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Evaluating the performance of cool pavements for urban heat island mitigation under realistic conditions: A systematic review and meta-analysis

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ABSTRACT

Cool Pavements (CPs) can maintain a lower surface temperature than conventional pavements and mitigate urban overheating. CPs decrease their heat gains by enhancing pavement's radiative properties, i.e. solar reflectance and thermal emissivity, by performing evaporating cooling, or by converting heat to other forms of energy. Several studies have reported substantial surface temperature decreases, however, a wide application of CPs is still impeded. Most of the CP studies report on in-lab investigations and numerical evaluations, while only few report on CP performance under real-life boundary conditions. This review reports on CP studies performed in the outdoors with respect to reflective, evaporative and thermal energy storage techniques. The corresponding protocols and performance are analyzed for various scales of evaluation and are critically discussed with respect to the corresponding limitations, research gaps and future paths. Also, a monitoring protocol is proposed for the outdoor evaluation of CPs. The analysis showed that there is a lack of relevant monitoring standards, whilst the reported CP cooling effects in the outdoors vary within 3–20 °C, 8–25 °C, 4–14 °C, and 4–19 °C with respect to reflective, permeable, thermal energy storage, and large-scale CP applications, respectively.

1. Introduction

Urban areas, and cities in general, typically have much higher temperature than the surrounding rural areas (Rosenfeld et al., 1995; Santamouris, 2020). This is a well reported phenomenon and is called Urban Heat Island (UHI) (Oke, 1982; Kousis and Pisello, 2020; Akbari and Kolokotsa, 2016). The magnitude of UHI varies among different areas according to the specific local characteristics.In principle, it is affected by factors such as the Land Use/Land Cover (LULC) (Hashem Akbari et al., 2003; Ngarambe et al., 2021), the thermal properties of the materials implemented into the built environment (Akbari et al., 2001; Santamouris, 2013), the anthropogenic heat (Taha, 1997; Hongyu et al., 2016), the fraction of evaporative surfaces (Steeneveld et al., 2014), the natural or artificial shading (He et al., 2021), and the wind and turbulence profiles with respect to the urban morphology (Khan et al., 2021). UHI magnitude is further augmented due to the increasing incidences of macro-scale extreme heat events owing to the climate change on a global scale (Heaviside et al., 2016; Khan et al., 2020; Chew et al., 2021; Oliveira et al., 2022). In fact, depending on the geographic location, the diurnal/nocturnal temperature profiles and the co–occurrence of drought among others, synergies between UHI and heat

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waves are reported to affect the quality of a typical urban environment and citizens' health in particular (He et al., 2021; He et al., 2022). For instance, outdoor and indoor thermal comfort (Van Hove et al., 2015; Arghavani et al., 2020), energy demand and consumption (Santamouris, 2014; Santamouris et al., 2015), greenhouse gases emission (Chen and You, 2020) and air pollution levels (Wang et al., 2021; Liang et al., 1029), residential water use (Wang et al., 2021), morbidity and mortality rates (Hsu et al., 2021) due to extreme air temperatures especially during the warm seasons of the year are found to be related to UHI (Cheng et al., 2019).

Over the last decades, several approaches, either passive or active, have been proposed and in many cases implemented for counteracting urban overheating and mitigating UHI (Wang et al., 2021). The main investigated approaches comprise (i) the implementation of built materials with advanced thermal properties as compared to the conventional ones (Santamouris, 2014), (ii) the efficient architectural design of urban areas with respect to the morphology and the geometry of the built environment (Huang and Wang, 2019), (iii) the implementation of green- or water-based strategies (Santamouris et al., 2018), and the evaluation and moderation of anthropogenic heat (Oke et al., 2017). Since built environment surfaces such as building roofs, facades and pavements, either streets or sidewalks, cover the biggest area of a typical city, a substantial number of studies focus on exploiting their thermal performance to this aim (Rosso et al., 2014). The main goal of these studies is the modulation of incoming solar radiation and the corresponding heat gains (Akbari et al., 2016). Urban surfaces are typically made of asphalt, concrete, or other conventional materials. The energy partition of typical urban surfaces differs from natural surfaces, e.g. soil and grass, and are characterized with low evaporative transpiration and high thermal inertia (Santamouris, 2014). Conventional materials used in the paving infrastructure such as traditional asphalt or cement are typically characterized by low radiative properties (i.e. low solar reflectance and thermal emissivity) and low permeability. Therefore, they are prone to high heat gains resulting to high surface temperature and release of sensible heat and consequently contributing to UHI effect (Santamouris et al., 2018; Qin, 2015).

As a result, the implementation of alternative materials or surfaces that can reject the incident solar radiation or the corresponding heat gains are considered as an effective mitigation strategy for reducing surface temperature (Santamouris and Yun, 2020; Kousis and Pisello, 2020). Under this scenario, the energy balance of an urban area may be modified for maintaining low ambient temperature as well (Pisello, 2017). Within a typical city, paving infrastructure, such as roads, sidewalks, pedestrians and parking lots, may cover more than 40 % of the total built-up area of the city (Santamouris, 2013). Therefore, modifying the thermal properties of urban pavements and hence their energy balance as UHI mitigation mechanism is a well investigated topic (Santamouris, 2013). Such modifications are comprised under the wide framework of "Cool Pavements" (CPs) that can be divided to three main categories; (i) reflective pavements, (ii) evaporative pavements and (iii) energy storage or conversion pavements (Qin, 2015).

Traditional reflective pavements (RP) cool the pavement solely due to their reflective property (Senevirathne et al., 2021). Unlike conventional counterparts, RP are usually light-colored and reflect a substantial part of incident solar radiation. Hence, they release back to the lower levels of urban canopies less sensible heat and decrease the air temperature above them (Santamouris, 2013). The majority of the reported RP paving solutions is developed by applying reflective coatings on already existing conventional pavements or by improving the pavement's texture, e.g. modifying the thickness and construction materials (Qi et al., 2019). Reflective coating represent a simple solution for increasing pavement's reflectance without affecting its mechanical properties. The reflectance of a RP pavement is specifically tuned over the wave-range of solar radiation, i.e. 300–2500 nm, which is the main heat source of urban surface such as pavements. The ultraviolet (UV) radiation (300–400 nm) contains negligible solar power, whilst it produces a negative impact to skin health. Therefore UV reflection of RP is typically lower than 10%. On the other hand, visible (VIS) radiation (400–700 nm) and near-infrared (NIR) radiation (700–2500 nm) contain together about 95% of the incoming solar power, while the NIR contains itself about 50% of the total solar power. Under this scenario, the first RP studies reported white or light-colored RP applications with high VIS reflectance and corresponding temperature reductions up to 10 °C (Santamouris, 2013). However, high VIS reflectance can cause glare issues or visual discomfort since it is the only region differently perceived by human's eyes. At the same time, NIR radiation cannot be perceived by humans while it also contains more power that VIS. Therefore, studies reported on cool coating specifically designed to highly reflect the NIR part of the incoming radiation (Xie et al., 2019; You et al., 2019; Kui et al., 2021). NIR reflective CP were found to decrease surface temperature up to around 12 °C. Moreover, since they can be colored, even black, and their application can be effective also in terms of aesthetics. Retro-reflective and photoluminescent are also reported recently as promising advanced CP candidates (Rossi et al., 2016; Kousis et al., 2020). Retro-reflective pavements directionally reflect the incoming solar radiation, and hence can minimize possible inter-building effects (Han et al., 2015). On the other hand, photoluminescent pavements apart from reflecting the incoming radiation they simultaneously re-emit a part of it Chiatti et al. (2021). In fact, tailoring the emission spectra of a surface within specific boundaries, such as the atmospheric window, and combining it with high solar reflectance, is a promising radiative cooling technique that is expected to play a pivotal role towards the mitigation of UHI (Xinxian et al., 2021). Additionally, thermochromic components are also tested for CP applications and are found to modulate surface temperature according to the desire and therefore to extend the life-cycle of the pavement (Hu et al., 2013; Jianying and Xiong, 2016; Li et al., 2020).

Making pavements evaporative is another popular CP technique (Wang et al., 2018). Evaporative cooling can be succeed through latent heat flux buffering due to liquid to vapor transition of the water captured by the pavement (Li et al., 2014). Since their cooling effect requires water availability they are more suitable for rainy and humid climate zones. Evaporative pavements are designed either to allow the water to pass through them, i.e. porous and pervious pavements, or to allow the water to pass around them, i.e. permeable, or to hold water in their upper layers, i.e. water-retaining pavements (Anupam et al., 2021). Porous CP are generally developed as cellular grid system. The developed system comprises interlocking blocks with a circular opening in the middle which is filled with sand, gravel, dirt or grass (Mullaney and Lucke, 2014). As a result they can hold enough water for evaporative cooling. Pervious CP pavements are a subcategory of porous pavements characterized by high void content and are typically developed with asphalt or concrete. As a result, they can percolate and retain more water than classic porous pavements, while simultaneously decrease surface run-off and deep drainage process (Guoyang et al., 2019). Permeable asphalt-based mixes such as open graded friction courses

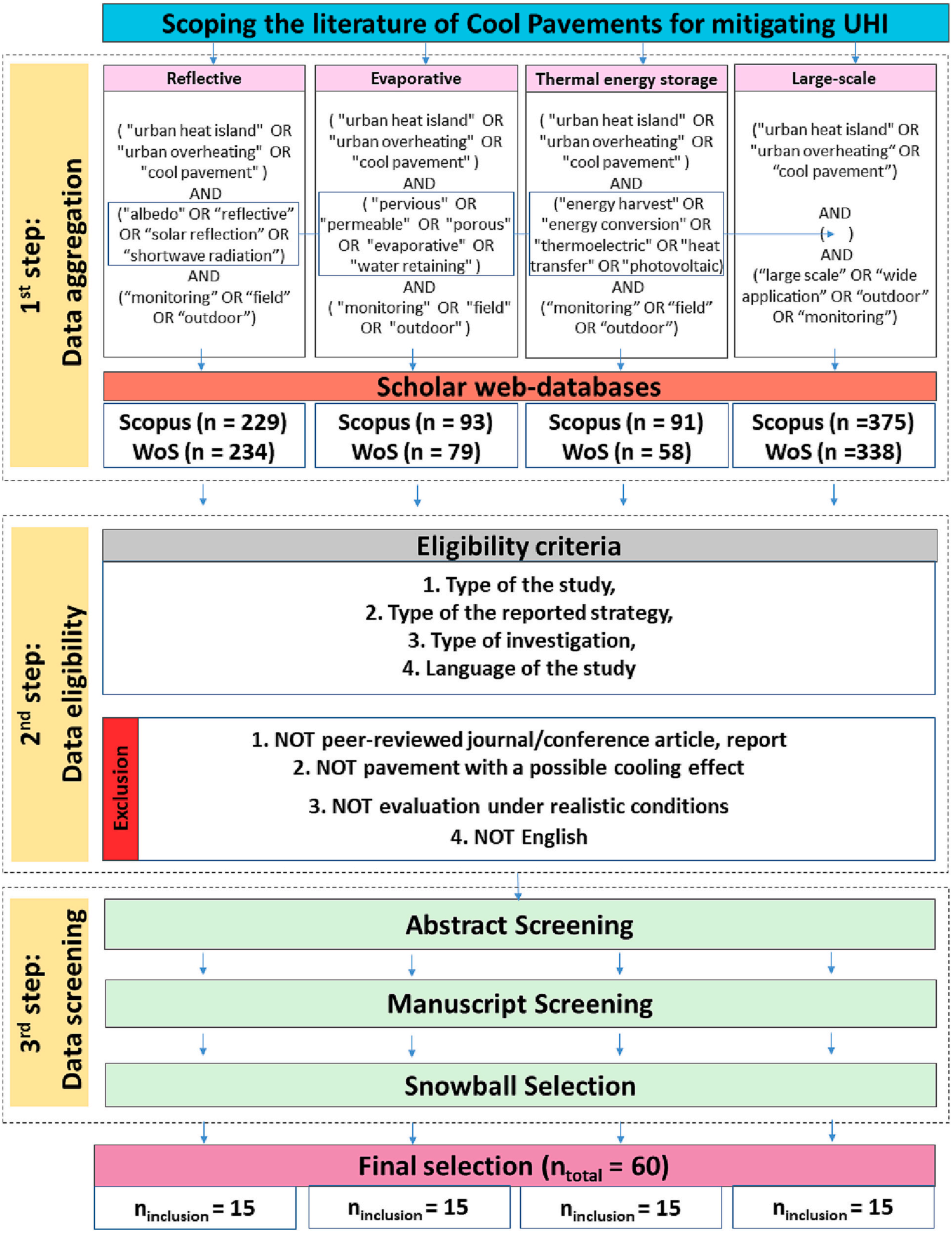


Fig. 1. Systematic methodology applied.

characterized by large percentage of air voids are typically used to reduce aquaplaning and increase pavement friction. However, due to the air voids they can retain and circulate water within the bottom layers around the pavements (Scholz and Grabowiecki, 2007). Other evaporative CP are designed to retain water within the upper layers of the pavement by developing a pervious surface layer above an impermeable bottom layer (Lucke and Beecham, 2011).

Pavements are continuously exposed to the incoming solar radiation during the daytime and hence, are characterized by substantial heat gains. Recently, there is an increasing interest on applying thermal energy storage techniques into pavements with the twofold scope of producing renewable and clear energy out of the heat gains of the pavement, while simultaneously decreasing its surface temperature. The first energy harvesting CP were developed by embedding pipes below the surface of the pavements through which water is circulated (Mallick et al., 2012). The cooler water can absorb heat from the pavements through convention and consequently cool the pavement. The next step of this simple cooling mechanism is the addition of thermoelectric generator into the paving configuration (Zhu et al., 2019). A smaller number of studies reported on the same mechanism, however, instead of water, the circulated fluid is air (Guo and Qing, 2017). Phase change materials are also reported as good candidates for CP applications (Anupam et al., 2020). Thermal energy storage CPs are a relatively new approach for decreasing pavements surface and can be considered still in their infancy.

Overall, several studies have demonstrated a significant passive cooling potentiality of CPs. The vast majority of them reports on laboratory experimental campaigns under dynamically controlled environments. On the other hand, a smaller number of studies reports on in-field investigation of CPs, i.e. under real-life conditions. Regardless of the substantial number of studies evaluating CPs potentiality as a UHI mitigation measure, the reported methodologies followed are devised according to authors' knowledge and previous experience due to absence of relevant standards. This study aims to systematically review the existing CP literature that reports on in-field investigation as well as on large-scale implementations around the globe in their real boundary context. The outdoor evaluation of CPs is specifically chosen here since it asses their cooling potentiality under real-life boundary conditions. Hence, if exploited, not only it may further the corresponding cooling magnitude but also may boost their popularity among policy-makers and industrial companies towards a better defined sustainable and resilient urban development.

Under this scenario, here, we review some of the main studies reporting on reflective, permeable and thermal energy storage CPs together with large-scale real life applications. The review is focused on the monitoring protocols followed as well as to the reported cooling rates of each CP type separately and presents a corresponding meta-analysis of the reported outcomes. The aim of the study is twofold. At first, it aims to identify research gaps and challenges concerning both the implementation and outdoor evaluation of CPs that currently impede their wide application into urban environments. Secondly, it aims to help towards the establishment of efficient standards and protocols that may be adopted by the research community and relevant industry in order to evaluate their cooling performance under a uniform and consistent framework dedicated to effectively mitigate urban overheating without compromising comfort of pedestrians, buildings function, and the corresponding environmental footprint.

2. Methodology

The aim of this study was to review the global literature that represents the state-of-the-art of each cool pavement category when evaluated under realistic outdoor conditions. Therefore, the review is developed under a systematic methodology by following three interrelated sub-steps (Fig. 1). At first, we defined the scientific question driving the review:

▪What is the progress and the outcomes of the methodologies followed within the last three decades while evaluating the cooling potentiality of cool pavements under realistic conditions?

Further sub-questions were also defined for structuring the analysis with respect to the specific state-of-the-art of each CP category, i.e. reflective, evaporative and thermal energy storage pavements, and the corresponding large-scale applications. Afterwards, specific inclusion/exclusion criteria were defined for the studies to be reviewed and performed a corresponding literature search through the main established scholarly databases, i.e. Scopus and Web of Science (WoS). Moreover, we utilized Google Scholar for directly identifying (i) relevant grey literature of possible interest, and (ii) articles referenced within previously reviewed articles under the framework of the current study.

The main web-search and the selection of the reviewed literature were carried out within January-February 2021. However, the studies of Middel et al. (2021), Cheela et al. (2021), and Yang et al. (2021), which were published on September, March and June of 2021, respectively, were taken into consideration while the analysis was ongoing since their outcomes report on real-life large-scale implementations of CPs, hence, are pivotal for the evaluation of CPs. The web-search was conducted by applying several search-terms combined with the boolean operators OR and AND. The final selection of the articles to be reviewed was performed through 3 screening steps. In the first and second steps, studies were included/excluded with respect to their abstract and whole manuscript, respectively. In the third step, a snowball selection was applied for identifying studies that were not identified directly through the keyword search in Scopus and WoS, but either as references within the articles selected through the second screening step, i.e. Rosado et al. (2014), Furumai et al. (2008), and Takahashi and Yabuta (2009), or as studies written by or related to authors identified within the second screening step, i.e Middel et al. (2021), Cheela et al. (2021), and Yang et al. (2021). It should be taken into account that the studies of Takahashi and Yabuta (2009) and Middel et al. (2021) selected within this third step, are not fulfilling the eligibility criterion of being peer-reviewed. However, being among the few studies reporting on real-life large-scale applications of CPs they were selected for the analysis.

Overall, 60 articles were reviewed, i.e. 15 concerning reflective pavements, 15 concerning evaporative pavements, 15 concerning thermal energy storage pavements, and 15 with respect to large-scale applications of CPs. The vast majority (84 %) of the identified CP studies was published from 2010 to 2021 (Fig. 2a). Most of the studies focusing on reflective CP solutions were found to originate from Italy, while most of the studies focusing on evaporative and thermal energy storage CP solutions were found to originate from Japan and China, respectively (Fig. 2b). The majority of CP large-scale applications was reported within Greece. Overall, the highest number of reported CP solutions was reported in China (Fig. 2c). Even though the CP community identified herein comprises mainly academic institutions, other sectors such as national agencies, public authorities, industry companies and military academies were identified as CP investigators (Table 1).

3. Analysis of the results

Reflective, evaporative and heat storage techniques can contribute to lower surface temperatures of urban pavements. In the following subsections, studies that performed outdoor monitoring campaigns with respect to the three CP types under outdoor real-life

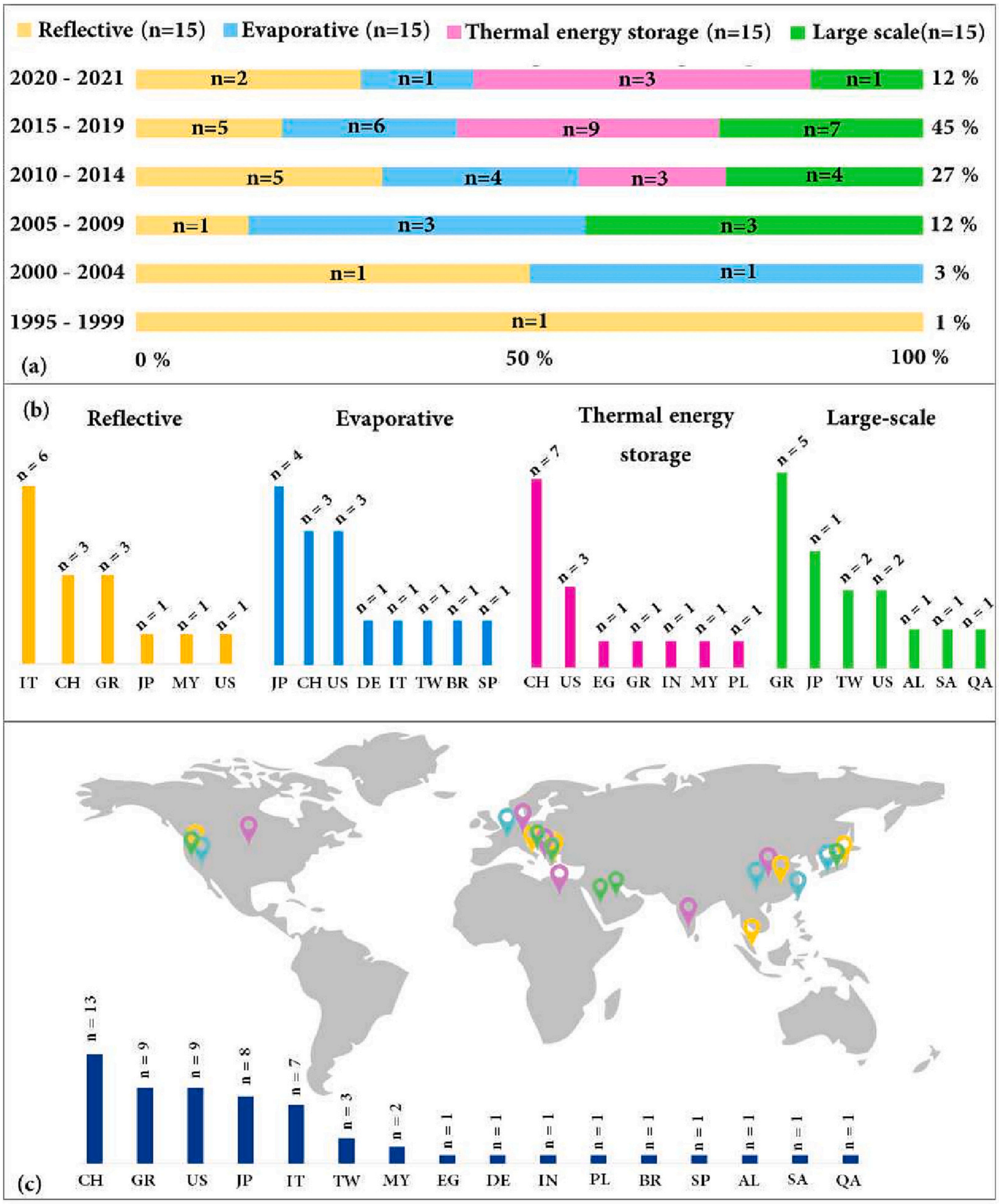


Fig. 2. (a) Publication time-frame of the reviewed studies, (b) country origin of the reviewed studies. (c) global distribution of the reviewed studies.

Table 1
Cool pavements community identified by the systematic literature review.

Institute index	Institute name	Country code	Sector	Number of studies performed with respect to: Reflective	Evaporative	Thermal energy storage	Large-scale	Synergy with (institute index):
1	ALD Architects	GR	industry	–	–	–	1	24
2	Arizona State University	US	academia	–	–	–	2	19, 45
3	Athens Municipality	GR	public authority	–	–	–	2	24
4	ENEA	IT	national agency	2	–	–	–	18, 42
5	Aktis S.A	GR	industry	1	–	–	–	24
6	Al-Azhar University	EG	academia	–	–	1	–	31
7	Central South University	CH	academia	–	–	1	–	9, 47
8	Chang'an University	CH	academia	1	–	2	–	16, 22, 46
9	Changsha University of Science and Technology	CH	academia	–	–	1	–	7, 47
10	Chaoyang University of Technology	TW	academia	–	1	–	–	25
11	CIRIAF	IT	research center	4	–	–	–	52, 30
12	Fujian Xinhaiwan Building Materials Technology	CH	industry	–	–	1	–	34
13	JFE Steel	JP	industry	–	–	–	1	–
14	Gdansk University of Technology	PL	academia	–	–	1	–	–
15	Hellenic Air Force Academy	GR	military academy	–	–	1	–	24, 36
16	Hubei University of Arts and Science	CH	academia	1	–	–	–	8
17	Ibaraki University	JP	academia	–	–	–	1	55
18	INRIM	IT	research center	1	–	–	–	4
19	Kent State University	US	academia	–	–	–	1	2, 45
20	Kinki University	JP	academia	–	1	–	–	37, 39
21	Kobe University	JP	academia	–	1	–	–	–
22	Liverpool John Moores University	UK	academia	–	–	1	–	8
23	Nagoya Institute of Technology	JP	academia					–
24	National and Kapodistrian University of Athens	GR	academia	3	–	1	6	1, 3, 5, 15, 36, 50
25	National Formosa University	TW	academia	–	1	–	–	10
26	National Taipei University of Technology	TW	academia	–	–	–	1	28, 26, 56
27	National Taiwan University	TW	academia	–	–	–	1	26, 28, 56
28	National Taiwan University of Science and Technology	TW	academia	–	–	–	1	26, 27, 56
29	National Pingtung University of Science and Technology	TW	academia	–	–	–	1	–
30	New York University	US	academia	1	–	–	–	11, 51, 52
31	Port Said University	EG	academia	–	–	1	–	6
32	Saitama University	JP	academia	1	1	–	–	–
33	South China University	CH	academia	–	1	–	–	–
34	Southeast University	CH	academia	-	–	1	–	12
35	Synthesis & Research Ltd.	GR	industry	–	–	–	1	24
36	Technical University of Crete	GR	academia	–	–	1	1	15, 24, 50
37	The Kanden LA Co., Ltd.	JP	industry	–	1	–	–	20, 39
38	Tianjin University	CH	academia	–	–	1	–	53
39	Toa Road Corporation	JP	industry	–	1	–	–	20, 37
40	Tongji University	CH	academia	–	2	–	–	–
41	University of Technology Malaysia	ML	academia	–	1	–	–	–
42	University of Rome Tre	IT	academia	1	–	–	–	4
43	University of California	US	academia	–	3	–	–	–
44	University of California, Berkeley	US	academia	1	–	–	–	–
45	University of California, Los Angeles	US	academia	–	–	–	1	2, 19
46	University of Leeds	UK	academia	–	–	1	–	8
47	University of London	UK	academia	–	–	1	–	7, 9
48	University of Massachusetts	US	academia	–	–	1	–	57

(*continued on next page*)

Table 1 (*continued*)

Institute index	Institute name	Country code	Sector	Number of studies performed with respect to: Reflective	Evaporative	Thermal energy storage	Large-scale	Synergy with (institute index):
49	University of Munster	DE	academia	–	1	–	–	–
50	University of New South of Wales	AU	academia	–	–	–	2	24, 36
51	University of Perugia	IT	academia	4	–	–	–	52, 30
52	University of Rome Sapienza	IT	academia	2	–	–	–	11, 30, 51
53	University of South Australia	AU	academia	–	–	1	–	38
54	University of Texas San Antonio	US	academia	–	–	2	–	–
55	University of Tokyo	JP	academia	–	–	–	1	17
56	University of Virginia	TW	academia	–	–	–	1	26, 27, 28
57	Worcester Polytechnic Institute	US	academia	–	–	1	–	48

conditions are reviewed and critically discussed.

3.1. Reflective pavements

One of the first studies investigating in-field the thermal properties of various paving applications is reported by Asaeda et al. (1996). They developed paving fields of 1 × 1 m area with common asphalt, concrete, macadam and sand and compared them with bare soil through three monitoring campaigns performed during the month of August in Tokyo, JP. The local boundary conditions were chosen with a cloud cover less than one-third of the sky and no precipitation. In order to measure the ground surface temperature and the corresponding heat flux, they installed several 1 mm diameter copper tubes, each including a thermocouple, along the central axis of the fields at different depths up to 30 cm below the surface. The asphalt field was found with the highest surface temperature, heat storage and its subsequent emission to the atmosphere as compared to both concrete and bare soil.

Carnielo and Zinzi (2013) developed four fields of cool colored (green, red, blue and grey) and one off-white pavements by applying reflective coatings on a moderately aged asphalt substrate. Each field covered an area of 4 × 4 m, i.e. the minimum representative area for assessing field albedo and thermal performance (ASTM Astm, 2006). The cool coatings were fabricated with a powder premixed product made of titanium dioxide-base photocatalytic cement. They performed a 20-days monitoring campaign during the month of August in Rome, IT, by positioning surface temperature sensors in the middle of the fields. The sensors were specifically shielded with a thin layer of the developed cool asphalt for minimizing overheating effects due to incident solar radiation. Except for brief time-periods during nighttime, the cool coating fields were found cooler than the aged asphalt during the whole period, with differences reaching up to 10 °C, 7.5 °C, 5 °C, 5 °C, 5 °C with respect to the off-white, gray, green, blue and red field.

Similarly, Guntor et al. (2014) reported on the application of highly-reflective coating above existing common surfaces and on their in-field evaluation. They fabricated a heat-reflective coating from crushed wasted tiles, sand, and epoxy resin and applied it atop of an asphalt pavement by covering an area of 2 × 3 m. They monitored the thermal behavior of the field together with a field made with uncovered asphalt continuously for 8 consecutive days during the month of December in Johor Bahru, MY. Similar to the surface temperature protocol of Asaeda et al. (1996) they drilled a 10 mm hole up to 300 mm depth of both fields and integrated thermocouples for investigating the thermal profiles of the soil underneath the asphalt. The temperature was measured even during a rainfall event to investigate the cooling pattern of asphalt pavement by considering the actual weather condition in tropical countries. Rosado et al. (2014) followed a similar protocol concerning the heat flux profile of the pavement layers. In their study, they developed an experimental site in California, US and demonstrated several CP technologies by testing their initial and long-term performances. The paving fields were made with gray Portland cement concrete (PCC), white PCC, slag PCC, bare asphalt concrete (AC), chip-sealed AC, and coated AC. They reported that raising the albedo from 0.1 to 0.3 can reduce pavement surface temperature during warm season by 12 °C. Cool elastomeric coatings were developed by Rossi et al. (2018) as well, i.e. a grey and an off-white ones, and were applied above aged but smooth asphalt fields located in the Istituto Nazionale di Ricerca Metrologica in Torino, IT. Even though the primary focus of their study was the luminance coefficient, they also performed one surface temperature measurement per day with the use of a thermal camera. The reported that during the hot hours of a clear sky day the grey and off-white coatings decreased the pavements temperature by 3 °C and 9 °C, respectively.

Other studies did not report on cool coatings for CP applications but on uniform cool paving solutions. Pisello et al. (2014) performed in-field monitoring of several low-cost gravel coverings for roofs and urban paving. To this aim, the in-field albedo of the gravel samples was measured with varying grain size and weather conditions. The albedo of each field was measured four or five days per month, continuously from 9:00 a.m. to 6:00 p.m. with a dual pyranometer. The external surface temperature of each gravel field was continuously recorded by a corresponding sensor positioned in the middle of the field. Kousis et al. (2020) investigated another uniform solution. They developed 5 concrete-based fields with photoluminescent components and performed their thermal monitoring within the summer months July 22 to August 29, 2019 in a specifically designated site in Perugia University (Sustainable URBan paving EXperimental (SURBEX) park).

Several studies reported on the CPs potentiality under real-life condition by developing and investigating the performance of cool paving specimens, typically characterized by width and length dimensions of 30 × 30 cm or 40 × 40 cm and a height of 5 cm. For

Table 2
Studies on the outdoor investigation of reflective cool pavements. T_{air}, T_{sur}, RH denotes relative humidity, WS and WD denotes wind speed and direction, DSW denotes downward shortwave radiation, USW denotes upward shortwave radiation, P denotes atmospheric pressure. R denotes precipitation.

Study (Publication year)	T-Tbase	Variables	Timestep	City	Area	Month	Standards	Type	Base material	Albedo	Reference	Other
Asaeda et al. (1996)	–	T_{sur} (0∼ −30 cm), RSW	1 h(day) 2 h (night)	Tokyo, JP	1 × 1 m x (10 or 30 cm)	8	–	field	asphalt, concrete, macadam, sand	–	bare soil	T_{air}, RH, WS, DLW, DSW, P
Doulos et al. (2004)	-20	T_{sur}	1 h	Athens, GR	40 × 40 cm	8	–	specim -ens	concrete, marble, granite, pave stone, stone, pebble mosaic	–	asphalt	–
Synnefa et al. (2006)	-4	T_{sur}	10 min	Athens, GR	40 × 40 cm	8,9,10	–	specim -ens	Acrylic Aluminum Alkyd	–	concrete	T_{air}, RH, WS, DSW
Synnefa et al. (2011)	-12	T_{sur}	15 min	Athens, GR	30 × 30 × 5 cm	7	–	specim -ens	asphalt	–	commom asphalt	T_{air}, RH, WS, DSW
Carnielo and Zinzi (2013)	-10	T_{sur}	–	Rome, IT	4 × 4 m	8	–	field	asphalt	–	common asphalt	–
Pisello et al. (2014)	-5.5	T_{sur}, albedo	10 min	Perugia, IT	4 × 4 m	9–11	ASTME1918	field	gravels	0.30–0.44	common grain size	T_{air}, RH, WS, WD DSW, R
Guntor et al. (2014)	-4.4	T_{sur} (0, −30 cm)	–	Johor Bahru, MY	2 × 3 m	12	–	fields	waste tiles, sand, epoxy resin	–	common asphalt	T_{air}, DSW
Rosado et al. (2014)	-12	T_{sur} (0∼ −18 cm), albedo	–	Calif -ornia, US	4 × 4 m	summer-fall	ASTME1918	field	asphalt/ concrete	0.23–0.60	common asphalt	T_{air}, RH, WS, WD DSW, R
Castaldo et al. (2015)	-24	T_{sur} albedo	–	Perugia, IT	10 m^2	1–12	ASTM E1918-06	field	asphalt	–	asphalt	T_{air}
Zheng et al. (2015)	-10	T_{sur}	60 min	Xi'an, CH	2.5, 5, 10 m^2	8	–	field	asphalt	–	asphalt	T_{air}
Rosso et al. (2017)	-10.6	T_{sur}	2 h	Perugia, IT	–	–	–	specim -ens	concrete	–	non-IR concrete	T_{air}, RH, WS, WD DSW, R
Rossi et al. (2018)	-9	T_{sur}	–	Torino, IT	4 × 4 m, 40 m^2	9	ASTM E1918	field	asphalt	–	common asphalt	–
Yi et al. (2019)	-10.2	T_{sur}	–	Jinhua, CH	30 × 30 × 5 cm	8	–	specim -ens	asphalt	–	common asphalt	–
Kousis et al. (2020)	-3.3	T_{sur},, albedo	10 min	Perugia, IT	4 × 4 m	7,8	ASTM E1918 UNI EN 197–1-2, 934–2	field	concrete	0.17–0.39	common concrete	T_{air}, RH, WS, SR
Chen et al. (2021)	-3	T_{sur} (-2 cm)	–	Changsha, CH	15 × 10 cm	summer	–	specim -ens	asphalt	–	common asphalt	T_{air}

Table 3
Same as Table 2, but for evaporative cool pavements.

Study (Publication year)	T-Tbase	Variables	Timestep	City	Area	Months	Standards	Type	Base material	albedo	Reference	Other
Asaeda and Ca (2000)	-10	T_{sur} (0∼ −60 cm), heat flux	5 min	Kuki, JP	2 × 2 m	2, 8	–	field	ceramic, concrete, grass	0.24–0.27	non- porous asphalt	T_{air} RH, WS, DSW, USW, ILW, ULW
Karasawa et al. (2006)	-16.6	T_{sur} (-1 mm), evaporation, water content	1 h	JP	1 × 1 m	8, 9	–	field	concrete	–	dense grade asphalt	$T_{air}$$T_{global}$ RH, WS, DSW
Lin et al. (2007)	-9 (grass)	T_{sur}, heat cond- uction	1 min	Nantou, TW	–	1, 7, 12	ASHRAE	field	concrete, asphalt	–	concrete	$T_{air}$$T_{global}$ RH, WS, DSW
Takebayashi and Moriyama (2009)	-15 (grass field)	T_{sur} (-1 cm)		Kobe City, JP	5.3 × 2.5 m	7, 8, 9	–	field	grass	0.18–0.26	common asphalt	T_{air} RH, WS, WD DSW, USW, ILW, ULW
Starke et al. (2010)	–	hydraulic conductivity, evaporation rate	–	Coesfeld, DE	–	1–12	–	field	conrete	–	–	precip- itation rate
Li et al. (2013a)	–	albedo	–	Davis, US	4 × 4 m	1–12	STM E1918	field	concrete, asphalt	0.08–0.29	–	T_{air}, WS, DSW
Li et al. (2013b)	–	T_{sur} (-25∼−0 cm)	10 min	Davis, US	4 × 4 m	9,10	ASTMC1701	field	concrete, asphalt	–	non-permeable fields	T_{air} (5.1, 12.7 cm)
Li et al. (2013c)	-25	T_{sur} (-6.35∼−12.7 cm) hydraulic conductivity, permeability, albedo	30 min	Davis, US	4 × 4 m	7	ASTMC1701	field	concrete asphalt	0.08–0.29	non-permeable fields	T_{air} (5.1, 12.7 cm) RH, DSR, WS, WD, R, P
Toraldo et al. (2015)	-14	T_{sur}, (-1,-4 cm)	10 min	Milan, IT	160 × 80 × 25 cm	1–12	–	specimens	asphalt	–	common asphalt	T_{air}, WS, RH, ISW
Del Carpio et al. (2016)	-18.4	T_{sur} (0, 1, 3 cm) albedo	60 min	, BR	1.08 m × 1.00 m × 0.05 m	1–12	ASTM E1918-06	field	asphalt concrete	0.20–0.49	asphalt	–
Higashiyama et al. (2016)	-20	T_{sur}	–	Hyogo, JP	–	7, 8	–	field	asphalt	–	common asphalt	–
Barthel et al. (2017)	-8	T_{sur}	10 min	Llinars del Vallés, SP	12 × 8 m	8	–	field	concrete	–	concrete	T_{air}, WS, RH, R
Liu et al. (2018)	-9.4	T_{sur}, evaporation rate, water level	1 h	Shanghai, CH	21 × 21 × 40 cm	3, 4, 5	–	specimen	concrete	–	non-capillary sample	T_{air}, WS, RH
Wang et al. (2018)	-10	T_{sur}, T_{air} at 0.3, 0.6, 0.9, 1.5 m	1 min	Guangzhou, CH	4 × 4 m	10	ASTMC1699	field	brick, concrete	0.14, 0.28	dense concrete	RH, WS, DSW, USW, ILW, ULW
Liu et al. (2020)	-15.3	T_{sur}, surface runoff and outflow	–	Shanghai, CH	6 × 6 m	1–12	ASTM 57, 2	field	concrete	–	common concrete	R

instance, Doulos et al. (2004) tested in-field 93 different commonly used pavement materials. The sampling tiles were placed on a specifically modulated horizontal platform covering a surface of 40 m^2. The surface temperatures of the sample materials were measured with an IR camera, every hour from 9 to 18 during the month of August in Athens, GR. It was found that tiles made of marble, mosaic and stone were cooler than the tiles made of concrete pavestone and asphalt.

Similarly, Synnefa et al. (2006) selected several commercially available reflective coatings for pavements and building application and tested them on the outdoors with respect to their thermal profile. They developed 14 samples-tiles and they placed them on an platform similar to the one developed by Doulos et al. (2004). The color of the developed cool coatings was gray, silver or white. Five specimens of a black coating, an uncoated concrete tile, a white marble tile and a white mosaic tile were also developed and utilized as the references for evaluating the cooling potentiality of the cool coatings. The experimental campaign was carried out within the months of August, September and October. Apart from monitoring surface temperature with a thermocouple, an infrared camera was implemented as well, for observing the temperature distribution on the surface of each specimen. The reported surface temperature reduction dew to the use of reflective coatings as compared to the white concrete tile were 4 °C and 2 °C, during daytime and nightime, respectively. The same scientific group (Synnefa et al., 2011) also developed and tested in-field cool colored asphalt specimens, i.e. a green, red, yellow, beige and an off-white, by following the same monitoring protocol during the month of July in Athens, GR.

Pavements that highly reflect shortwave radiation within the visible spectrum can cause glare issues, visual discomfort and in many cases aesthetic issues. Therefore, nonwhite color pigments with high reflectance specifically within the near-infrared spectrum are also developed and tested as pavement coatings. For instance, Rosso et al. (2017) applied infrared-reflective (IR) pigments above concrete elements. The concrete specimens were made with white Portland cement and recycled glass aggregates. Surface temperatures were monitored with an infrared camera three times per day, i.e. at 11:00, 13:00 and 15:00, under clear sky and sunny conditions during a day of August in Perugia, IT. The final surface temperature was assessed as the mean value of multiple measurements. Under the same framework, Yi et al. (2019) developed heat-reflective coatings of different colors, i.e. white, yellow, red, green, orange and blue, by implementing epoxy resin modified with high-viscosity polyurethane. They characterized them in terms of bond strength, abrasion ans skid resistance and measured their surface temperature both in-lab and in-field. Infrared detection guns were used to measure the surface temperature of the specimens, and infrared imaging devices were used to take thermal-imaging images. Even though the white and yellow coatings exhibited a substantial cooling effect, they resulted, at the same time, to a strong glare on the actual road surfaces, which may affect drivers' safety.

3.2. Evaporative pavements

Evaporative pavements can decrease their temperature by taking advantage of water and its evaporative cooling effect (see Table 3). Asaeda and Ca (2000) performed one of the first relevant studies, where they developed a porous block pavement with a large inside pore size, a dark non-porous asphalt pavement, a natural grass field, and ceramic porous pavement with a small inside pore size. Surface temperatures were obtained every 5 min by copper constant thermocouples embedded on the surfaces as well as at various depths under the surfaces. For the measurement of the ground heat flux, heat plates were installed at the interface of the pavement and the sand below. The results showed that during the hottest hours of the day the surface temperature of the ceramic field which unlike the porous field can retain water for several days was almost 10 °C lower than the porous and asphalt one, and almost equal to the grass field temperature.

Lin et al. (2007) investigated how pavement affects outdoor thermal environment during summer and winter in subtropical Taiwan. The experiment was carried out on five pavements in three areas of Taiwan. The experiment was performed twice in each area, during both summer and winter conditions. The data were recording every 1 min from 6:00 to 18:00. The results showed that surface temperature of artificial pavements were 10 °C higher than that of vegetation surface at noon in the summer. However, the difference among the various pavement types were not significant in winter. In the study of Takebayashi and Moriyama (2009) surface temperature changes of several parking lots located in a public parking area were monitored. The examination site, approximately covering an area of 56 m × 18 m comprised 36 parking lots, each one covering an area of 5.3 m × 2.5 m. The green cover area of each block varied from 21 to 100%, while the albedo values varied from 0.18 to 0.26. Moreover, during the weekend, when the lot was empty, the surface temperature distribution was monitored by using an infrared camera, while the solar reflectance for each parking space was measured using a net radiation meter. These observations were carried out every 3 h. The surface heat budget for each parking lot and the sensible heat flux from each parking lot were then estimated.

A small number of studies focusing on evaporative CP did not report on temperature reductions but on the corresponding hydraulic performance for water runoff. For instance, Starke et al. (2010) compared the evaporation rates of impermeable pavements with the ones of water-permeable pavements made with Cobble-stone paving stone, Pervious concrete paving stones, and common concrete stone. In addition, they measured pavement's hydraulic conductivity by a dripinfiltrometer. In more detail, they fixed to a pavement a steel ring of 54 cm diameter and they laterally sealed it with bentonite to prevent leakage. The area in the ring and the area around were irrigated by a dedicated system while the level of irrigated water was controlled by a distance sensor at 1 mm. Therefore, they retrieved the hydraulic conductivity of the area in the ring by measuring the flow rate. They also utilized tunnel-evaporation gauge for measuring evaporation rates of the pavements.

Another study not reporting on surface temperature reduction but on monitoring methodology with respect to albedo of evaporative pavements was reported by Li et al. (2013a). They developed nine fields test with three different pavement materials, i.e. (i) interlocking concrete, (ii) open-graded asphalt concrete and (iii) portland cement concrete. For each pavement surface type, one impermeable and two permeable fields were developed. For each test section, the albedo measurement was conducted at five different locations with a dual-pyranometer: the southeast, northeast, northwest corner and southwest corners, and center. At least six

Table 4
Same as Table 2, but for thermal energy storage cool pavements.

Study (Publication year)	T-Tbase	Variables	Timestep	City	Area	Period	Standards	Type	Base material	effiec-iency	reference	Others
Mallick et al. (2012)	–	T_{sur} (0 and below)	–	Worcester, USA	–	–	–	field	asphalt	–	–	WS, ISR
Ma et al. (2014)	-0.7	T_{sur}	–	CH	30 × 30 × 5 cm	2	–	specim- en	asphalt	–	common asphalt	T_{air}
ShengYue et al. (2014)	-3.4	T_{sur} of each of 3 layers	1 h	Longhai, CH	30 × 30 cm	7	–	specim-ens	asphalt	–	common asphalt	–
Ryms et al. (2015)	-5	T_{sur}	–	Gdansk, PL	0.25 × 0.33 m	4–6	–	specimens	asphalt	–	asphalt	T_{air}
Efthymiou et al. (2016)	-18	T_{sur}	1 h	Athens, GR	3.5 × 1.3 m	6–11	–	field	photov-oltaic	–	asphalt bare soil	–
Zhou et al. (2015)	-7	T_{sur} (0 ∼−10 cm), fluid flow	1 h	Tianjin, CH	12 × 8 m	7–9, 11–4	–	field	aspahlt	17%	common asphalt	T_{air} ISR
Jin et al. (2017)	-4.3	T_{sur}	10 s	CH	0.15 m x 0.15 x 0.05 m	4–6	–	specimens	asphalt	–	asphalt	–
Jiang et al. (2017)	-10	T_{sur}, V,I	10 min	Xi'an, CH	30 × 30 × 10 cm	6,12	–	specim- en	asphalt	6%	common asphalt	T_{air} ISR
Datta et al. (2017)	–	T_{sur} (0,-18 cm)	–	Texas, USA	45 × 45 x90cm	4–7	–	specim-ens	asphalt	–	–	–
Jiang et al. (2018)	-9	T_{sur}, Voltage output	10 min	Xi'an, CH	30 × 30 × 10 cm	2–6	–	specim- en	asphalt	–	common asphalt	T_{air} ISR WS WD
Tahami et al. (2019)	–	T_{sur}, voltage, current, power	–	US	30 × 30 cm	7	–	specim- en	asphalt	–	–	–
Wei et al. (2019)	-3.5	T_{sur}	–	Xi'an, CH	10.2 × 6.4 cm	9	–	specim- en	asphalt	–	asphalt	–
Elqattan and Elrayies (2021)	-14.1	T_{sur}	30 min	Cairo, EG	30 × 30 cm	5	–	specim-ens	aluminum	–	concrete mosaic	T_{air} ISR WS WD
BR et al. (2021)	-2.8	T_{sur}(0,-75, −100, −200 mm)	–	India	1 × 1 × 0.3 m	4–6	–	specimens	concrete	–	concrete	T_{air}
Khamil et al. (2021)	-5.5	T_{sur}	–	Kuala Lumpur, MY	32 × 30 cm	8	–	specimens	asphalt	–	asphalt	–

measurements were performed at each location. They moreover investigated the stormwater runoff and temperature decrease performance of the developed pavements during both wet and dry conditions from fall to summer in Davis, US (Li et al., 2013c). In order to monitor the surface and the near-surface air temperatures as well as the heat flux within the layers of the pavements, they utilized eight thermocouples, each placed at a different position, above, blow and on the pavement. The surface pavement permeability (also known as saturated hydraulic conductivity or infiltration rate) was measured for each field five times at each corner, i.e. southeast, northeast, northwest, and southwest corners, as well as at the center. In order to examine the cooling effect under both wet and dry conditions they continuously irrigated the pavement fields for 10 h, i.e. approximately 3.5 m^3 of water were irrigated to each of the paving fields. The results showed that permeable pavements under wet conditions in the early afternoon could have up to 10–25 °C lower surface temperature than impermeable pavements.

Wang et al. (2018) performed another outdoor investigation of evaporative pavements incorporating dynamic irrigation of the developed fields. They investigated the cooling potential of sintered ceramic porous brick and open-graded permeable concrete pavements. They carried out a 4-day-long monitoring campaign in Guangzhou, CH during the hot period of the year. The surface temperature was measured by a thermocouple position atop of the field covered by a aluminium foil. Also, four component net radiometers were placed above the fields to measure the corresponding albedo values, while air temperature and relative humidity were measured at 0.3, 0.6, 0.8 and 1.5 m above the surface for the pavements. The irrigation of the fields is reported at 12:00 and was approximately 0.8 m^3 water at 27 °C per field. They reported surface temperature reductions up to 10 °C directly after the sprinkling. Higashiyama et al. (Higashiyama et al., 2016) developed 5 paving water-retaining fields into two construction sites. The water-retaining CPs were constructed by pouring different cement-based grouting components, i.e. cement, ceramic waste powder, fly ash and natural zeolite, into open graded (porous) asphalt pavement. The surface temperature of each field was measured by a thermocouple placed 5 mm below the surface layer of the field. Another thermocouple was placed 1.5 m above the fields for measuring the air temperature. The results showed that when the surface temperature of the conventional porous asphalt pavement was exceeding 60 ° the water retaining pavements were maintaining averagely around 10 °C lower surface temperature.

Permeable pavements are reported to improve stormwater hydrology and mitigate urban inundation. However, their performance can be sharply weakened when are implemented in an area characterized by high water table and low-permeability soil. Under this framework Liu et al. (2018) propose an innovative evaporative figuline pavement with water retaining zone that comprises capillary columns. At first they performed an outdoor investigation by developing and monitoring relatively small specimens (21 cm x 21 cm). Subsequently they developed the corresponding paving fields, each covering an area of 4 × 4 m^2 (Liu et al., 2020). They benchmark the cooling potential of the figuline field against an impermeable cement concrete pavement, a pearmeable interlocking coarse concrete pavement and a water retaining fine concrete pavement. The monitoring campaign lasted for 12 consecutive months. They utilised stalls with triangular wires for capturing the runoff and outflow of each field, while thee same parameters were monitored by a ultrasonic liquid level meter. The surface temperature was measured only after seven consecutive days without rainfall by means of infrared camera from 08:00 to 20:00 every 1 h. The figuline pavement was found up to 15.3 °C cooler than the impermeable pavement under hot-summer conditions.

3.3. Thermal energy storage pavements

Conventional pavements such as asphalt and cement based pavements absorb more solar radiation than other materials in summer, and emit more heat into the atmosphere in winter. Hence they could be utilized for heat harvest applications (Asaeda et al., 1996). The concept of extracting solar energy from asphalt pavements has been proposed with respect to three main approaches, i.e. heat-transfer pavement, thermoelectric pavement and photovoltaic pavement (see Table 4). The main approach behind heat-transfer pavements incorporates the implementation of water pipes below the surface of the pavement for decreasing the pavements' temperature while simultaneously storing and exploiting the corresponding transferred energy. Consequently, by harvesting heat energy, the amount of heat emitted back from the pavement is reduced, hence it could contribute to lower air temperature above the pavement. The main factors that regulate the heat transfer performance of energy harvesting applications are related to the local microclimate boundary conditions and specifically to the intensity of solar radiation, ambient temperature, wind speed, pavement surface temperature, pavement material, the layout of the heat exchanger, and the circulating water flow rate of the system (Zhou et al., 2015).

In one of the first outdoor demonstrations of energy harvesting paving applications, Mallick et al. (2012) developed a heat exchanger based on a slab comprising a dense graded hot mix asphalt (HMA) layer. They integrated within the HMA a copper tube frame, and compact it inside wood carts. They monitored the surface temperature and heat flux by inserting several thermocouples within the slab at different heights. However, since the main goal of this study was to evaluate the surface temperature distribution with respect to both the diameter of the pipe and the water flow rate, no cooling effect was reported with respect to conventional pavements. ShengYue et al. (2014) developed and tested both in-lab and in-field unidirectional heat-transfer asphalt pavement specimens capable of confining heat transfer along a fixed direction. The specimens comprised three layers of compacted asphalt mixtures made with inorganic powders with high thermal conductivity. The upper layer was fabricated with the lowest conductivity while the bottom with the highest, i.e. the resulted structure was characterized by gradient conductivity. The results of a 2-day outdoor monitoring showed temperature reductions of 3.4 °C and 1.2 °C in the surface temperature of the energy harvesting specimens during the day and night, respectively, as compared to the control specimens.

Another study reporting on energy storage pavements comprising a pipe network was conducted by Zhou et al. (2015). They developed a heat-exchange pilot-scale pavement covering a 12 × 8 m area and benchmarked its thermal performance with a common asphalt pavement covering a 2 × 8 m area. In order to evaluate the effectiveness of the developed pavement they also developed a monitoring system of 54 pressure- and water-proof temperature sensors installed on both the experimental and reference pavements.

Table 5
Studies on the outdoor monitoring of large-scale implementation of cool pavements.

Study (Publication year)	City	Area	Type of CP	Base material (BM)	albedo of BM	Cool pavement application	albedo of CP	Pavement temperature	cooling effect ambient temperature
Furumai et al. (2008)	Minato, JP	public square	Evaporative	–	–	water retention pavement	–	13 °C	–
Furumai et al. (2008)	Mitaka JP	small park	Evaporative	–	–	water retention pavement	–	19 °C	–
Takahashi and Yabuta (2009)	Tokyo JP	parking lot	Evaporative	dense-graded asphalt	–	water retention pavement	–	14 °C	–
Gaitani et al. (2011)	Athens, GR	4160 m^2	Reflective	white concrete, black asphalt	0.45 (concrete)	1. photocatalytic asphalt, 2. colored infrared reflective concrete	0.68	4.8 °C	1.6 °C (simulation)
Fintikakis et al. (2011)	Tirana, AL	25000 m^2	Reflective	dark concrete, black asphalt	0.15–0.2	colored infrared reflective concrete	0.65–0.75	8 °C	2.1 °C (simulation)
Santamouris et al. (2012a)	Athens, GR	16000 m^2	Reflective	dark concrete, black asphalt	<0.4	1. colored infrared reflective concrete, 2. marble	0.70–0.78	–	1.2–2.0 °C (simulation)
Santamouris et al. (2012b)	Athens, GR	4500 m^2	Reflective	concrete, black asphalt	0.35–0.45 (concrete), <0.2 (asphalt)	colored infrared reflective concrete	0.60	7.6 °C	1.9 °C (simulation)
Kyriakodis and Santamouris (2018)	Athens, GR	37000 m^2	Reflective	grey concrete, black asphalt	0.04 (asphalt)	1. colored infrared reflective asphalt, 2. photocatalytic concrete	0.35–0.66	11 °C	1.5 °C (simulation)
Kolokotsa et al. (2018)	Athens, GR	–	Reflective	–	–	marble-cement	0.69	4 °C	0.3 °C (simulation)
Cheng et al. (2019)	Taipei, TW	200 m sidewalk, 200 m bike lane	Evaporative	black asphalt, grey concrete	–	1. porous brick 2. porous asphalt	–	6.6 °C (summer), 0.7 °C (winter)	–
Middel et al. (2020)	Los Angeles, US	13000 m^2	Reflective	dark asphalt	0.06–0.08	reflective coating	0.18–0.25	6 °C	–
Middel et al. (2021)	Phoenix, US	57936 m^2	Reflective	dark asphalt	0.12	reflective coating	0.33–0.38 (initially), 0.19–0.30 (after 10 months)	12 °C	0.5 °C
Cheela et al. (2021)	Makkah, SA	3500 m^2	Reflective	black asphalt	–	reflective coating	–	–	–
Cheela et al. (2021)	Doha, QA	200 m road, 200 m sidewalk/ bicycle lane	Reflective	black asphalt	–	colored cryogenic material with hallow ceramic microspheres	–	7 °C	–
Yang et al. (2021)	Pingtung, TW	850 m^2	Evaporative	–	–	1. semi- permeable asphalt 2. fully- permeable asphalt	–	–	–

Finally, in order to quantify the amount of heat exchange between the pavements and the heat collector they specifically monitored the water flow and the inlet/outlet water temperature of the heat exchanger. The monitoring campaign was carried out during both summer and winter periods and the results showed temperature reductions up to 7 °C during the summer period, and a average thermal storage effectiveness of the system of 17%.

The natural next step of water-pipe CPs was to optimize their heat storage mechanism not only for a higher cooling effect but also for a more efficient heat conversion and its utilization as a renewable form of energy (Zhu et al., 2019). Several studies investigated the factors and characteristics regulating the performance of energy harvesting pavements. Galvanized steel pipes were reported to outperform pipes made with propyleneglycol and polyvinyl chloride in terms of daily efficiency (Al-Saad et al., 1994). Characteristics such as the flow rate within the pipe and pipe diameter were found to be positively correlated with the efficiency of the solar collector (Gao et al., 2010; Mallick et al., 2012), while a negative correlation is reported for the space of pipe (Sheeba and Rohini, 2014). The optimum depth of the pipe is suggested to be defined with respect to the thermal conductivity of pavement (Dawson et al., 2012).

One of the first real-life investigation of thermoelectric paving components was performed by Jiang et al. (2017). They developed a thermoelectric generator system (TEG) capable of converting heat to electricity due to a temperature gradient between its two sides resulting to voltage output, i.e. Seebeck effect (Schreier et al., 2013). They reported two monitoring campaigns, one dedicated to the output voltage of the system during an autumn day, and one dedicated to system's cooling potentiality during a spring day. The outcomes confirmed that the higher the temperature gradient the higher the output voltage. Moreover, the surface temperature of the TEG slab, measured with a Infrared Thermal Imaging Camera, was found up to 10 °C lower than a conventional asphalt during the daytime. The same scientific group performed subsequently another study focusing mainly on the thermal performance of the TEG system from February to July and reported surface temperature reduction up to 9 °C in summertime (Jiang et al., 2018). Another in-field study based on the Seebeck effect was reported by Datta et al. (2017) that exploited the gradient between the surface temperature of the pavement and the corresponding substrate layer. Nevertheless, the study focused on the output voltage of the system and not to its cooling effect. Similarly, the in-field study of Tahami et al. (2019) focused specifically on increasing the temperature gradient of the TEG system by incorporating microencapsulated phase change material in powder form.

Recently Elqattan and Elrayies (2021) proposed a novel configuration concerning thermoelectric pavements by utilizing energy through solar panels for the needs of the system. They suggested that an eco-friendly real life implementation should exploit the application of solar panels on the top of neighboring building and traffic lights. Under this scenario, they performed a one day monitoring campaign and showed that the thermoelectric pavement maintained up to 14 °C lower temperature as compared to a conventional concrete mosaic specimen. The only identified study investigating the cooling potentiality of a photovoltatic (PV) pavement, without however, analyzing the heat transfer mechanism, is performed by Efthymiou et al. (2016). They developed a PV pavement above a metallic surface and performed two monitoring campaigns within two consecutive summer periods. The PV pavement field was found be up to 14.1 °C cooler than conventional asphalt especially around 14:00 when the maximum values of incident solar radiation typically occur.

Phase change materials (PCM) are also tested as thermal energy storage CP that since they can simultaneously reduce shrinkage and thermal stresses of the pavement and therefore extend its durability. Ryms et al. (2015) used ceresin, a by-product of crude oil distillation, as a PCM within expanded clay aggregates in asphalt specimens and monitored their surface temperature profile continuously for three summer days. They reported a temperature reduction up to 5 °C as compared to conventional asphalt. Similarly, Jin et al. (2017) investigated the incorporation of polyethylene glycol as PCM in asphalt pavements, and reported it capable of reducing surface temperature up to 4.3 °C. Moreover, BR et al. (2021) investigated two types of PCMs, i.e. Organic Mixture 35 (OM 35) and Organic Mixture 42 (OM 42), within expanded clay aggregates coated with cement paste. Specimens made with both PCM were found to maintain up to 1.85 °C (OM 35) and 2.76 °C (OM 42) lowers temperature than conventional asphalt under outdoor investigation within the months of April, May and June.

3.4. Large-scale application of Cool Pavements

Large-scale applications of CPs can be identified on a global scale with respect to reflective and evaporative CPs (Table 5). Gaitani et al. (2011) applied photocatalytic asphalt and colored concrete with high infrared reflection within a square at the center of Athens, GR that covers 4160 m^2. In March 2009 they performed several monitoring campaigns during the daylight. They showed experimentally that the CPs maintained up to 4.8 °C lower temperature than classic asphalt, and numerically that CPs may decrease average near-surface air temperature up to 1.6 °C. The same scientific group performed several other CPs large scale public areas' rehabilitation within the city of Athens covering in total more than 61660 m^2 (Santamouris et al., 2012a; Santamouris et al., 2012b; Kyriakodis and Santamouris, 2018; Kolokotsa et al., 2018). Numerical analysis of the applied CPs showed that depending on the location they may decrease the near surface air temperature up to 2 °C. Recently, several CPs projects have been carried out within the cities of Los Angeles (Middel et al., 2020), Phoenix (Middel et al., 2021), Makkah (Cheela et al., 2021) and Doha (Cheela et al., 2021) by applying reflective coating on existing pavements. Some preliminary outcomes of these applications suggest a 0.5 °C ambient temperature reduction due to the applied CPs.

With respect to evaporative CPs, several large-scale applications have been carried out, however, only a small number of them has been monitored and evaluated with respect to their cooling performance (Santamouris, 2013). For instance, Furumai et al. (2008) and Takahashi and Yabuta (2009) reported on the development of water retention pavements at a public square, a park, and a parking lot within the city of Tokyo, with a subsequent surface temperature reductions from 13 to 19 °C. Cheng et al. (2019) and Yang et al. (2021) reported recently on the application of porous bricks and porous asphalt at sidewalks and bike lanes in the cities of Taipei and Pingtung in Taiwan. The former study reported surface temperature reductions up to 6.6 °C during the summer period and up to 0.7 °C during the winter.

4. Discussion and meta-analysis

Fig. 3 illustrates the main descriptive characteristics of the monitoring protocols followed by the reviewed studies with respect to the duration of the monitoring campaign (Fig. 3a), the type of the investigated cool solution (Fig. 3b), the time-step of the monitoring (Fig. 3c), the type of the reference for evaluating the cooling potential (Fig. 3d), and the number of layers at which the pavements' surface (Fig. 3e) and air temperature (Fig. 3f) are measured. The majority of the studies on reflective CPs report on a one-month monitoring campaign (53%), while a couple of studies report on three- (13%) and six-months (13%) monitoring campaigns. The monitoring duration of evaporative CPs varies between twelve (33%), two (27%) and one or three (both 20%) months. Thermal energy storage CPs are monitored mainly either for one month (40%) or three months (20%). 40% of the studies reporting on a large-scale application of CPs did not report on the monitoring duration, while 27 % and 13% report a monitoring time-frame of one and two months, respectively. With respect to the type of the investigated solutions, fields that typically cover an area of 4×4 m^2 are preferred as compared to specimens for reflective (60%) and evaporative (87%) CPs investigation. On the other hand, mainly due to relatively higher costs, the majority of studies focusing on thermal energy storage CPs report on relatively small specimens (80%). Large-scale

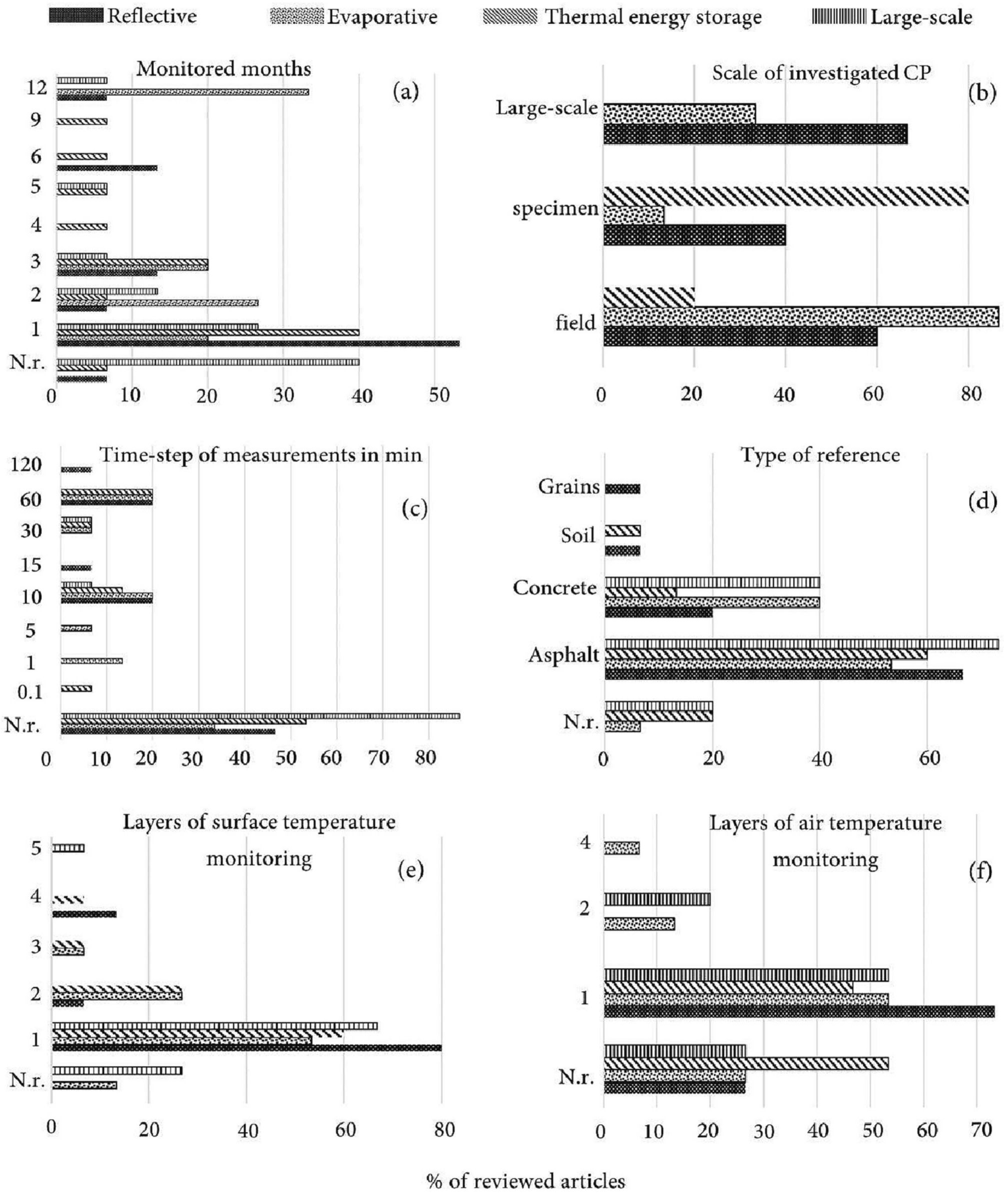


Fig. 3. Monitoring protocols followed within the reviewed studies. N.r. denotes "Not reported".

applications of CPs are identified only for reflective (67 %) and evaporative (33 %) solutions. A substantial fraction (>30%) of the studies referring to all the reviewed CP types did not report the monitoring time-step of the CPs' surface temperature. When reported, however, reflective CPs are monitored from 10 min (20%) and 15 min (7%) up to 60 min (20%) and 120 min (7%). Monitoring time-steps of evaporative pavements are also reported to vary with values equal to 1 min (13%), 5 min (7%), 10 min (20%), 30 min (7%) and 60 min (20%). With respect to thermal energy storage pavements four different monitoring time-steps are reported, i.e. 60 min (20%), 10 min (13%), 30 min (7%) and 0.1 min (7%).

In order to evaluate the cooling potential of the proposed CP solution, studies typically use as a reference classic materials of the built environment, such as asphalt and concrete. In fact, the majority (> 50 %) of studies reporting on the four identified CP categories used asphalt as the main reference since it is the most used material in the paving infrastructure and is typically characterized by lower solar reflectance than concrete. On the other hand, a fraction of 40% with respect to both evaporative and large scale applications reported a concrete reference as the main reference for evaluating the proposed solution. Measuring effectively the temperature of the proposed CP solutions is crucial for evaluating the corresponding cooling potential. The majority (>50%) of the studies reporting on all reported types of CPs measured the surface temperature of the proposed cool solution with one temperature sensor placed on the external surface. Yet, a small number of studies reported temperature sensors placed not only on the surface layers but also within the underground layers of the paving solutions. In fact, depending on the study the temperature of the CP solutions is measured from 1 up to 5 different layers. Measuring the near-surface air temperature and subsequently evaluating the potential of CPs with respect to ambient cooling is an ongoing challenge. Even though theoretically a wide application of CPs can result in lower ambient temperatures, their ambient cooling potential cannot be easily identified when the CPs application is up to few squared meters.

Therefore, the majority of the studies monitor air temperature at a height varying from 50 to 150 cm above the CP surface for characterizing the boundary conditions of the monitoring campaign and not for evaluating possible cooling effects on air temperature. Only a small number of evaporative and large scales CP studies (20 % for both categories) reported air temperature monitoring within more than one layer above the CP surface, i.e. up to 4 layers.

Fig. 4a illustrates the distribution profiles of the cooling effects reported for each CP category. The highest cooling effect is reported for the evaporative CPs with a mean value of 14.2 °C followed by the cooling effect of reflective and thermal energy storage CPs with mean values of 9.9 °C and 6.9 °C, respectively. Similarly, the mean cooling effect with respect to the reported large-scale CP

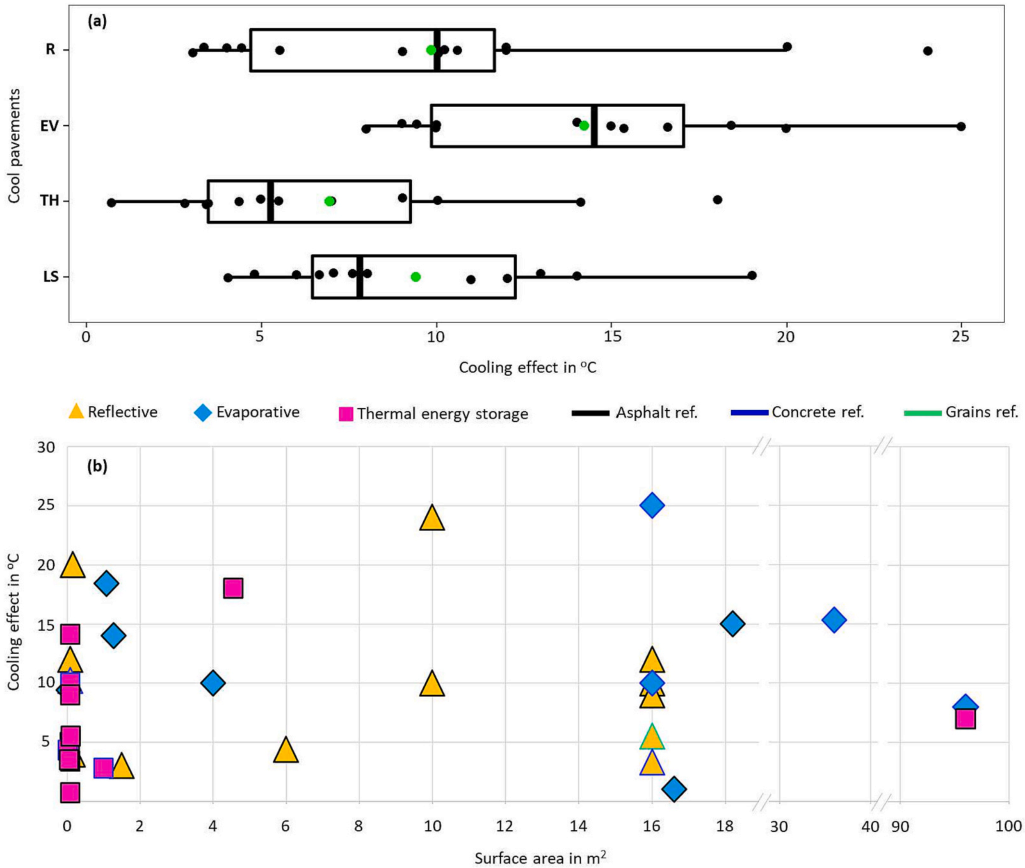


Fig. 4. (a) Distribution of reported cooling effects of each CP solution (green dots represent the average value) - R, EV, TH and LS denote Reflective CP, Evaporative CP, Thermal energy storage CP and Large scale CP, respectively. (b) Cooling effect of the reported solutions with respect to the area coverage (the black, blue and green lines in the legend are the outlines of the shapes representing each CP category.

applications is 9.4 °C. Fig. 4b illustrates the cooling effect of all the CPs reviewed herein with respect to the surface area that they cover and the reference used for the performance evaluation. A clear trend in-between the cooling effect and the surface area cannot be identified. However, it is clear that when asphalt is chosen as the main reference the cooling effect tends to be higher with respect to each category.

Fig. 5 illustrate the normalized divergence of the cooling effect from the corresponding average value with respect to each CP category, i.e. reflective CPs (Fig. 5a), evaporative CPs (Fig. 5b), thermal energy storage CPs (Fig. 5c) and large scale CP applications (Fig. 5d). With respect to the reflective paving solutions, the studies can be divided into the ones investigating small pavement specimens and the ones investigating pavement fields. Concerning both types of investigation, the majority of the studies are performed in the Mediterranean countries of Greece and Italy which are characterized by dry summer conditions. Therefore the outdoor monitoring was carried out during the warm periods of the year, i.e. mainly during the months of July and August. The main base materials of the proposed reflective pavements are concrete and asphalt enhanced with an upper highly reflective coating, while few studies report on acrylic, stone/grains, pebble, mosaic, sand or epoxy resin based solutions. The highest cooling effect and therefore,

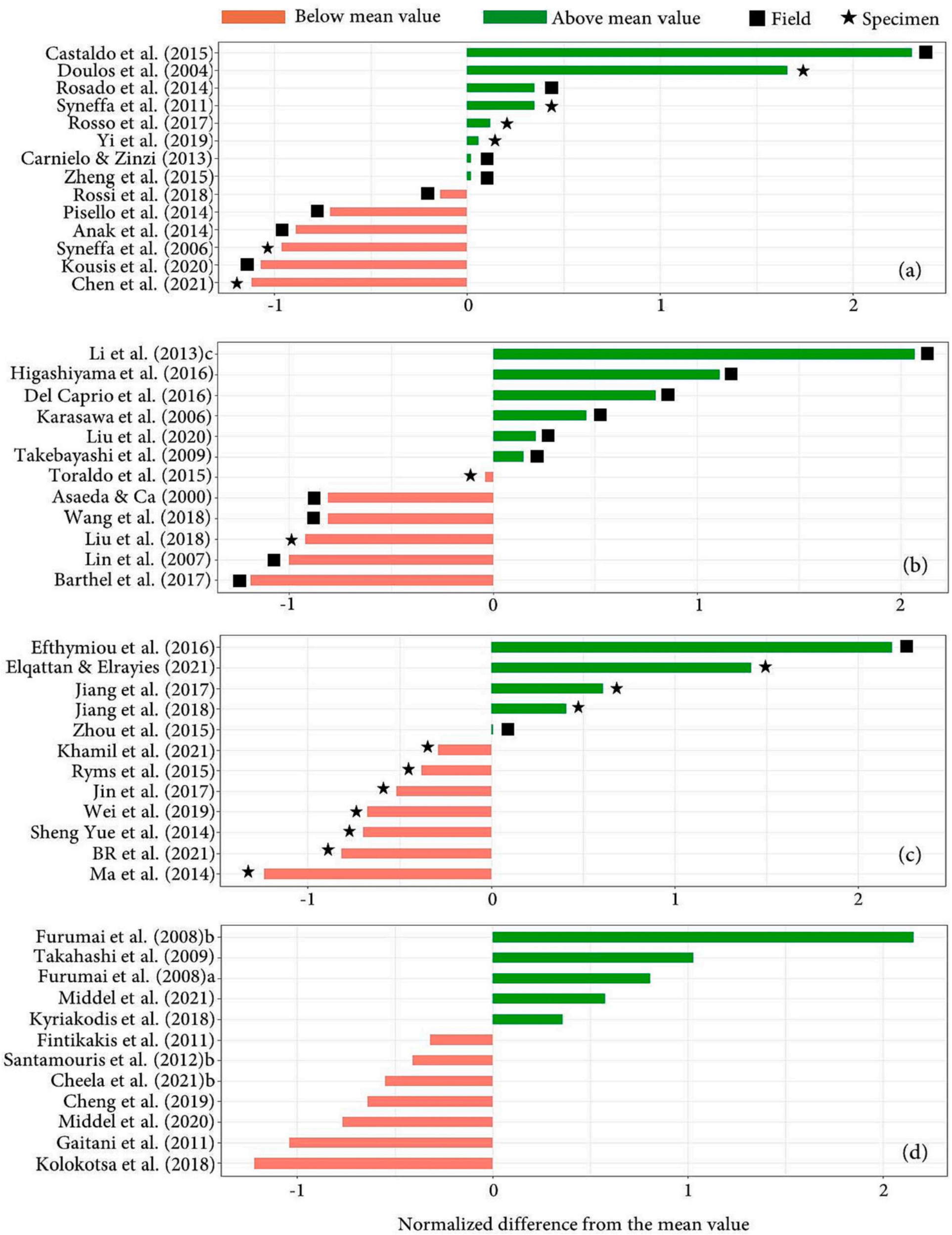


Fig. 5. Normalized divergence from average value with respect to the reported cooling effect of the reported (a) reflective CP, (b) evaporative CP, (c) thermal energy storage CP and (d) large-scale CP applications.

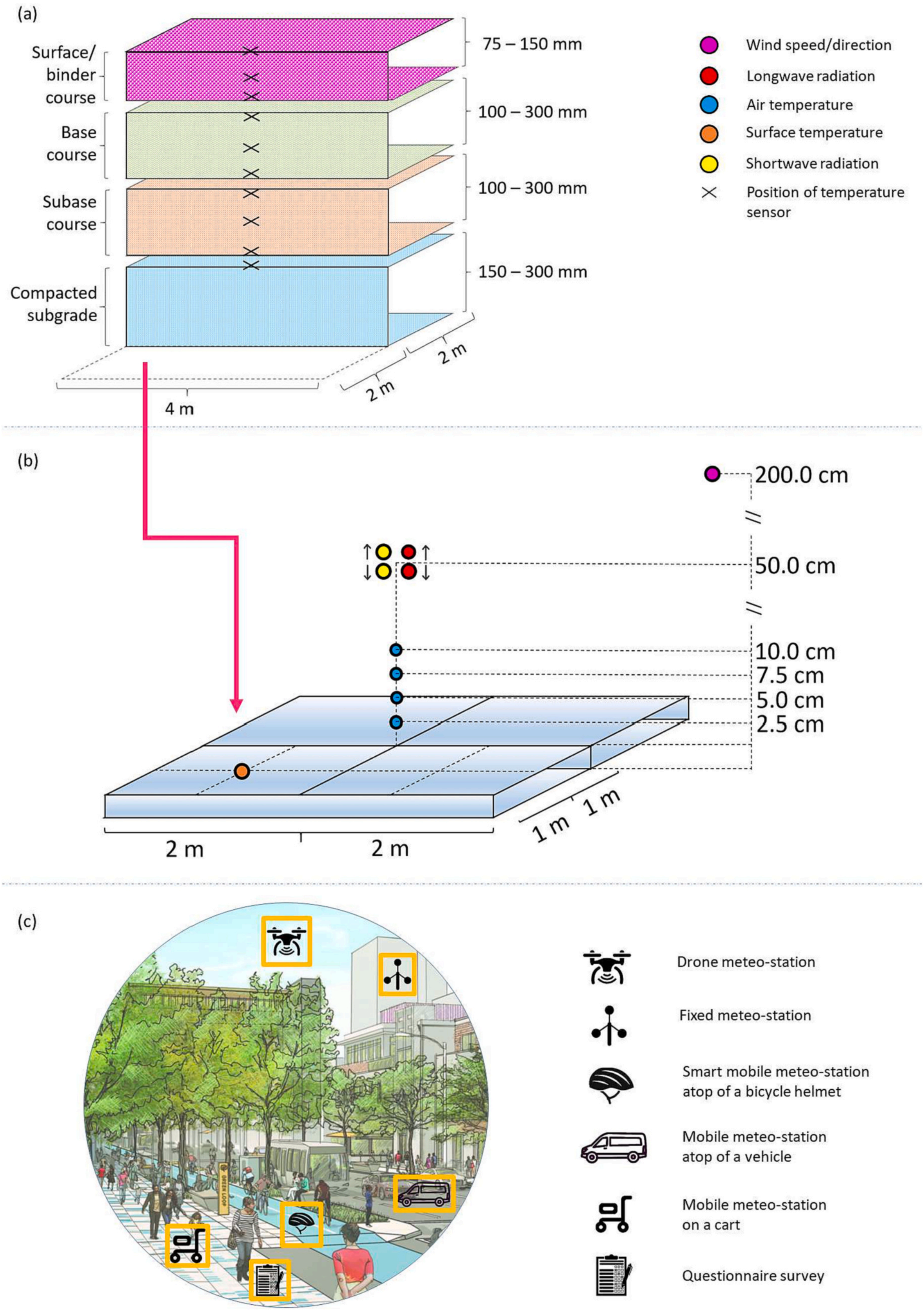
the highest positive divergence above the average value was reported by Elqattan and Elrayies (2021) and is followed by the study of Doulos et al. (2004). The former study reports on a cool natural stones field and the latter on small specimens. In fact, the corresponding cooling effects substantially outperformed the other studies investigating reflective CPs and were determined as compared to classic asphalt. The highest negative divergence from the mean value with respect to field investigation of reflective CPs was reported by Kousis et al. (2020) (concrete reference) and the corresponding negative divergence of specimens investigation by Chen et al. (2021) (asphalt reference).

With respect to the evaporative paving solutions most of the identified studies investigated paving fields and only two paving specimens. Since, the cooling effect highly depends on the availability of moisture near the surface layer and the evaporation rate, the majority of the studies are performed in Asian countries, e.g. China, Japan and Taiwan. These areas are characterized by humid climates that are preferred for permeable applications exploiting evaporative cooling. Different studies report monitoring campaigns throughout different periods of the year. However, three studies reported on a campaign that lasted one year. The main references for evaluating the cooling potentiality of the proposed CP are common impervious asphalt or concrete blocks and fields. The base materials of the proposed solutions vary among concrete, asphalt,ceramic, brick and grass. The reported protocols include in many cases monitoring of both surface and lower layers temperature (up to −25 cm), as well as evaporation rate, runoff, water retaining capacity, and hydraulic conductivity. The main standards reported with respect to their permeable nature are the ASTMC1701 concerning to infiltration rate and the ASTM 57 concerning the utilized stones for supporting drainage asphalt and concrete systems. Five studies reported also on the albedo values of the paving solution without, however, always following the corresponding standard that requires a field of at least 4×4 m^2 for measuring the reflected shortwave radiation. Fig. 5b illustrates the normalized divergence of the cooling effect from the corresponding average value and the corresponding overall central tendency of the reviewed evaporative CPs. The highest cooling effect and therefore, the highest divergence above the average value is reported by Li et al. (2013c) and is followed by the Study of Higashiyama et al. (2016).

With respect to the energy harvesting paving solutions most of the identified studies investigate specimens covering an area no larger than 45×45 cm, while only two studies report on fields covering an area of 3×1.3 m and 12×8 m. Energy harvesting and conversion solutions intrinsically require substantial amounts of incident solar radiation. Therefore, almost all the identified studies are performed in areas characterized by warm, temperate, or tropical weather conditions. Since energy-harvesting pavements are the newest advance of the CPs, no standards exist for their evaluation. Moreover, since thermal energy storage CP solutions may comprise pipe networks or electricity generators, apart of the solutions' temperature, parameters such as fluid flow, voltage and current are also monitored within some studies. Fig. 5c illustrates the normalized divergence of the cooling effect from the corresponding average value of the reviewed thermal energy storage CPs. The highest cooling effect and therefore, the highest divergence above the average value, is reported by Efthymiou et al. (2016) and is followed by the study of Elqattan and Elrayies (2021). The former study reports on a photovoltaic field and the latter on thermoelectric paving configuration.

Table 6
Drawbacks/research gaps/barriers of Cool paving solutions.

		Reflective	Evaporative	Thermal energy storage
Drawbacks	UV effects on human skin	✓		
	Glaring effect	✓		
	Effects on adjacent buildings	✓		
	Increase humidity		✓	
	Decrease sweat cooling of pedestrians		✓	
	Pollutants migration to groundwater		✓	
	Low thermal inertia		✓	
	Low thermal conductivity		✓	
	Surface roughness effects to evaporation rate		✓	
	Low Shortwave radiation reflection		✓	✓
	Decrease pavements strength			✓
Barriers	Absence of water		✓	
	Clogging		✓	
	Microclimate effects to evaporation rate		✓	
	Complex construction techniques			✓
	Complex maintenance techniques			✓
	Need for additional energy input			✓
	Low power output			✓
	Corrosion			✓
	Void effects on thermoelectric generator			✓
	Durability/aging	✓	✓	✓
Research gaps	Life cycle assessment	✓	✓	✓
	Life cycle cost assessment	✓	✓	✓
	Effect on near-surface air temperature	✓	✓	✓



(caption on next page)

Fig. 6. Thermo-optical monitoring scheme of (a) pavement structure, (b) overall test-field, (c) large scale application of cool pavement.

5. Research gaps and challenges

Novel research methodologies should be driven by the main challenges, and the corresponding research gaps and barriers (Table 6) of each CP solution type (Santamouris, 2013; Qin, 2015; Wang et al., 2021; Anupam et al., 2021). For instance, reflective CPs are prone to some key issues that are generally overlooked within the studies reporting on both in-field and in-lab investigation, and can further hinder their real-life application. Depending on the architectural design of the implementation, the reflected visible radiation can be responsible for glaring issues and may simultaneously increase the thermal load of pedestrians. Also, if shortwave radiation is not reflected by the pavements directly to the atmosphere it may affect the thermal load of the neighboring buildings and could increase their skin temperature. Durability, i.e. maintaining high reflectance of shortwave radiation in the long run is still another key issue that is not addressed under realistic conditions. Moreover, the reflectance of the ultraviolet radiation should be constrained at low levels for avoiding negative effects on human skin.

Evaporative pavements perform substantial cooling when water content is available. However, since evaporating cooling is performed within the upper layer (0–25 mm) of the pavement, in events of water absence the thermal mass of the lower layers of the pavement may lead to substantial increase of surface temperature. At the same time, only a few number of evaporating CP studies investigate the corresponding solar reflectance. In fact, low albedo evaporative pavements can be substantially hotter than conventional ones especially during periods that lack of rain and water content in general. Low thermal inertia and thermal conductivity in particular, may further increase the surface temperature of evaporative CPs. Humidity formation near the pavement surface due to evaporative cooling should be further assessed and evaluated with respect to possible effects on the sweat cooling of pedestrians. The transposition of pollutants within the lower levels of pavements is another issue of evaporative CPs that needs to be prevented to ensure good groundwater quality. In addition, the evaporation rates should be clearly investigated as a function of both surface roughness and varied microclimate boundary conditions. Finally, air voids should be further exploited since in many cases may cause raveling and water damages to the pavement itself, as well as clogging issues that reduce the infiltration rate.

Thermal energy storage paving applications are still in their infancy as compared to reflective and evaporative CP solutions. Therefore, they are prone to several defects and limitations. For example, positioning pipes or other complex structures below the road surface may decrease pavement strength and its resistance to heavy traffic loads. Therefore, due to their complex nature thermal energy storage pavements require complex construction and maintenance techniques that need to be further optimized. Moreover, the performance of thermoelectric generator should be further assessed with respect to the voids around the embedded pipes that may affect the fluid circularity. Fluid circularity should be also considered under cross-fall conditions that may require additional energy input for ensuring good performance. Also, characteristics such as power output and the corresponding efficiency should be clarified for all energy harvesting CPs solutions.

Considering all three CP categories, still, no outdoor monitoring campaign has effectively assessed possible air temperature reductions owing to the corresponding CP solution. In fact, air temperature reductions due to CP application is a crucial point that needs to be investigated both by research community and industry under common standards for boosting CP applications in real life. Of course, capturing possible air temperature reductions caused by outdoor evaluation of CP solutions is a rather tricky challenge. In fact, air temperature reduction cannot be evaluated when small specimens are investigated. Similarly, even though paving fields cover a bigger area than specimens, they still cover a relatively small area as compared to a real-life implementation that is needed for cooling down near-surface air temperature in practice. In addition, there is a discrepancy among studies concerning the protocols followed for evaluating the thermal properties of the pavement itself. Most of the studies monitor the temperature of the upper layer of the pavement, i.e. surface/binder course and hence, cannot further evaluate the heat flux within the pavement. Therefore, the evaluation of the pavement's cooling effect should be carried out by placing several sensors below and above the pavement surface, taking into account all the layers of the pavement as well as the near-surface air levels. A schematic representation of a proposed monitoring protocol can be seen in Fig. 6. Under this framework, temperature sensors may be placed within the upper, lower and middle points of each layer of a 4×4 m^2 pavement test field (Fig. 6a). Moreover, positioning above the middle of the field several cost-effective air temperature sensors, e.g. thermocouples, at different heights at least up to 20 cm above the field's surface could be considered as a standard for near-surface air temperature profile evaluation (Fig. 6b). As a result, thermal fluctuations can be reckoned from the lower layers of the pavement up to the layers of air near the surface and used for defining accurately the corresponding thermal properties of the pavement, while they can moreover be utilized as inputs for numerical simulations of microclimatic modeling. An ideal monitoring protocol dedicated to the thermo-optical properties of a CP should also comprise a pair of two pyranometers and two pyrgeometers positioned above the middle of the field in order to measure the incoming/outgoing short-wave and far infrared radiation, respectively. Hence, the energy balance of the proposed CP can be thoroughly defined. In addition wind profile may be monitored at 2 m height in close proximity to the test fields and can be used for reckoning the instantaneous convective heat flux from the pavements to the ambient.

Apart from field tests that are intrinsically prone to limitations, real life large-scale applications of CPs are a first-class opportunity to evaluate the corresponding cooling performance. In fact, recent large-scale applications reported in the cities of Los Angeles, Phoenix, Makkah, Doha, Taipei and Pingtung should be exploited through excessive monitoring campaigns and, at the same time, can engage and raise the interest of policymakers, authorities, the public, and the corresponding stakeholders. The corresponding studies should not rely only on simulating the effects on air temperature. Instead, extensive monitoring campaigns should be carried out within the implementation area comprising extensive monitoring networks incorporating both fixed and mobile stations (Fig. 6c).

Smart mobile stations are reported on vehicles (Kousis et al., 2021), bicycle helmets (Pigliautile and Pisello, 2018), drones (Santamouris et al., 2020), carts (Middel and Scott Krayenhoff, 2019) and wearable devices such as smartwatches (Nazarian et al., 2021) and can be used within almost any urban environment for monitoring the main microclimate parameters related to urban architecture and materials used. These technological advancements should be therefore exploited by the academic community for the establishment of multi-domain monitoring protocols and standards that will ensure data of high accuracy and a detailed understanding of the interrelations among cooling solutions, local microclimates, and pedestrians' comfort. As a result, a successful implementation of real-life UHI mitigation solutions will be rendered feasible, opening, in turn, new ways and possibilities for further funding related to heat mitigation projects at various scales, e.g. country, city and neighborhood scale.

Furthermore, apart from gauging CPs cooling effect, monitoring campaigns should be undertaken under a human-centered approach by evaluating the effects on pedestrians' comfort, e.g. thermal and visual comfort. Under this scenario, quantitative monitoring techniques through mobile stations capturing variables such as mean radiant temperature, sky view factor and albedo, should be combined with qualitative monitoring techniques performed through the involvement of citizens traversing across the implementation areas and responding to specifically designed questionnaires (Rosso et al., 2016). Improving citizens' comfort while simultaneously decreasing ambient temperature during the hot period of the year is indeed the main goal of almost any CP application. Life cycle assessments in conjunction with life cost assessments related to the overall pavement's life-span, i.e. costs related to their construction operation and maintenance, should be considered for any proposed solution and optimize it accordingly with respect to the EU directions towards carbon neutrality. The interplay between pavements and neighboring buildings needs to be furthermore assessed under different architectural designs and boundary conditions. The effects of CPs on the energy consumption of the building and hence, on the corresponding carbon emissions should be thoroughly evaluated and optimized with respect to the EU directions towards carbon neutrality.

Under this scenario, apart from the microscale monitoring methods, mesoscale remote sensing techniques (RST) could be exploited to evaluate pavements' thermal regime (Zhou et al., 2018; Tepanosyan et al., 2021) as well as other relevant microclimate analysis since RST data are consistent both spatially and temporally (Cheval et al., 2020). In fact, investigating urban pavements through satellite monitoring could provide a good overview of the corresponding surface temperature and hence, establish efficient comparative assessments (Santamouris, 2013). Several studies have implemented satellite images for investigating the spatial distribution of urban surfaces' temperature and have evaluated the corresponding effects on the thermal environment of the cities (Streutker, 2002; Golden and Kaloush, 2006; Ko et al., 2022). Nevertheless, when RST are implemented their intrinsic constraints such as time limitations related to satellites' orbit, image resolution and the corresponding interpretations should be taken into account (Santamouris and Kolokotsa, 2016).

6. Conclusions

Urban climate research utilizes a variety of datasets and variables typically comprising ground-based data, gridded data, remote sensing data, or ancillary data, such as demographics and societal information, land use land cover and urban morphology information as well as information related to climate change adaptation and resiliency (Rizeei and Pradhan, 2019; Cheval et al., 2020; Rahman et al., 2020; Tsurumi et al., 2021). Urban adaptation and resiliency assessments are of critical importance for both the research community and policymakers that aim to establish smart city frameworks within urban areas (Huang-Lachmann, 2019). Among the numerous effects of climate change at the urban scale, the contribution of urban overheating to the magnitude and formation of Urban Heat Island (UHI) (Athukorala and Murayama, 2021) is considered of high importance and thus is well documented (Santamouris et al., 2015). However, although significant research has been carried out with respect to UHI magnitude and mitigation, the research on the microclimate characteristics and the physical properties of the materials used in the built environment is rather limited (Brozovsky et al., 2021).

Three main alternative types of Cool Pavements (CPs) have been proposed and tested to date for their cooling potential. The main goal of their application is to maintain low superficial temperature and hence contribute towards lower ambient temperature and improve the thermal comfort of pedestrians, especially during the warm months of the year.

Under this scenario, here we report on the outcomes of a systematic methodology and meta-analysis that aims to review, characterize and critically discuss the outcomes of outdoor monitoring evaluation of cool pavement technologies in terms of followed protocol and cooling potential. The main stimulus of this review is to qualitatively and quantitatively discuss the existing literature focusing on CPs evaluation and application under realistic conditions. Moreover, it aims to contribute towards the establishment of efficient protocols that will improve the research of CP and help the research community to better communicate relevant outcomes under a robust framework of a sustainable and resilient perception. The three main CP techniques that were reviewed in the present study are (i) reflective pavements, (ii) evaporative pavements and (iii) thermal energy storage pavements. In addition, studies reporting on large-scale application of CPs across the world were also analyzed.

The key findings of the review are summarized below:

1. Outdoor monitoring of CP applications has revealed a good potentiality of maintaining lower surface temperature than conventional pavements.
2. The reported cooling effects vary within 3–20 °C, 8–25 °C, 4–14 °C, and 4–19 °C with respect to reflective, permeable, thermal energy storage, and large-scale CP applications, respectively
3. Reflective and energy-harvesting pavements are suitable for climate zones characterized by a high amount of incoming solar radiation

4. Permeable pavements are more suitable for climate zones where weather patterns follow tropical fluctuations with high moisture content
5. Reflective pavements typically comprise a relatively simpler structure that can be easily applied as compared to permeable and energy harvesting pavements, since in most cases are developed by applying a thin reflective coating above a classic substrate, e.g. asphalt or concrete
6. Evaporative pavements come together with other positive effects, such as reduction of runoff, increased water quality and tree growth and noise absorption
7. Even though energy thermal energy storage CPs have a relatively complex structure can intrinsically reduce the use of fossil fuels and exploit renewable energy sources whilst the corresponding research is rather in its infancy
8. There is a lack of studies evaluating CPs under real or realistic conditions in the outdoors
9. There is a lack of monitoring protocols and standards with respect to the outdoor investigation and evaluation of CPs

A wide real-life application of CPs is still hindered due to several factors. Lack of effective synergies between the research groups, policy-makers, governmental organizations and industrial companies under a multidisciplinary and sustainable approach is considered one of the main barriers. At the same time, the research community needs to further upgrade the evaluation methodology of the CP techniques. In fact, to date, the vast majority of CP studies report on in-lab experiments and numerical simulations. Even though their outcomes are a fine indication of CPs cooling potentiality, they do not correspond to real-life boundary conditions and hence can be questioned by non-academia decision-makers. A smaller number of studies report on the outdoor investigation of CP applications. Their outcomes, which are considered more representative since they correspond to real-life or realistic boundary conditions, could play a crucial role in furthering CP applications into real life by raising the interest of decision-makers. Therefore, outdoor monitoring protocols and the corresponding evaluation methodologies should be thoroughly devised and performed not only with respect to the accumulated knowledge of each research group but also under specific protocols developed by the CP community. Under this scenario, future advances of CPs field are expected to be of substantial importance and become a key-role player towards sustainable and resilient urban environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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