitigate UHI. Yaghoobian & Kleissl published an article about the effects of modifying building and street pavements on the energy consumption of buildings [66].

Nano-based coatings have been developed for building envelope materials in order to improve near infrared (NRI) reflecting properties in 10% [67]. The direct benefits of cool roofs in an urban environment were quantified in the city of Hyderabad [68], with the measured annual energy savings from whitening previously black roofs ranging from 20 to 22 kWh/m^2 of roof area, which corresponded to a cooling energy use reduction of 14–26%.

In 2013, Li *et al.* showed that permeable pavements with high albedo mitigate UHI effects and improve air quality and human comfort [69]. In addition, Dehdezi *et al.* performed microstructural and mechanical analysis on concrete with micro-encapsulated PCM as a potential methodology for UHI reduction [70]. Speak *et al.* analysed the effect of green roofs' damage by mismanagement in a drought period on urban cooling in England, concluding that the temperature increased in 0.63°C compared to healthy and well maintained green roofs [71].

In 2014 (the last year in this period), Ouldboukhitine *et al.* published an article about a controlled field experiment conducted in La Rochelle, France, along with a numerical simulation of green roof effects on UHI [72]. The research showed that the superficial temperature of a green roof can be 20°C lower than the rest of the environment and reduces a building's energy consumption. Other numerical simulations showed that albedo increase and evaporative flow it is possible to find a structure to mitigate UHI effect.

The analysis shows that, in the second period, researchers developed new methodologies for the mitigation of UHI caused by urban pavements and developed numerical methods for analysis. In general, the number of field experiments decreased. In addition, researchers applied different UHI mitigation methodologies for dry regions with a Mediterranean climate, like Greece or California. Similarly, regions with more humid climates (e.g. France, England, Japan) developed green roofs to obtain thermal comfort in buildings located in cities, reducing their energy consumption.

3.1.3. Third period (2015-2016)

In the third period (2015-2016), Qin published the most cited article, a review of the systematisation of cool pavement technologies and methods used to mitigate UHI [7]. The article synthesises the existing definition, physical mechanism and typical cooling techniques of cool pavements, presenting the influence of cool pavements on the urban thermal environment at that time. In addition, the review suggests that the definition of cool pavements and their impact remain incomplete; thus, it proposes future research topics.

In the same year, Greek researchers published research about a microclimatological experiment that was carried out in the city of Thessaloniki, with the aim of investigating the effects of atmospheric temperature, relative humidity and globe temperature on different types of anthropogenic pavements (shapes and materials) [73]. In the area of numerical simulation, the most important articles published in 2015 were the evaluation of reflective cool pavements in urban canyon conditions [44], and a study of the impact of building geometry on the thermal performance of road pavement solar collectors where demonstrated that better effects (lower temperatures of road surfaces) were obtained with an asymmetrical canyon height (~20% reduction) [74].

Regarding publications on laboratory experiments, researchers published articles on investigations into permeable concrete modifications [35] and on the design and performance of asphalt concrete mixtures that retain water with the purpose of analysing their mechanical and hydrological characteristics [75]. In 2016, research was published that analysed albedo-aging models of asphalt pavements, and it evaluated the effect of changing paving materials on UHI mitigation [36].

In the area of UHI mitigation, the University of Hong Kong published the main scientific articles regarding the most suitable materials for the climatic conditions in Hong Kong [76] and the thermal analysis of the differences between green walls and concrete walls [77]. In the research on the latter, strong evidence was published regarding thermal performance of climber green walls using field monitoring data that were obtained from different weather scenarios —sunny, cloudy and rainy— while the behind-mesh concrete surface performed consistently in all scenarios, generating a cooler surface.

In experimental research conducted in Singapore [78], the thermal effects of different green roofs comprising different vegetation species was investigated compared to concrete. The main conclusion was that plant selection on roofs with coatings and green gardens is very important because not all plants have a positive effect on reducing the environmental temperature.

In summary, in this period the main topics were the modification to cool pavements, numerical simulations at urban canyon scale and new technologies for the mitigation of thermal effects by using green walls in tropical climatic zones.

3.1.4. Fourth period (2017-2019)

During this last period (2017–2019), the most cited article was a review of asphalt concrete and its possible effects on mitigating UHI effects. In this research, it was concluded that the thermal properties of flexible pavements significantly contribute to UHI effect in cities; however, several mitigation strategies were proposed [8].

In the area of road pavements, the most relevant articles were on the simulation and design of thermoelectric asphalt with capabilities for generating energy [49] and on the simulation and design of convection-powered solar collectors in asphalt [79], with the purpose of minimising pavement temperatures in urban conditions. Another research document on pavements [80] presents a laboratory study of a new permeable concrete with capillary columns. The article shows that the capillary column was important because its increased evaporation by raising water from the bottom of the pavement to the surface. An article in 2017 that evaluated the environmental benefits of photocatalytic cool concrete pavements through a lifecycle analysis showed that overlays containing titanium dioxide had five times less global warming potential compared with grey cement [31]. In addition, a four-year experiment on the effects of permeable and non-permeable pavements on the thermal condition of underlying soils and vegetation demonstrated that porous pavements may mitigate UHI because they produce temperatures that are 4–5°C lower than those of conventional concrete and asphalt pavements [81].

In the area of numerical simulations, in 2018 Kandya & Mohan published an article evaluating UHI mitigation strategies through modifications of the building envelope using eQUEST software [82]. A composite of bamboo and concrete (bamcrete) was analysed, which can be used for the construction of building walls in climatic conditions in India. The authors showed that the use of bamcrete is economical and has important energy-saving and cooling benefits [82]. In addition, simulation of the urban environment (in certain parts of the city) was developed to identify the possibility of replacing currently used surfaces with cooler surfaces, to evaluate the potential transformation of the urban landscape for the mitigation of UHI [83].

During this period, Chung & Park published an article on their experimental study of the thermal performance of PCM that was fabricated with wood and plastic compounds and used for building roofs. This research demonstrated the effectiveness of plates containing PCM in mitigating UHI effects; however, the melting temperature of the PCM directly influenced the material's performance [84].

Overall, in the last period, scientific articles studied the effect of reducing thermal effects of UHI and transforming the thermal heat of pavements to other types of energy, with the possibility of using it in the urban environment. Another topic investigated in this period was the development of environmentally friendly materials [9], fabricated locally with the purpose of minimising energy, as well as improving economic and ecological effects. Finally, articles on numerical simulations were also published. This type of research is less expensive than field experiments and controlled field experiments.

We would also like to analyse a type of modern retro-reflective pavement with high potential for mitigating and minimisation of the UHI's effects, which were not included in the results of our search in WOS and SCOPUS. In recent years, in most cases, researchers from Italy and Japan have researched the problem of using these materials in urban environments [85]. In 2016, Rossi *et al.* demonstrated that using retro-reflective pavements in an urban canyon can increase albedo over the canyon's lid by 4.6% compared to white and beige diffusive materials with the same global reflectance [86]. In another study, the effect of aging on retro-reflective materials over their reflectivity possibility was analysed by Morini *et al.* The authors determined that, during aging, retro-reflective materials demonstrate a slight decrease in reflected radiation towards the incidence direction, which occurs together with a slight increase towards the nearby directions. In general, these materials have not undergone significant changes in their reflective abilities, and their urban cooling potential was preserved [87]. Castellani *et al.* noted that retro-reflective pavements that were produced of different materials and with different chemical additives had different indicatrices of reflected radiation [88]. The importance of using materials with optimal reflected radiation indicatrices for vertical and horizontal surfaces for UHI mitigation in various climatic zones was shown in Manni *et al.* [85]. Finally, Ichinose *et al.* noted that these types of materials can be used not only as a coating for opaque surfaces in an urban environment but also as a transparent film in the glazing of buildings [89].

3.1.5. General analysis of systematic literature review

Fig. 5 shows a summary of the main topic for each investigation period. The figure shows the evolution of the scientific area connected with concrete and UHI for roofs, pavements, urban planning policies, and numerical simulation based on the analysis of the most relevant articles from each period.

The most recent period is characterised by scientific articles that are not only concerned with reducing the thermal effects of UHI but also transforming the thermal heat of pavements into other types of energy, with the possibility of using it in the urban environment. Another topic is the development of environmentally friendly materials that are produced locally, with the purpose of minimising energy, as well as economic and ecological effects [9]. Finally, the development of numerical simulations (which became more detailed and developed) helped to minimise more expensive research, such as field experiments and controlled field experiments.

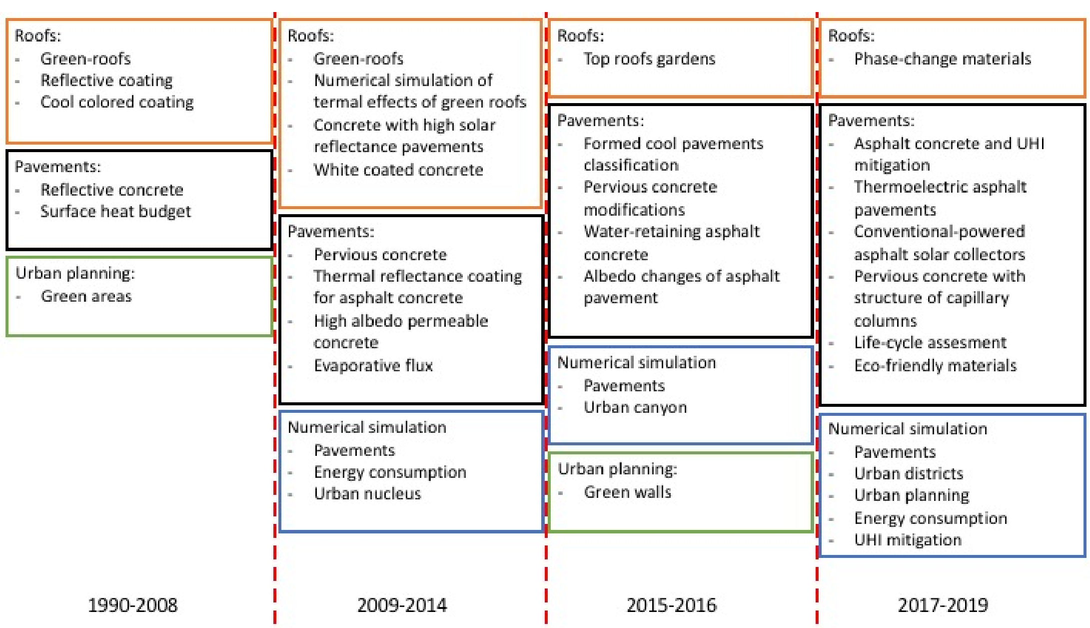

Fig. 5. Summary of major advances in the development of topics of scientific articles analysed manually.

Tables A.1-A.9 show the overall classification and information of all articles analysed in this investigation. Fig. 6 shows a geographical distribution map of all the scientific articles concerning field experiments and controlled field experiments from Tables A.1-A.4. The map shows that the US, China and Japan are the countries carrying out the most research on this topic. In addition, the figure shows that, in Latin America, only Brazil has conducted experiments on this topic. The geographical location of experiments is relevant because is related to the climatic conditions used in the research.

Fig. 6. Geographic location of field and controlled experiments (Tables A.1-A.4).

3.2. Bibliometric analysis

In order to analyse the temporal evolution, Fig. 7 shows the strategic diagrams of the thematic networks for the four periods considered (1990-2008, 2009-2014, 2015-2016, and 2017-2019), which were obtained with the use of the SciMAT tool. Fig. 7 is based on the scheme shown in Fig. 1. Table 3 shows the strategic map obtained for the thematic network and the period in terms of the number of documents (with reference to each one), *h-index* and number of articles. Next, an analysis of the results obtained for each period was carried out.

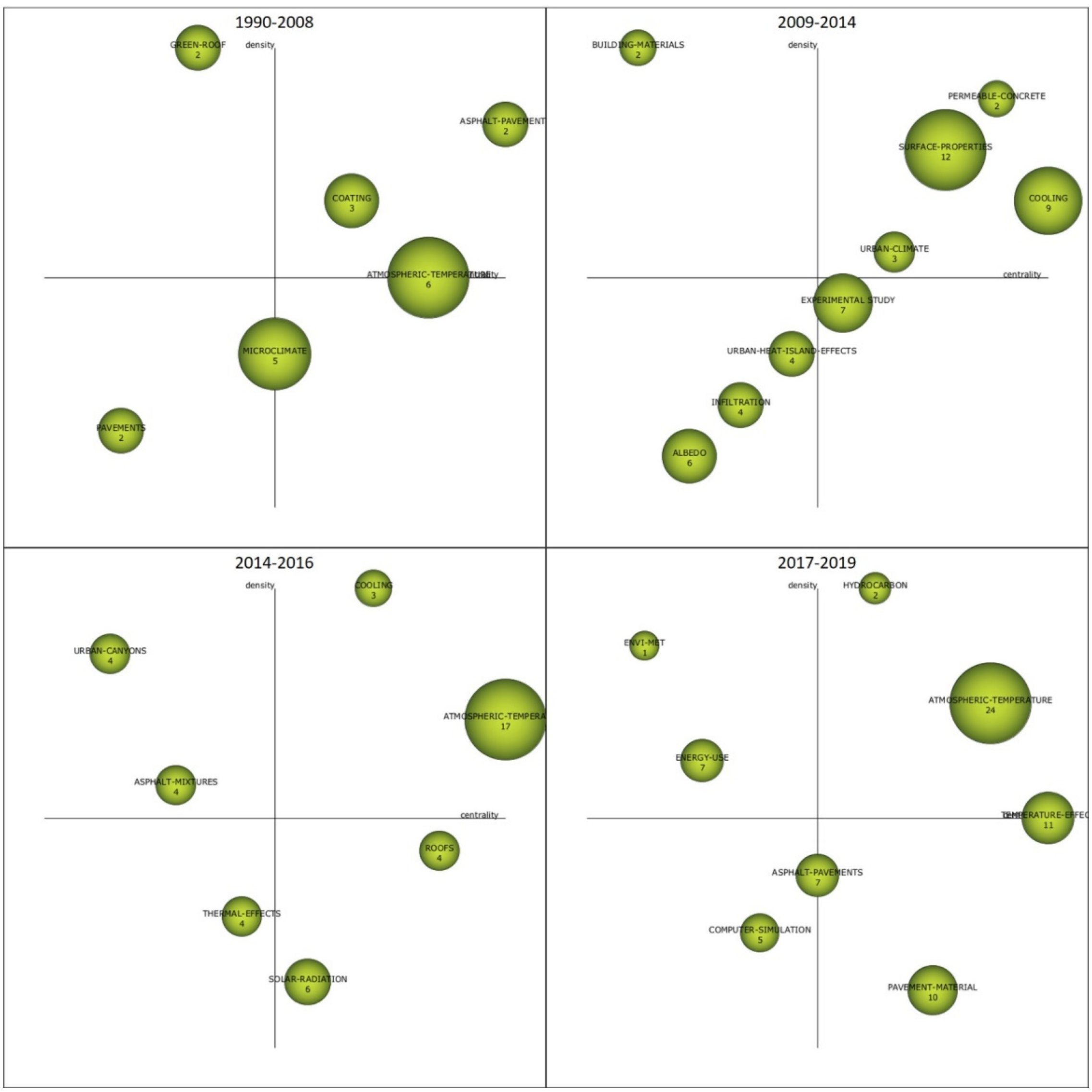

Fig. 7. Diagrams of thematic networks for the four periods considered.

3.2.1. First period (1990-2008)

In the first period (and according to the strategic diagram presented in Fig. 6), 15 articles were published for 6 main research topics (Table 3). COATING and ASPHALT-PAVEMENTS are the motor themes in this period and these two themes correspond to 5 articles (Table 3). GREEN-ROOF is a topic with 2 scientific articles that were developed but isolated. COATING and GREEN-ROOF topics correspond to the most cited articles in all of this research. ATMOSPHERIC-TEMPERATURE is a theme that lies between basic and motor themes and this topic corresponds to 6 articles, with a total of 1049 citations. MICROCLIMATE is located between basic and emerging themes and PAVEMENTS is an emerging issue. GREEN-ROOF articles are classified in a similar way as ATMOSPHERIC-TEMPERATURE, just as two articles on COATING correlate with ATMOSPHERIC-TEMPERATURE and a third with the MICROCLIMATE theme.

3.2.2. Second period (2009-2014)

In the second period (and according to the strategic diagram presented in Fig. 7), 9 main research topics can be observed for the 27 articles published (Table 3). BUILDING-MATERIALS is defined as a well-developed and isolated topic. Four motor themes are presented: SURFACE-PROPERTIES, COOLING, PERMEABLE-CONCRETE and URBAN-CLIMATE. EXPERIMENTAL STUDY is presented as a basic and transversal theme. URBAN-HEAT-ISLAND-EFFECTS, ALBEDO, and INFILTRATION are emerging themes. 2 of the articles have the theme: PERMEABLE-CONCRETE and these are also present in the COOLING and INFILTRATION topics, demonstrating a connection between these themes in this period. For all of this, thematic descriptions of each article can be combined with themes. For example, the article by Starke *et al.*, "Urban evaporation rates for water-permeable pavements" [59], can be assigned to PERMEABLE-CONCRETE, COOLING, URBAN-CLIMATE and INFILTRATION topics. As noted above: "In an article by Starke *et al.*, the authors conclude on the possibility of using permeable concrete as a method of mitigating UHI, due to its evaporation characteristics of 16% more than non-permeable concrete".

3.2.3. Third period (2015-2016)

In the third period (and according to the strategic diagram presented in Fig. 7), 7 main research topics can be observed in the 27 articles published in this period (Table 3). COOLING and ATMOSPHERIC-TEMPERATURE are motor themes, with 4 and 17 associated articles, respectively. COOLING remains the motor theme in the second period. URBAN-CANYONS and ASPHALT-MIXTURES are very developed topics in this period, with 4 associated articles for each topic. In the manual analysis of the articles, two more of the cited articles in this period are connected with numerical simulation in urban canyon conditions [44,74]. ROOFS and SOLAR-RADIATION are basic themes in this period with 4 and 6 articles, respectively. Among them is an article on experimental research on roof gardens in Singapore [78] and this article covers 2 of these topics. THERMAL-EFFECTS is an emerging issue with 4 articles, including 3 numerical simulations and 1 microclimatic field experiment (Table 3).

3.2.4. Fourth period (2017-2019)

The last period is characterised by the main motor themes: ATMOSPHERIC-TEMPERATURE, TEMPERATURE-EFFECT and HYDROCARBON, while articles associated with HYDROCARBON provide a general review of concrete asphalt use [8] and a study on the effects of permeable pavements on flora [81]. PAVEMENT-MATERIAL in this period is a basic topic and this topic corresponds to 10 articles. ENVI-MET and ENERGY-USE are well developed and isolated topics. For ENVI-MET there is a relatively relevant article [83] by a scientific team from Greece, simulating parts of the city of Thessaloniki. In this last period, we obtain an emerging theme: COMPUTER SIMULATION.

Table 3. Strategic maps of thematic networks.

Name	Core documents (CD)	CD h-Index	CD Citations	Cit. per doc.
	1990-2008			
ASPHALT-PAVEMENTS	2 [52,54]	2	64	32
COATING	3 [34,38,55]	3	697	232
GREEN-ROOF	2 [29,38]	2	579	289
MICROCLIMATE	5 [34,54,57,90,91]	4	382	76
ATMOSPHERIC-TEMPERATURE	6 [29,38,53,55,57,92]	6	1.049	174
PAVEMENTS	2 [52,56]	2	43	21
	2009-2014			
Name	Core documents (CD)	CD h-Index	CD Citations	Cit. per doc.
BUILDING-MATERIALS	2 [61,67]	2	103	51
PERMEABLE-CONCRETE	2 [59,69]	2	103	51
SURFACE-PROPERTIES	12 [61,62,95,96,63–65,69,70,72,93,94]	8	411	34
COOLING	9 [41,59,62–64,66,68,69,97]	8	365	40
EXPERIMENTAL STUDY	7 [41,62,72,93,94,96,98]	4	81	11
URBAN-CLIMATE	3 [59,66,98]	3	61	20
URBAN-HEAT-ISLAND-EFFECTS	4 [70,93,94,97]	3	26	6
ALBEDO	6 [37,61,68,71,72,94]	5	256	42
INFILTRATION	4 [58,59,63,69]	4	148	37
	2015-2016			
Name	Core documents (CD)	CD h-Index	CD Citations	Cit. per doc.
ATMOSPHERIC-TEMPERATURE	17 [7,36,101–107,50,74–78,99,100]	8	223	13
ASPHALT-MIXTURES	4 [50,75,104,108]	4	26	6
URBAN-CANYONS	4 [7,44,74,109]	4	114	28
COOLING	3 [50,77,101]	3	36	12
ROOFS	4 [36,78,101,102]	4	48	12
SOLAR-RADIATION	6 [36,73,77,78,103,110]	5	86	14
THERMAL-EFFECTS	4 [73,74,102,109]	4	42	10
	2017-2019			
Name	Core documents (CD)	CD h-Index	CD Citations	Cit. per doc.
HYDROCARBON	2 [8,81]	2	31	15
ATMOSPHERIC-TEMPERATURE	24 [8,31,82,84,111–118,32,119–122,40,47–49,79–81]	6	117	4
ENERGY-USE	7 [30,31,48,82,115,117,123]	4	25	3
TEMPERATURE-EFFECT	11 [8,32,123,33,40,80,84,112,119,120,122]	4	52	4
ASPHALT-PAVEMENTS	7 [8,49,79,111,115,120,122]	5	51	7
PAVEMENT-MATERIAL	10 [30,33,39,40,81,119,124–127]	3	25	2
COMPUTER-SIMULATION	5 [32,79,80,112,117]	4	25	5
ENVI-MET	1 [83]	1	9	9

3.2.5. General assessment of bibliometric analysis

Fig. 8 presents the thematic evolution for the investigated periods. The first column of nodes presents the articles that were published between 1990 and 2008, which represent 14% of all the documents analysed. In this period, science was focused on analysing the microclimatic effect of UHI. On the other hand, in the last years of the 2000s, the first articles concerning mitigation methods for UHI thermal effects on roofs were published and articles on the analysis of the possibility of methodical implementation of UHI mitigation for city and road pavements began. The result of this analysis was the conclusion that, for urban microclimatic conditions, the use of concrete and concrete asphalt is better than the use of asphalt and that the effect of solar radiation reflectance is a key method of possible UHI mitigation. The main articles and their characteristics are presented in Tables A.1, A.5, A.8 and A.9.

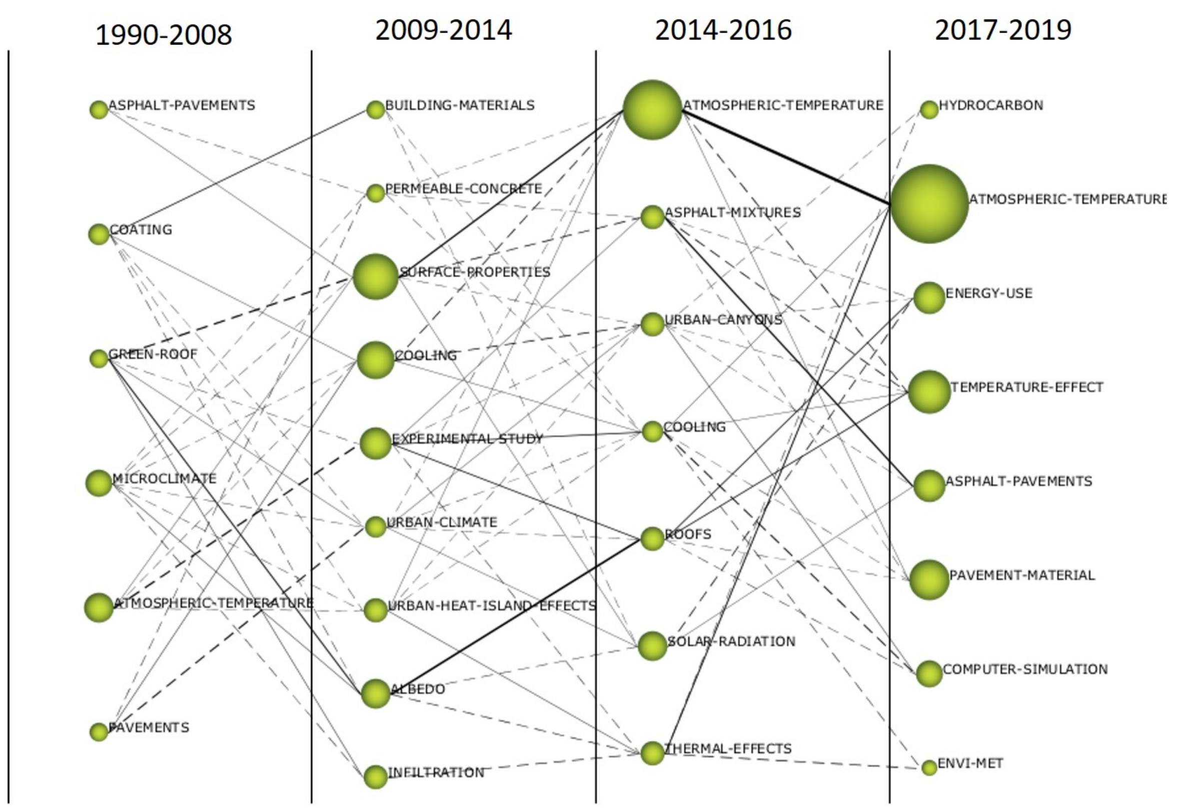

Fig. 8. Thematic evolution for the periods 1990-2008, 2009-2014, 2015-2016 and 2017-2019.

In the second period (2009-2014), almost all of the themes have connections and leave MICROCLIMATE articles from the last period. Logically, they are connected, since there is a lot of knowledge about thermal parameters and radiation for different urban pavements. In this period, there is a development phase of mitigation methods for UHI with PERMEABLE-CONCRETE use and changing ALBEDO pavement surfaces, with the purpose of COOLING urban surfaces. In addition, numerous scientific articles relating to EXPERIMENTAL STUDY are presented in this period.

A good connection can be observed between the SURFACE-PROPERTIES theme in the 2009-2014 period and the ATMOSPHERIC-TEMPERATURE theme in the 2014-2016 period. With these investigations, the idea that the surface characteristics of pavements in urban areas directly affect atmospheric temperature has been established. In the 2014-2016 period in the manual analysis, we did not find many outstanding articles however, in the results from SciMAT it can be observed that the 2014-2016 period has fewer topics than the previous period. Generally, articles connected with the development of ASPHALT-MIXTURES are concerned with finding a balanced asphalt recipe, to increase resistance to intensive use as well as mitigating UHI. A second, new topic in this period (already noted in the manual analysis) is URBAN-CANYONS and numerical simulations.

The connection between the SOLAR RADIATION topic in the 2015-2016 period and ASPHALT-PAVEMENTS in the 2017-2019 period is characterised by the development of articles on energy transformation through modern systems of solar collectors and photovoltaic panels. In general terms, this last period is characterised by the intensive development of COMPUTER-SIMULATION. There are also articles on the estimation of benefits in ENERGY-USE with implementation of UHI mitigation methodologies. ATMOSPHERIC TEMPERATURE and TEMPERATURE EFFECT themes are highly developed and many articles are connected to them.

On the other hand, there are sometimes errors with the correspondence of an article to a specific SciMAT topic. Thus, the article of "Aging albedo model for asphalt pavement surfaces" [36] was automatically assigned to the ATMOSPHERIC-TEMPERATURE, ROOFS and SOLAR RADIATION topics by SciMAT (Table 3) when, in fact, this article is about asphalt road pavements. Another example is the article "The UHI effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete" [8], which was automatically assigned to the topic HYDROCARBON (Table 3), which it usually has no connection to. For these reasons, the use of SciMAT is adequate when combined with a good analysis of the entire bibliography under conditions of a low number of scientific articles. Of course, with a larger number of articles (e.g. more than 1000), the contribution of an article that has been incorrectly assigned to a subject will be minimised and will not greatly affect the results of thematic evolution of the area of science.

On the other hand, in order to identify the more detailed characteristics of scientific articles, it has been observed that the use of this tool is insufficient. For this reason, in this study, in order to determine the development of UHI mitigation methods, it has been preferable to use the results of the manual analysis. Since SciMAT analysis is based on abstract texts, author keywords, additional keywords and article titles, in some cases it may cause errors in interpretation of the article content. Occasionally, summaries have content that does not accurately reflect the content of the entire article. For these reasons, bibliometric analysis tools (such as SciMAT) are preferable when used exclusively for analysis with a more significant number of articles. For study areas with fewer articles, it is advisable to use the tool but also perform a manual analysis to contrast the results.

4. Discussion

4.1. Research hotspots and future directions

The results show a clear decreasing trend in the number of investigations using field and controlled field experiments, as shown in Fig. 4. The geographical distribution of field experiments carried out is presented in maps in Fig. 6. This geographical distribution may help future researchers to carry out field experiments in climate types not previously investigated. Currently, field experiments are used to validate numerical models, and the results of these validations are part of other investigations.

Recently, there has been a trend of combining the theme of urban pavements with the theme of energy conservation in homes [66,115,123]. The interest in improving pavement characteristics for adaptation to and mitigation UHI effect explains the increase in the number of laboratory experiments that seek suitable materials and new techniques, such as innovative concrete elements with infrared-reflective pigments [117] or finding the optimum PCM melting temperature for the constructive elements of buildings [84].

In the future, research may focus on urban pavements built with combinations of ecological, biodegradable, and reusable materials, using LCA analysis and examining their energy effects, in order to minimize energy consumption for heating and cooling in buildings, taking into account interior and exterior thermal comfort under climate change conditions. These investigations could help create a more comfortable and sustainable urban environment.

4.2. Policy recommendations

The results of this research provide researchers and professionals working with pavements and UHIs a valuable document that has analysed, in-depth, the research trends in recent decades and indicates where future research themes lie. Additionally, this document can be used as a basis for the development of public policies in different decision-making organisations. After analysing all the articles, it is noted that it is necessary to adopt more forceful policy measures to legislate certain aspects of UHIs.

If a significant percentage of the impact of the UHI phenomenon is due to the materials used in the buildings, as well as the urban planning of the city, another part of the impact is closely linked to the climatic zone where the city is located. This is because different base weather conditions will affect internal city conditions.

Currently, state-building and urban planning regulations that take into account the effects of UHIs are scarce. For this reason, it is important to adapt national building codes with appropriate measures. As discussed above, the effect of the UHI is closely related to the climate zone, so it is advisable to adapt state rules to local regulations. In these local regulations, the conditions of the present and future urban development of the city may be adapted while considering the prevailing climate of the area, as well as the adaptation of local materials for the construction of surfaces. Finally, it is not recommended to implement general mitigation techniques across all cities, since the thermal effects of the UHIs depend on the size of the cities and climatic zones where the cities are located. For example, for cities with an equatorial climate, such as Singapore [78], it is possible to use green roofs and facades as a mitigation measure. On the other hand, for Mediterranean climatic conditions, such as in Greece [38,55], Australia [118], and Italy [67], this mitigation technique is not optimal; it is more highly recommended to use surfaces with a high albedo [38,55,67,118], as well as to use cool pavements [31,32].

5. Conclusions

In the present research, the temporal evolution of the general topics on pavements and UHI from 107 scientific articles collected in the WoS and Scopus databases between 1990 and 2019 was analysed. To carry out the study, the articles were analysed in 4 discrete periods: 1990-2008, 2009-2014, 2015-2016, and 2017-2019. For the analysis, 2 methodologies were applied: (i) manual and (ii) bibliometric analysis.

The analyses that were carried out have shown that the number of articles that have dealt with the study themes have been increasing in recent years, especially in the last decade. The EU has published the majority of the articles (34%). The magazine with the highest participation is *Energy and Buildings* (14%).

It has been shown that the use of the SciMAT bibliometric analysis tool showed a reasonably correct coherence in the establishment of main themes of articles compared to the manual method. General thematic evolution has occurred in the different periods, when trends are observed over time. The first period comprised major themes such as COATING and ASPHALT-PAVEMENTS and the most recent period concentrated on themes related to ATMOSPHERIC TEMPERATURE and its effects, as well as emerging themes such as COMPUTER SIMULATION.

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Appendix

Table A.1. Articles on field experiments and controlled field experiments in the period 1990-2008.

Type of exp.	City	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Nat. Exp./num. Sim	Tokyo, JP	Temperature effect	Concrete	Microclimatology		Urban	Evolution Tokyo Metropolitan area and its heat island model [51]	1990	31
Nat. Exp.	Haifa, IL	Temperature effect	Pavements	Microclimatology		Urban	Nocturnal variation of air-surface temperature gradients for typical urban and rural surfaces [92]	1991	9
Nat. Exp.	Tama, JP	Radiation balance	Green areas - asphalt surface	Microclimatology		Urban	Reductions in air conditioning energy caused by a nearby park [34]	1998	178
Nat. Exp./num. Sim	Kyoto, JP	Surface heat budget	Pavements	Microclimatology		Urban	Measurement of thermal environment in Kyoto city and its prediction by computational fluid dynamics simulation [53]	2004	74
Field exp.	Nant, FR	Water balance	Asphalt concrete	Sensors		Street	Development of an urban lysimeter to assess runoff losses on asphalt concrete plates. Results show that runoff losses are significant [52]	2004	22
Field exp.	Phoenix, US	Temperature effect	Concrete	Soil and vegetation		Urban	The effect of urban ground cover on microclimate, growth and leaf gas exchange of oleander [54]	2005	50
Field exp.	Atenas, GR	Radiation balance	Cool coloured coating	UHI mitigation	Cool, coloured roof	Coating	A study of the thermal performance of reflective coatings for the urban environment [55]	2006	300
Field exp.	Kobe, JP	Surface heat budget	Green roof	UHI mitigation	Green roof and sun reflection roof	Roof	Surface heat budget on green roof and high reflection roof for mitigation of UHI [29]	2007	340
Field exp.	Atenas, GR	Radiation balance	Cool coloured coating	UHI mitigation	Cool, coloured roof near irreflective colour pigment	Coating	On the development, optical properties and thermal performance of cool coloured coatings for the urban environment [38]	2007	331
Nat. Exp.	Brussels, BE	Temperature effect	Concrete	Soil and vegetation		Urban	The role of soil and microclimatic variables in the distribution patterns of urban wasteland flora [90]	2007	59
Nat. Exp.	Nanjing, CN	Temperature effect	Cement	Microclimatology		Urban	A fieldwork study on the diurnal changes of urban microclimate in four types of ground cover and UHI [57]	2008	152

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Table A.2. Articles on field experiments and controlled field experiments in the period 2009-2014.

Type of exp.	City	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Nat. Exp.	Burleson County, US	Temperature effect	Pervious concrete	Effect to soil and vegetation		Urban	Potential use of pervious concrete for maintaining existing mature trees during and after urban development [58]	2009	39
Field exp.	Berkley, US	Radiation balance	Concrete coloured	UHI mitigation	Cool coloured concrete (high solar reflectance)	Roof	A novel technique for the production of cool coloured concrete tile and asphalt shingle roofing products [61]	2010	94
Field exp.	Munster, DE	Temperature effect	Concrete water-permeable	UHI mitigation	Water-permeable pavements	Street	Analysis of the urban evaporation rates for water-permeable pavements. A comparison of two kinds of pavements shows a 16% increase in evaporation levels of water-permeable pavements [59]	2010	33
Field exp.	Kobe, JP	Temperature effect	Green roof	UHI mitigation	Green roofs	Roof	Evaluation of growth and green coverage of ten ornamental species for planting as urban rooftop greening [60]	2010	22
Nat. Exp.	Iowa city, US	Surface heat budget	Pervious concrete	UHI mitigation	Porosity and albedo for pervious concrete	Street	Cyclic heat island impacts on traditional versus pervious concrete pavement systems [37]	2011	63
Nat. Exp./num. Sim	Nanjing, CN	Temperature effect	Concrete	Soil and vegetation		Urban	A numerical and field investigation of underground temperatures under UHI [63]	2011	20
Nat. Exp.	Manchester, GB	Temperature effect	Concrete	Microclimatolo gy		Urban	The effect of tree shade and grass on surface and globe temperatures in an urban area [64]	2012	190
Nat. Exp.	Hyderabad, IN	Reduced cooling energy use	Cool roof	UHI mitigation	White coating to uncoated concrete roof	Roof	Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions [68]	2012	68
Field exp.	Osaka, JP	Surface heat budget	Modification of concrete	UHI mitigation	Heat budget- albedo, evaporative efficiency, heat conductivity, heat capacity	Street	Study on surface heat budget of various pavements for UHI mitigation [42]	2012	30
Nat. Exp.	Rijeka, HR	Temperature effect	Concrete	Microclimatolo gy		Urban	Analysis of pavement surface heating in urban areas [128]	2012	11
Field exp.	Davis, US	Surface heat budget	Concrete	UHI mitigation	High albedo and permeable pavement	Street	The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management [69]	2013	103
Nat. Exp.	Manchester, GB	Temperature effect	Green roof	UHI mitigation	Green roofs	Roof	Reduction of the urban cooling effects of an intensive green roof due to vegetation damage [71]	2013	43
Field exp.	Ancona, IT	Radiation balance	Modification of concrete	UHI mitigation	Nanobased coatings with improved nir reflecting properties	Roof/w all	Nanobased coatings with improved NIR reflecting properties for building envelope materials: Development and natural aging effect measurement [67]	2013	25
Field exp.	La Rochelle, FR	Temperature effect	Green roof	UHI mitigation	Green roofs	Roof	Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings to reduce the total energy demand and to improve the urban microclimate [72]	2014	44
Sim. Num./field exp.	Davis, US	Surface heat budget	Cool pavements	UHI mitigation	Thermal inertia and albedo	Street	Understanding pavement-surface energy balance and its implications on cool pavement development [43]	2014	95
Nat. Exp.	Nanjing, CN	Temperature effect	Concrete	Effect to soil and vegetation		Urban	Effect of ground covers on soil temperature in urban and rural areas [97]	2014	4
Field exp.	Onogawa, JP	Temperature effect	Concrete	UHI mitigation	Katsuren travertine	Street	Experimental evaluation of mitigation of thermal effects by "katsuren travertine" paving material [93]	2014	4
Nat. Exp.	Pantnagar, IN	Temperature indoor comfort	Cool roof	UHI mitigation	Cool-roof and cooling energy demand	Roof	Experimental determination of comfort benefits from cool-roof application to an un-conditioned building in India [94]	2014	3

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Table A.3. Articles on field experiments and controlled field experiments in the period 2015-2016.

Type of exp.	City	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Nat. Exp.	Thessaloniki, GR	Radiation balance	Concrete	Microclimatology		Urban	Microclimate development in open urban spaces: The influence of form and materials [73]	2015	35
Field exp.	Hong Kong	Radiation balance	Green-walls	UHI mitigation	Green-walls	Wall	Thermal performance of climber greenwalls: Effects of solar irradiance and orientation [77]	2015	36
Field exp.	Singapore	Temperature effect	Green areas-asphalt surface	UHI mitigation	Green areas	Urban	Impact of plant evapotranspiration rate and shrub albedo on temperature reduction in the tropical outdoor environment [78]	2015	28
Nat. Exp.	Hong Kong	Temperature effect	Green-walls	UHI mitigation	Green-walls	Wall	Assessing growth performance and deficiency of climber species on tropical greenwalls [76]	2015	13
Nat. Exp.	Guangzhou, CN	Temperature effect	Pavements	Microclimatology		Urban	Diurnal thermal behaviour of pavements, vegetation, and water pond in city with a hot-humid climate [129]	2015	15
Nat. Exp.	Mexicali, MX	Radiation balance	Pavements	Microclimatology	Select the best cool pavement	Street	Radiation balance of urban materials and their thermal impact in semi-desert climate [110]	2015	6
Nat. Exp.	Rijeka, HR	Temperature effect	Pavements	Microclimatology		Urban	Analyses of Urban pavement surface temperatures [106]	2015	3
Field exp.	Rantoul, US	Radiation balance	Concrete albedo	UHI mitigation	Aging albedo model	Street	Aging albedo model for asphalt pavement surfaces [36]	2016	27
Nat. Exp.	Putrajaya, MY	Temperature effect	Concrete	UHI mitigation	Select the best material for mitigation	Street	Effect of pavement materials on surface temperatures in tropical climate [100]	2016	18
Field exp.	Florianapolis, BR	Temperature effect	Pavements	UHI mitigation	White portuguese mosaic	Street	Urban pavements used in Brazil: Characterisation of solar reflectance and temperature verification in the field [104]	2016	11
Nat. Exp.	Greenbelt, US	Temperature effect	Pavements	Microclimatology		Urban	In situ air temperature and humidity measurements over diverse land covers [130]	2016	0

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Table A.4. Articles on field experiments and controlled field experiments in the period 2017-2019.

Type of exp.	City	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Nat. Exp./num. Sim	Thessaloniki, GR	Temperature effect	Concrete	UHI mitigation	Modelling for mitigation, best material para mitigation	Urban	Urban space's morphology and microclimatic analysis: A study for a typical urban district in the Mediterranean city [83]	2017	15
Nat. Exp.	Vertemate, IT	Mixed effect	Concrete	Effect to soil and vegetation		Urban	Nature based solutions to mitigate soil sealing in urban areas: Results from a 4-year study comparing permeable, porous, and impermeable pavements [81]	2017	25
Nat. Exp.	Vienna, AT	Temperature effect	Green areas - pavement surface	Microclimatology	Green areas	Urban	Analysis for improving the passive cooling of a building's surroundings through the creation of green spaces in the urban built-up area [113]	2017	8
Field exp./num. Sim	Perugia, IT	Temperature effect	Modification of concrete	UHI mitigation	Innovative concrete elements with ir reflective pigments	Street/ wall	New cool concrete for building envelopes and urban paving: Optics-energy and thermal assessment in dynamic conditions [117]	2017	13
Field exp.	Seoul, KR	Temperature effect	Roofs	UHI mitigation	Phase-change materials (PCMs) and wood-plastic composites	Roof	An experimental study on the thermal performance of phase-change material and wood-plastic composites for building roofs [84]	2017	10
Field exp.	Beirut, LB	Temperature effect	Green areas	UHI mitigation	Roof gardens	Roof	Roof top gardens as a means to use recycled waste and A/C condensate and reduce temperature variation in buildings [123]	2017	7
Field exp.	Llinars del Valles, ES	Temperature effect	Modification of concrete	UHI mitigation	Self-cooling concrete	Street	Outdoor performance tests of self-cooling concrete paving stones for the mitigation of UHI effect [119]	2017	4
Field exp.	Vienna, AT	Temperature effect	Albedo of concrete	UHI mitigation	Light-coloured traffic areas albedo change	Street	Reduction of UHIs with white topping [131]	2017	4
Nat. Exp.	Osijek, HR	Temperature effect	Concrete	Microclimatology			Analysis of influential factors on heat accumulation in structural elements of road underpasses [120]	2017	2
Field exp.	Xi´an, CN	Temperature effect	Pavements	UHI mitigation	Road thermoelectric generator system	Street	Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction functions [49]	2018	26
Field exp.	Guangzhou, CN	Temperature effect	Modification of concrete	UHI mitigation	Permeable paving materials, sintered ceramic porous brick	Street	Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment [112]	2018	28
Field exp.	Yixing, CN	Temperature effect	Structure of pavement	UHI mitigation	New structure of permeable pavement	Street	A new structure of permeable pavement for mitigating UHI called evaporation-enhancing permeable pavement [80]	2018	22
Nat. Exp.	Melbourne, AU	Temperature effect	Pavements	UHI mitigation	Select of the best cool pavement	Street	Daytime thermal performance of different urban surfaces: a case study in educational institution precinct [118]	2018	4
Nat. Exp.	Sarawak Kota, MY	Temperature effect	Pavements	UHI mitigation	Concrete, permeable and stormpav	Street	The impact of road pavement on UHI phenomenon [121]	2018	1

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Table A.5. Articles about laboratory experiments in the period 1990-2014.

Type of exp.	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Lab. Exp.	Radiation balance	Modification of concrete	UHI mitigation	Slag aggregation to increase albedo	Roof	Mix design and benefit evaluation of high solar reflectance concrete for pavements [56]	2007	24
Lab. Exp.	Surface heat budget	Modification of concrete	UHI mitigation	Heat-reflective coating for asphalt	Street	Cooling principle analyses and performance evaluation of heat-reflective coating for asphalt pavement [62]	2011	32
Lab. Exp.	Water balance	Modification of concrete	Devices			Development of a new laboratory evaporation measurement device as decision support for evaporation-optimized building [98]	2011	7
Lab. Exp.	Mechanical properties	Modification of concrete	UHI mitigation	PCMs	Street	Effect of phase-change materials on thermal and mechanical properties of asphalt mixtures [41]	2012	20
Lab. Exp.	Mechanical properties, porosity	Modification of concrete	UHI mitigation	Microencapsulated PCMs	Street	Thermal, mechanical and microstructural analysis of concrete containing microencapsulated PCM [70]	2013	23

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Table A.6. Articles about laboratory experiments in the period 2015-2016.

Type of exp.	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Lab. Exp.	Mechanical, hydrological properties	Modification of concrete	UHI mitigation	Pervious concrete	Street	Experimental study on the effects of fine sand addition on differentially compacted pervious concrete [35]	2015	38
Lab. Exp.	Temperature effect	Cool coloured coating	UHI mitigation	Cool white roof coating based on styrene acrylate copolymer and cement for waterproofing purpose	Roof	The study of an energy efficient cool white roof coating based on styrene acrylate copolymer and cement for waterproofing purpose - Optical properties, estimated cooling effect and relevant properties after dirt and accelerated exposures [101]	2015	15
Lab. Exp./sim. Num.	Radiation balance - albedo	Modification of concrete	UHI mitigation	Albedo and pervious	Street	The albedo of a pervious Portland concrete is 0.05~0.15 lower than the albedo of conventional cement concrete [103]	2015	11
Lab. Exp.	Hydraulic properties	Concrete	Drainage system			Addressing the demands of the new German permeable pavement design guidelines and the hydraulic behaviour of a new paving design [132]	2015	1
Lab. Exp.	Temperature effect	Asphalt concrete	UHI mitigation		Street	Thermal properties of asphalt pavements under dry and wet conditions [108]	2016	17
Lab. Exp.	Mechanical properties	Concrete	UHI mitigation	Water-retentive asphalt concrete	Street	Experimental study on materials composition design and mixture performance of water-retentive asphalt concrete [75]	2016	13
Lab. Exp.	Surface heat budget	Thermophysical properties	UHI mitigation	Six different paving mixtures	Street	Comprehensive laboratory evaluation of thermophysical properties of pavement materials: Effects on UHI [50]	2016	11
Lab. Exp.	Temperature effect	Concrete	UHI mitigation	Recycled glass and zeolite in concrete	Street	Reduce the slab surface temperature to mitigate the UHI by using recycled glass as a fine aggregate and zeolite as cement in concrete [105]	2016	3

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Table A.7. Articles about laboratory experiments in the period 2017-2019.

Type of exp.	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Lab. Exp.	Temperature effect	Asphalt	UHI mitigation	Convection-power asphalt solar collectors	Street	Construction and configuration of convection-powered asphalt solar collectors for the reduction of urban temperatures [79]	2017	18
Lab. Exp.	Mechanical properties	Concrete	UHI mitigation	Discarded cigarette butts	Street	Physico-mechanical properties of asphalt concrete incorporated with encapsulated cigarette butts [111]	2017	24
Lab. Exp.	Temperature effect	Concrete	UHI mitigation potential	Modification of pervious concrete	Street	Laboratory-simulated investigation on thermal behaviours of permeable concrete pavements [40]	2017	8
Lab. Exp.	Temperature effect	Modification of concrete	UHI mitigation	Voids of pervious concrete	Street	Comprehensive laboratory testing and evaluation of the evaporative cooling effect of pavement materials [122]	2017	0
Lab. Exp.	Thermoelectric properties	Structure of pavement	UHI mitigation	Expanded graphite/cement based composites to convert the thermal energy of solar radiation into electric energy	Street	Enhanced thermoelectric properties of cement-based composites with expanded graphite for climate adaptation and large-scale energy harvesting [114]	2018	18
Lab. Exp.	Mechanical properties	Concrete	UHI mitigation potential	Modification of pervious concrete	Street	Strength, permeability, and freeze-thaw durability of pervious concrete with different aggregate sizes, porosities, and water-binder ratios [39]	2018	10
Lab. Exp.	Mechanical properties	Concrete	UHI mitigation potential	Modification of pervious concrete	Street	Draining capability of single-sized pervious concrete [124]	2018	17
Lab. Exp.	Mechanical properties	Modification of concrete	UHI mitigation potential	Rubber particle size in pervious concrete	Street	Mechanical properties, permeability, and freeze-thaw resistance of pervious concrete modified by waste crumb rubbers [133]	2018	7
Lab. Exp.	Mechanical properties	Modification of concrete	UHI mitigation potential	Palm oil fuel ash to modify pervious concrete	Street	Sustainable clean pervious concrete pavement production incorporating palm oil fuel ash as cement replacement [30]	2018	13
Lab. Exp.	Temperature effect	Pavements	UHI mitigation	Water-retaining paver block	Roof/street	A new water-retaining paver block for reducing runoff and cooling pavement [32]	2018	78
Lab. Exp.	Mechanical properties	Modification of concrete	UHI mitigation	Silica fumes for modify pervious concrete	Street	Laboratory evaluation of eco-friendly pervious concrete pavement material containing silica fume [126]	2018	3
Lab. Exp.	Mechanical properties	Modification of concrete	UHI mitigation	Pervious concrete with ground-granulated blast furnace slag	Street	Pervious concrete pavement incorporating ground-granulated blast furnace slag to alleviate pavement runoff and improve urban sustainability [127]	2018	7
Lab. Exp.	Temperature effect	Pavements	UHI mitigation	Cement-based grouting material containing cement, ceramic waste powder, natural zeolite	Street	Fatigue and aggregate fretting resistance of surface-temperature reducing pavement [134]	2018	0
Lab. Exp.	Temperature effect	Pavements	UHI mitigation	Phase-change materials for modifying open graded friction course	Street	Preparation and effectiveness of composite PCM for performance improvement of Open Graded Friction Course [33]	2019	16

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Table A.8. Articles of numerical simulations.

Type	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Sim. Num.	Temperature effect	Concrete	Microclimatology		Urban	Numerical investigation into the influence of geometry and construction materials on urban street climate [91]	1993	5
Sim. Num.	Temperature effect	Concrete albedo	UHI mitigation	Pavement thickness	Street	Impact of pavement thickness on surface diurnal temperatures [135]	2007	6
Sim. Num.	Temperature effect	Concrete	UHI mitigation	Porosity and albedo	Street	Porous asphalt pavement temperature effects for UHI analysis [65]	2012	52
Sim. Num.	Temperature effect	Concrete and asphalt	UHI mitigation	Modelling for mitigation	Urban	An indoor-outdoor building energy simulator to study urban modification effects on building energy use - Model description and validation [66]	2012	34
Sim. Num.	Surface heat budget	Cool pavements	UHI mitigation	Thermal inertia and albedo	Street	Understanding pavement-surface energy balance and its implications on cool pavement development [43]	2014	95
Sim. Num.	Radiation balance	Concrete albedo	Microclimatology		Urban	Urban canyon albedo and its implication on the use of reflective cool pavements [44]	2015	88
Sim. Num.	Temperature effect	Pavements	UHI mitigation	Road pavement solar collectors	Street	A study of the impact of building geometry on the thermal performance of road pavement solar collectors [74]	2015	12
Sim. Num.	Temperature effect	Green roof	UHI mitigation		Roof	Numerical simulation of the dual effect of green roof thermal performance [102]	2015	15
Sim. Num.	Temperature effect	Concrete albedo	UHI mitigation		Wall, roof, street	The role of materials selection in the UHI effect in dry mid-latitude climates [109]	2016	11
Sim. Num.	Temperature effect	Concrete	UHI mitigation	Ccoloured coating of concrete	Street	Comparison on coloured coating for asphalt and concrete pavement based on thermal performance and cooling effect [107]	2016	4
Sim. Num.	Temperature effect	Structure of pavement	UHI mitigation			Microscale heat Island characterisation of rigid pavements [47]	2017	6
Sim. Num.	Temperature effect	Modification of concrete	UHI mitigation	Bamboo-concrete composite	Wall, roof	Mitigating the UHI effect through building envelope modifications [82]	2018	17
Sim. Num.	Mechanical properties	Concrete	UHI mitigation	Pervious concrete mix design	Street	Methodology to develop pervious concrete mixtures for target properties emphasizing the selection of mixture variables [125]	2018	6
Sim. Num.	Temperature effect	Concrete	Environmental effect		Street	Use phase assessment of photocatalytic cool pavements [31]	2018	7

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Table A.9. Other types of articles.

Type	Investigated effect	Object of study	Classification of study	Type of UHI mitigation	Area of study	Main highlight of the publication	year	Num. of cit.*
Review		Concrete	UHI mitigation			Concrete's contribution to sustainable development [136]	2008	11
Review			UHI mitigation			Continuous Surface Temperature Monitoring to estimate sensible heat loss by building finishes [137]	2011	2
Review		Cool pavements	UHI mitigation		Street	A review on the development of cool pavements to mitigate UHI effect [7]	2015	189
Review	LCA	Pavement preservation	UHI mitigation, environment			Contextual heat island assessment for pavement preservation [48]	2018	7
Review		Road pavements	Environment		Street	A review of eco-friendly functional road materials [9]	2018	6
Satellite data	Temperature effect	Pavements	Sensors			Simple correction methods of infrared thermography for building exterior surfaces [96]	2010	0
Other			UHI mitigation	Solar heat reflective coating	Street	Effectiveness of solar heat reflective coatings in reducing asphalt concrete temperature [95]	2012	6
Other	Radiation balance	Pavements	Microclimatology		Urban	Influence of urban areas on environment: Special reference to building materials and temperature anomalies using geospatial technology [138]	2015	10
Other	Temperature effect	Concrete	Microclimatology		Urban	Analysis of the UHI effect in Shijiazhuang, China using satellite and airborne data [99]	2015	38
		Concrete	UHI mitigation			The UHI effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete [8]	2017	87
	LCA	Pavements	Environment			Removing Shadows from Consequential LCA through a Time-Dependent Modelling Approach: Policy-Making in the Road Pavement Sector [139]	2019	3
No inf.		Cool pavement campaign	Energy and ecological effect		Street	Energy and environmental consequences of a cool pavement campaign [115]	2017	12
No inf.	Temperature effect	Pavements albedo	Microclimatology		Urban	Seasonal and diurnal characteristics of land surface temperature and major explanatory factors in Harris County, Texas [116]	2017	15

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