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Review

Evaluation of the Pavement Geothermal Energy Harvesting Technologies towards Sustainability and Renewable Energy

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Abstract: Continually using fossil fuels as the main source for producing electricity is one of the main factors causing global warming. Through the past years, several efforts have been made, looking for sustainable, environmentally friendly, and clean energy alternatives. Harvesting geothermal energy from roadway pavement is one of the alternatives that have been developed and investigated recently. Herein, a systematic review and bibliometric analysis were conducted to provide a comprehensive overview of the potentials of harvesting thermal energy from asphalt pavement and to assess the level of achievement being attained towards developed technologies. A total of 713 articles were initially collected, considering the period between 2006 and 2021; later, a series of filtration processes were performed to reach 47 publications. The thermal energy harvesting technologies were categorized into three main sectors, at which their basics and principles were discussed. In addition, a detailed description of the systems' configurations, materials, and efficiency was presented and described. Finally, gaps and future directions were summarized at the end of this paper. The fundamental knowledge introduced herein can inspire researchers to detect research gaps and serve as a wake-up call to motivate them to explore the high potentials of utilizing pavements as a clean and sustainable energy source.

Keywords: geothermal; thermoelectric; energy harvesting; pavement; sustainability; systematic literature review

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1. Introduction

In recent decades, a huge increment in the fossil-fuel-related energy demand was observed due to rapid worldwide economic growth [1,2], resulting in a significant increment in greenhouse gas emissions levels, especially that of carbon dioxide (CO_2). Continually using fossil fuel accounted as the main factor accelerating global warming [3–5], with more than 70% of the total greenhouse gas emissions into the atmosphere [6]. As a result, significant damages and harmful effects toward biological, physical, and socioeconomic systems were observed, such as increases in heat increments, flash floods, drought, urban heat islands, and rising sea-levels [7–9]. In 2021, the intergovernmental panel on climate change (IPCC) [10] reported that the scale of recent changes in aspects of the climate system is unprecedented for centuries or several thousands of years. Furthermore, the IPCC revealed that the carbon dioxide (CO_2) concentration in the atmosphere in 2019 was the highest it had been in the past two million years. Besides, it was reported that the average earth temperature in 2021 increased by 1.5 °C above the common average level before the Industrial Revolution [10]. Thus, looking for clean and sustainable energy alternative sources is of utmost importance.

Recently, renewable energy harvesting techniques have been initiated and developed, aiming to reduce the rates of greenhouses gas emissions [11]. According to Edenhofer et al. (2021) [12], burning coal emits 1.4–3.6 pounds of CO_2E/kWh, while using renewable energy sources such as solar energy only emits 0.02–0.04 pounds of CO_2E/kWh. Therefore, many countries have established new strategies for decreasing fossil fuel use and increasing renewable energy source usage. For example, 27.3% of the total generated electricity in Germany was produced via renewable energy in 2014, resulting in reducing the emissions of greenhouse gases to their second-lowest level since 1990 [13]. Generating electricity for sustainable and renewable sources is expected to increase, especially with the existence of abundant resources worldwide. For example, India is a preferable location for utilizing a solar system for electricity production because it is a tropical country, and it receives around 5×10^3 trillion kW h equivalent in solar energy [14]. On the other hand, Malaysia and Brazil, with their huge water resources, can be considered as potential locations for generating renewable energy via hydroelectric power stations [15,16]. Among other renewable energy sources, roadway pavement is considered one of the promising alternative sources that can be utilized to generate clean and sustainable energy.

Traditionally, the roadway's main function is to carry different traffic loads [17]; however, researchers believe that multitasking, or smart pavement will bring more benefits to the economy and environment, especially with the promising potentials of using autonomous and electric vehicles in the near future [17]. Detecting and monitoring pavement diseases and traffic flow through reliable sensor networks, coupled with video cameras, is an essential step towards smart pavement. Powering these sensor networks is one of the main challenges that may delay smart pavement development. Therefore, energy harvesting from roadway pavement has been established recently, and many studies have been published in this regard [18]. As a result, several technologies and methods have been developed, such as a piezoelectric transducer system [19], a thermoelectric generator system (TEG) [20], and a solar panel system [21], as shown in Figure 1.

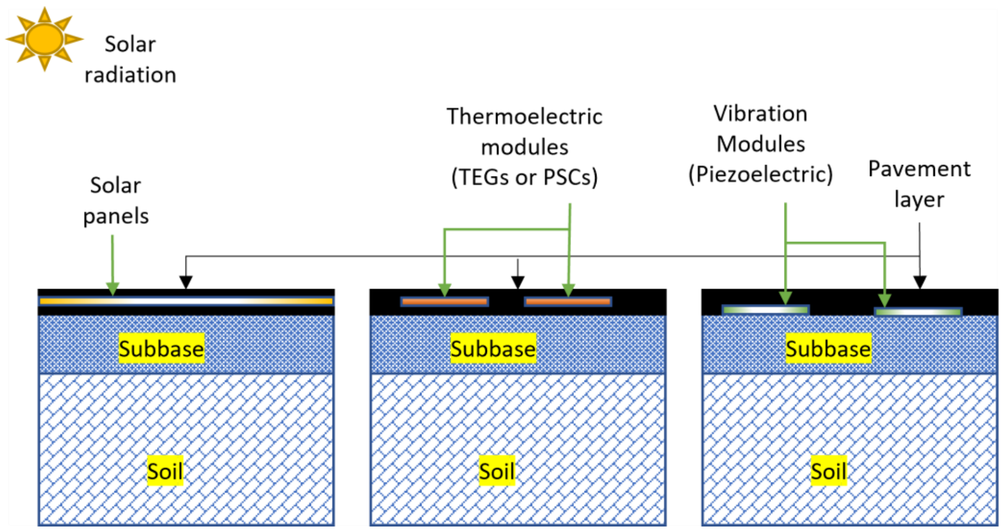

Figure 1. Schematic diagram illustrating pavement energy harvesting technologies [17]. (This drawing was created by the authors).

Besides producing energy, thermal energy harvesting technologies would bring more benefits to the environment and to the asphalt pavement itself [22]. In fact, the asphalt color is black, which has a high ability to absorb solar energy and store heat. It has been reported that asphalt pavement temperatures can reach higher than 60 °C in the summer at midday [23]. This characteristic could cause negative effects on the pavement and the surrounding environment, such as (i) rapid asphalt pavement aging. The bitumen ductility is reduced due to the oxidization and volatilization of its light components under high-temperature values, resulting in a decreased ability of the pavement to resist cracking and fatigue issues, leading to decreasing the lifetime of the pavement [24,25]. (ii) Augmentation of heat-related pavement diseases, such as rutting [26]. Under the combination of traffic loads and extreme temperatures, asphalt pavement is subject to plastic deformation, or so-called rutting, resulting in the reduction of the roadway's functionality, as well its level of safety [27,28]. (iii) Increase in urban island heat effects [28,29]. Rapid land urbanization of cities is leading to the covering of the natural land with paved surfaces, especially with roadways. According to Akbari et al. (2016) [29], roadways account for more than 30% of the total area of cities. Along the same lines, Gilbert et al. (2017) and Anting et al. (2017) [30,31] argue that this percentage could be larger in big cities. During daytime in the summer season, a huge amount of heat is absorbed and stored by asphalt pavement, and during the nighttime, the pavement releases this heat into the atmosphere, which is considered one of the biggest reasons for urban island heat effects [29]. Therefore, implementing thermal energy harvesting technologies in pavement may help to extract the solar heat during the daytime, resulting in a decrease in the stored heat and the surface temperature of the pavement [32]. Thus, these technologies would minimize thermal-related pavement diseases and increase the pavement's lifetime, as well as reducing heat island effects.

In this paper, a systematic review and bibliographic analysis are presented to provide a comprehensive overview of the potentials of harvesting thermal energy from asphalt pavement and to assess the level of progress that being reached towards developing such technologies. This in-depth overview will help to highlight the research gaps in this particular research area and provide recommendations and future directions. First, a detailed description of the methodology used to conduct this study is introduced, including keyword designation, resource selection, data collection, and data filtration. Next, data analyses are described in descriptive and bibliometric modules, considering several parameters, including publication distribution by years, regions, journals, and technologies. Later, pavement thermal energy harvesting technologies are discussed under three categories, namely (i) path solar collector systems (PSCs), (ii) thermoelectric generator systems (TEGs), and (iii) pyroelectric materials systems. Finally, gaps, future directions, and conclusions are introduced at the end of this paper.

2. Methodology

The main goal of this study is to summarize and evaluate the knowledge domains covered by existing studies on pavement thermal energy harvesting technologies towards sustainability and green energy production. This review was conducted by following the guidelines of systematic review [33,34] coupled with bibliometric analyses [35,36]. The systematic literature review is characterized as a scientific and repeatable approach for determining, selecting, and analyzing high-quality literature in order to produce concise results [37,38]. The systematic framework can review a specific topic using standardized, technological, and intelligent techniques, resulting in objectivity and explicitness [39]. On the other hand, the bibliometric review is a type of statistical analysis that employs visualization techniques such as bibliometric mapping. The aim of the bibliometric analysis is to determine the structural and dynamic behavior of scientific research, as well as interconnections [40,41].

Recently, several publications in different knowledge sectors have been conducted following systematic review combined with bibliometric analysis to integrate qualitative and quantitative methods in a single study [42]. The main advantage of this type of review methodology is a strengthening of the outcomes and a minimizing of the weakness of systematic and bibliometric review when conducted alone [43]. In systematic literature reviews, the highlighted gaps are biased conclusions, heterogeneity of results, and subjective interpretations [44,45]. On the other hand, the results of bibliometric reviews are dependent on techniques, databases, and discipline differences, and inaccurate data might lead to incorrect conclusions [46]. The combination of systematic and bibliometric review methodology helps to increase the findings' reliability and overcome the impact of the biased judgment of the manual qualitative review approach [47,48]. The present study used the PRISMA guidelines in order to review the current literature. First, the scope of this study was defined to fit the developed objectives and to answer the research questions. Next, the keywords were designed carefully, taking into consideration that only the targeted publications should be collected. Later, collected publications were refined following several steps, such as removing repeated and non-English publications. Finally, the refined publications were analyzed and discussed under different headings. Figure 2 illustrates the framework and the steps that were used to conduct this study. Moreover, after the literature sample was obtained, scientometric analysis was performed using VOSviewer software which was developed by the Centre for Science and Technology Studies, Leiden University, The Netherlands with open access license.

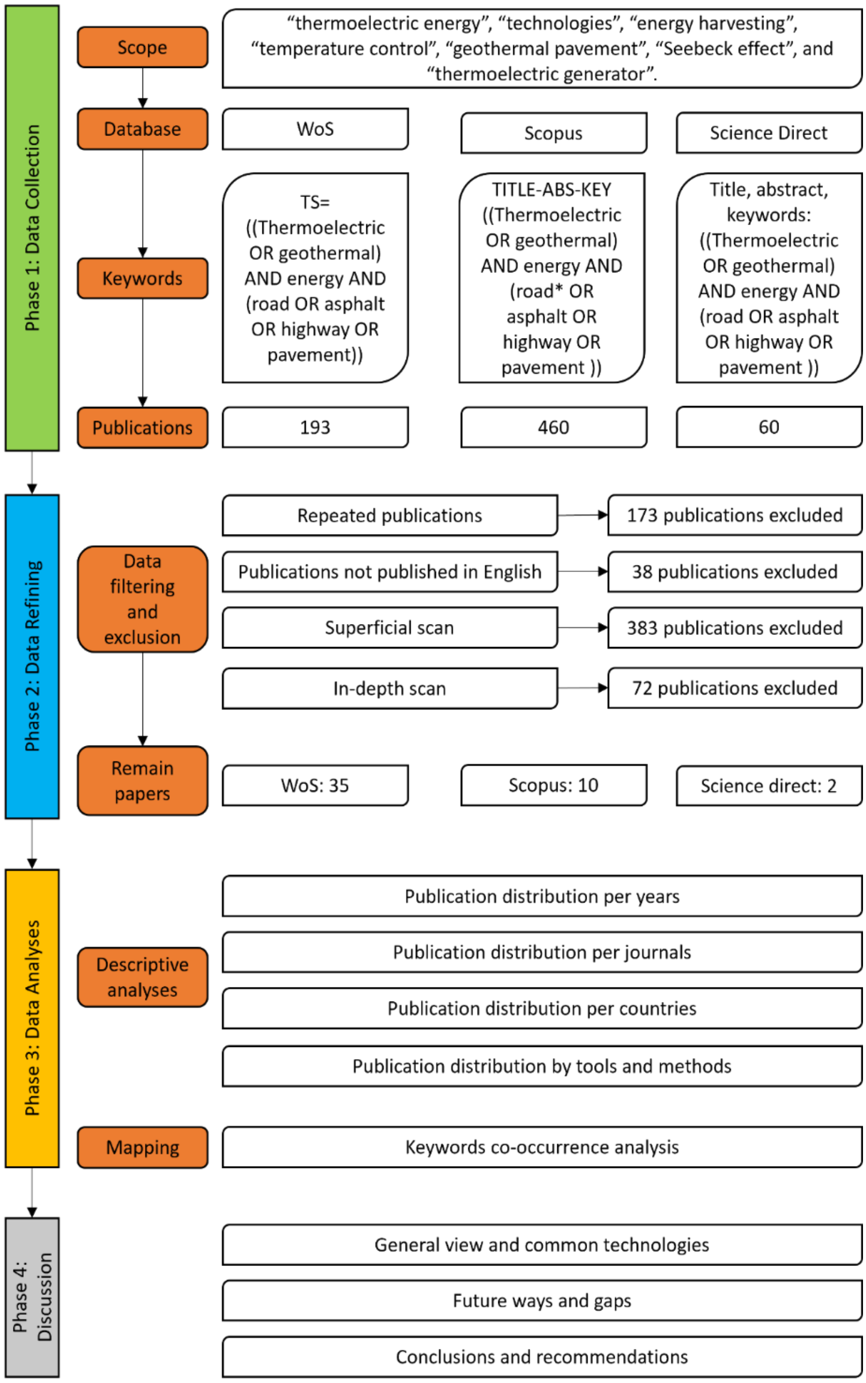

Figure 2. Flowchart of the study.

2.1. Data Collection

This phase was established for the purpose of data collection, which includes relating previously published studies. The protocol of the data collection was designed based on the objective of this study and the scope was set to include "thermoelectric energy", "technologies", "energy harvesting", "temperature control", "geothermal pavement", "Seebeck effect", and "thermoelectric generator". The period from 2006 to August 2021 was chosen as the timespan for the collected studies.

2.1.1. Databases and Resources

In this study, three different databases, including the Web of Science (WoS), Scopus, and ScienceDirect, were selected for the purpose of data collection. According to Braun et al. (2019) [49], WoS and Scopus are the most transparent and reliable bibliometric tools, which makes them the most comprehensive scientific databases for publication visualization and research analysis [49]. Scopus is counted as one of the best publication databases because of its large range of journal articles and multidisciplinary studies [50,51]. On the other hand, the WoS core collection includes several citation indexes, such as the Science (SCIE), Arts and Humanities (A&HCI), Social Sciences (SSCI), and Conference Proceedings (CPCI) Citation Indexes, which include high-quality articles for performing a systematic review and bibliometric analysis [52,53]. ScienceDirect is also frequently used by researchers, and it is a renowned database for its literature collection.

2.1.2. Keywords

To achieve the aim of this study, different combinations of keywords were chosen and designed for all selected databases. The terms 'roadway thermoelectric energy', 'asphalt thermoelectric energy', 'highway thermoelectric energy', 'pavement thermoelectric energy', 'roadway geothermal energy', 'asphalt geothermal energy', 'highway geothermal energy', and 'pavement geothermal energy' were selected as keyword combinations for the sake of searching. The reason behind choosing these terms was to maintain open the prospect for collecting studies on pavement geothermal energy harvesting while also allowing unrelated publications to be ruled out later. Table 1 summarizes and describes the keyword combination methods that were used, as well as the publications that were gathered from each database. A total of 713 articles, consisting of original research works, reviews, and conference articles, were collected according to the specified protocol. Figure 3 shows the yearly distribution of the collected raw data. Based on Figure 3, it can be noticed that the publications increased gradually over the years to reach the maximum by 2021, with a total of 95 publications. The most collected publications came from the Scopus database when compared with the WoS and ScienceDirect databases.

Table 1. Database and Keyword Arrangement.

Database	Keywords	Duration	Publications
Web of Science (WoS)	TS = ((Thermoelectric OR geothermal) AND energy AND (road OR asphalt OR highway OR pavement))	2006–August 2021	193
Scopus	TITLE-ABS-KEY ((Thermoelectric OR geothermal) AND energy AND (road * OR asphalt OR highway OR pavement))	2006–August 2021	460
ScienceDirect	Title, abstract, keywords: ((Thermoelectric OR geothermal) AND energy AND (road OR asphalt OR highway OR pavement))	2006–August 2021	60
Total			713

* Represents any number of characters, even zero. Example: road* returns roadway, roads, roadways.

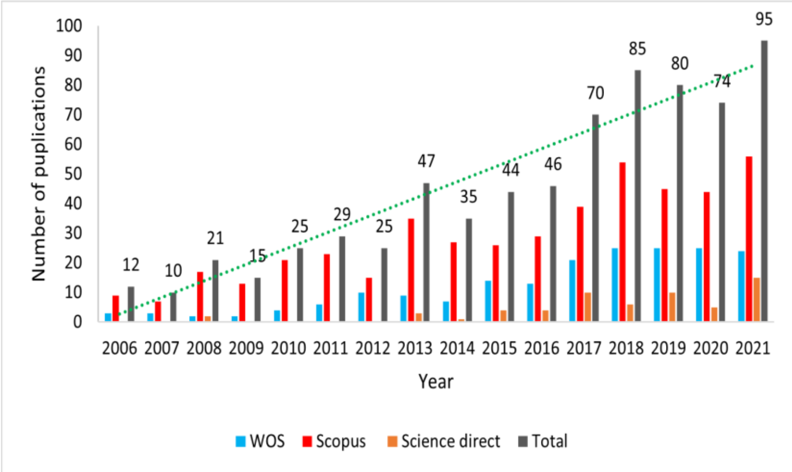

Figure 3. Yearly distribution of the raw collected publications.

2.2. Data Refining

In this phase, the collected data from the different databases were filtered, and only publications within the scope of the study were taken to the next phase. The filtration was conducted in four steps. The first step was the exclusion of common papers, at which repeated publications with the same title from the same or different databases were removed. As a result, 173 articles were removed at this stage. The second step was the exclusion of non-English publications, at which those publications with different languages, such as Chinese or Korean, were excluded, and only publications in the English language were taken into consideration. Therefore, a total of 38 publications were removed. The third stage involved the superficial-scanning exclusion, in this stage the articles' titles and abstracts were carefully checked, and those which did not fall within this study's designed scope were removed. A total of 383 publications were removed based on superficial scanning. Finally, the deep-screening exclusion was performed; the remaining publications were checked carefully by exploring their titles, abstracts, and methodologies, leading to the exclusion of 72 publications. As a result of these filtration steps, a total of only 47 publications were considered in this study. The procedures and stage-by-stage filtering processes are shown in Table 2.

Table 2. Publication's exclusion summary.

Database	Exclusions				
	Collected Data	Common Papers	Other Languages	Superficial Scan	Deep Scan
WOS	193	0	11	107	40
Scopus	460	119	27	273	31
SD	60	54	0	3	1
Total Removed	0	173	38	383	72
Total Remaining	713	540	502	119	47

3. Data Analysis

Phase 3 was established to analyze the refined, collected data based on different criteria, including, (i) yearly distribution of the publications, (ii) publication distribution per journal, (iii) publication distribution per country, and (iv) publication distribution by tools and methods. In addition, a bibliometric analysis was conducted by using bibliometric mappings of the keywords' co-occurrence.

3.1. *Yearly Publication Distribution*

Figure 4 illustrates the annual distribution of the published papers within the time span from 2006 to August 2021. Based on Figure 4, it can be observed that the number of publications on geothermal pavement energy harvesting between the years of 2006 and 2016 was poor, with a total of only 8 articles. On the other hand, the number of publications increased gradually starting in 2017, indicating a growing interest in pavement geothermal energy harvesting. Furthermore, WoS produced the maximum number of research articles when compared with Scopus and ScienceDirect, as shown in Figure 4. Finally, publications from 2021 were fewer when compared with those from 2020, and this may be due to the duration considered in this work (through August 2021).

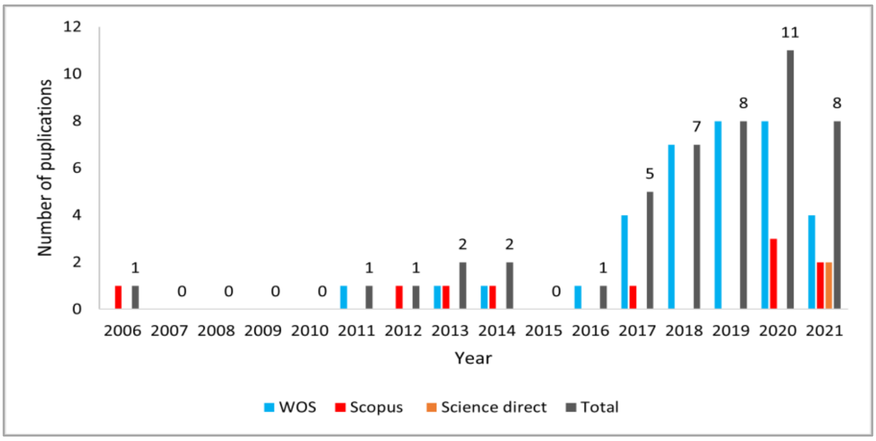

Figure 4. Yearly publication distribution of the refined publications.

3.2. *Publication Distribution by Journals*

In this SLR, a total of 36 different sources were evaluated from which the selected data was published. This proves that geothermal energy harvesting from roadway pavement is a hot-trend research topic, and many sources are interested in considering articles on this subject. Surprisingly, only 1 source published >2 articles, which was Applied Energy journal, with a total of 7 (15%) articles. On the other hand, Advanced Materials Research, Renewable and Sustainable Energy Reviews, Transportation Research Record, International Journal of Energy Research, and International Journal of Pavement Research and Technology published two journals each, for a total of 10 articles. The rest of the papers were published in different sources with a percentage of 64% with a maximum of one article each, as shown in Figure 5.

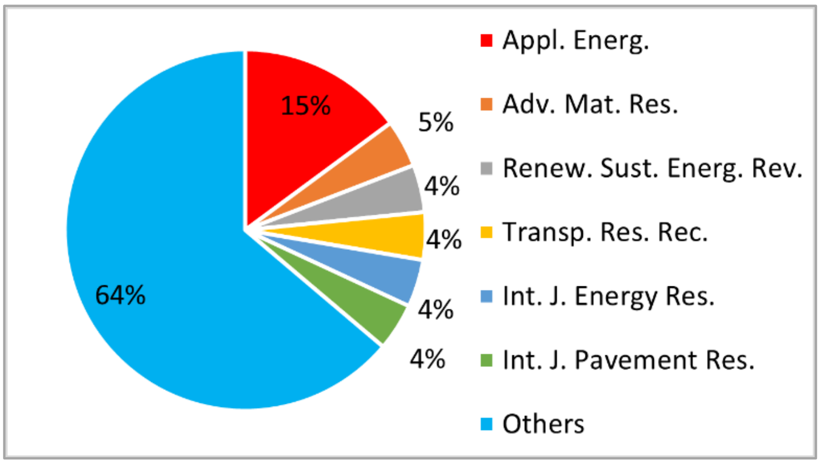

Figure 5. Percentage of articles published per journal.

3.3. Publication Distribution by Locations

To group the collected publications based on the study locations and identify the geographical locus, content analysis was conducted. It is worth noting that a number of countries were participating in the investigation of the capabilities of harvesting energy from asphalt pavement, with 15 countries across the globe identified. The United States (USA), China, and Malaysia, with 16 (34%), 10 (22%), and 6 (13%) publications, respectively, were the three countries with the highest number of published articles, as shown in Figure 6. Australia, India, and Sweden published two articles each. Other countries, including Qatar, Japan, the United Kingdom (UK), the Republic of Korea, South Korea, France, Indonesia, and Lebanon published only one article each, with a total percentage of 19%. According to this analysis, it is clear that scholars in the United States and China are the most enthusiastic about this research area.

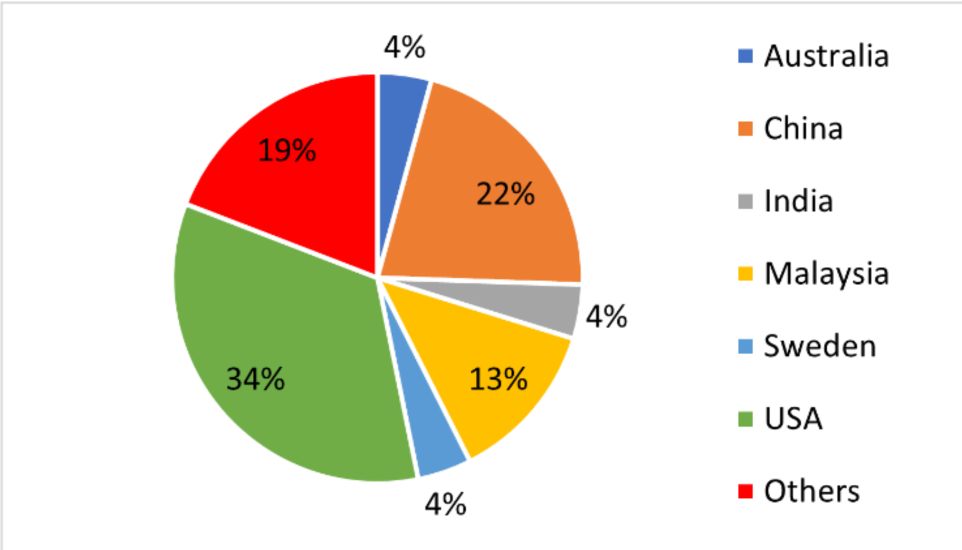

Figure 6. Thermal energy harvesting research articles across countries.

3.4. Publication Distribution by Approaches and Techniques

Content analysis was performed to categorize the publications based on the approaches used to conduct them, as well as the technologies that were used and investigated. Figure 7 shows the percentage distributions of the collected publications in terms of approaches and methods. It was noticed that experimental studies were the most plentiful, with a percentage of 36.2%, while mixed methodology, i.e., experimental and numerical approaches, scored as second, with a percentage of 29.8%. It should be mentioned that review publications comprised 14.9% of the total number of publications in this field, which indicates that sufficient reviews are available for readers at the current time. Apart from publication type, the collected publications were analyzed based on the technologies being used and implemented, as shown in Figure 8. It was observed that the thermoelectric generator (TEGs) system at a solid-state was the most common technique among the others, with a percentage of 6.7%. The path solar collector systems (SPCs) scored second, with a percentage of 22.2%. On the other hand, pyroelectric and combined (TEGs mixed with PSCs) systems both scored third, with a total percentage of 5.6% for each. These statistics may help authors to understand the research trend and fill the gaps to enhance and improve thermal energy harvesting technologies.

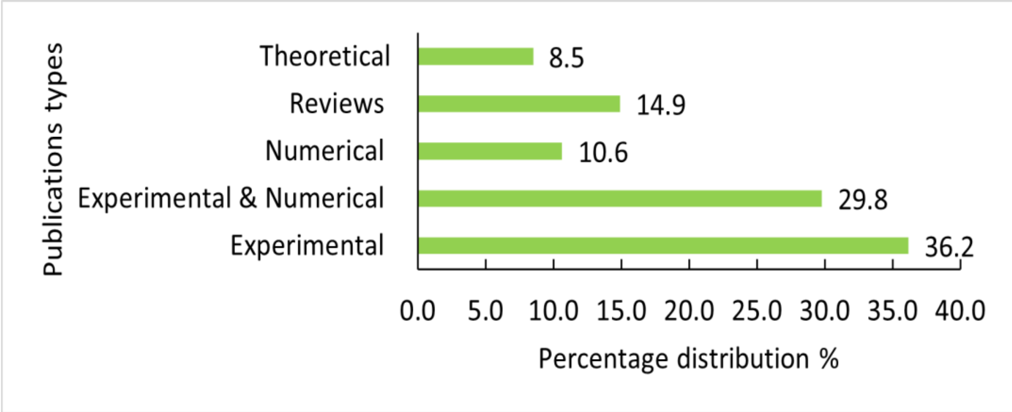

Figure 7. Publications distribution based on used approach.

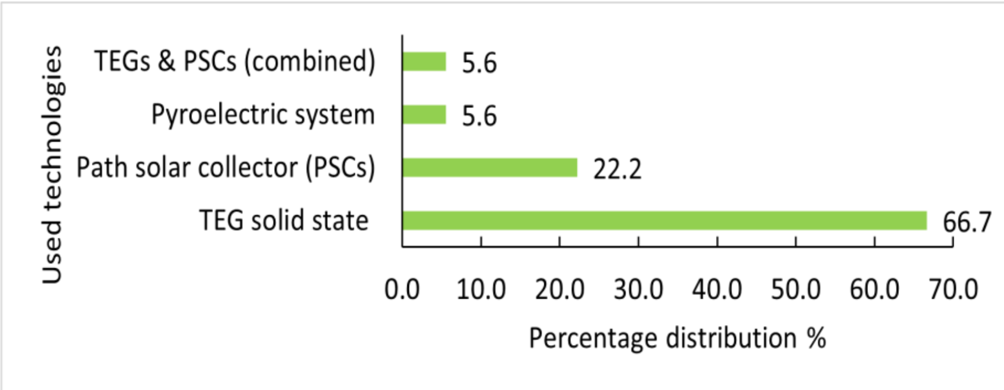

Figure 8. Publication distribution based on the used technique.

3.5. Keywords Bibliometric Mapping and Analyses

Bibliometric analysis is one of the tools that can be used to understand the relationships between different studies in a certain field [54,55]. In addition, bibliometric mapping allows researchers to understand the research trend and identify gaps and future directions [44]. Therefore, keyword bibliometric mapping was conducted in this study.

For a certain research domain, keyword bibliometric mapping and analysis may help to provide a general overview of the study by presenting a concise illustration of the contents and describe the existing research patterns [56,57]. Herein, VOSviewer software was used to conduct the authors' keyword co-occurrence analysis for the selected articles (47 publications). This type of analysis can be used to investigate the progress of the research field over time, as well as to identify the authors' commonly used keywords to show their contributions [54]. Among the 47 publications, a total of 127 keywords were found, with 21 keywords meeting the threshold point, as the minimum number of co-occurrences for a keyword was set to 2. Author keyword mapping and the summary of the top 6 keywords' co-occurrence are illustrated in Figure 9 and Table 3, respectively. It was found that 'energy harvesting' and 'thermoelectric' are the most common keywords used in the analyzed articles for the average published years of 2018 and 2017. 'Asphalt pavement' and 'pavement' scored as the second-most used author keywords, with a co-occurrence rate of 7 and 6 respectively for the average published years of 2019 and 2016. In Figure 9, the size of the circle and the font illustrate the keyword co-occurrence rate, where a larger size corresponds to a higher rate of co-occurrence.

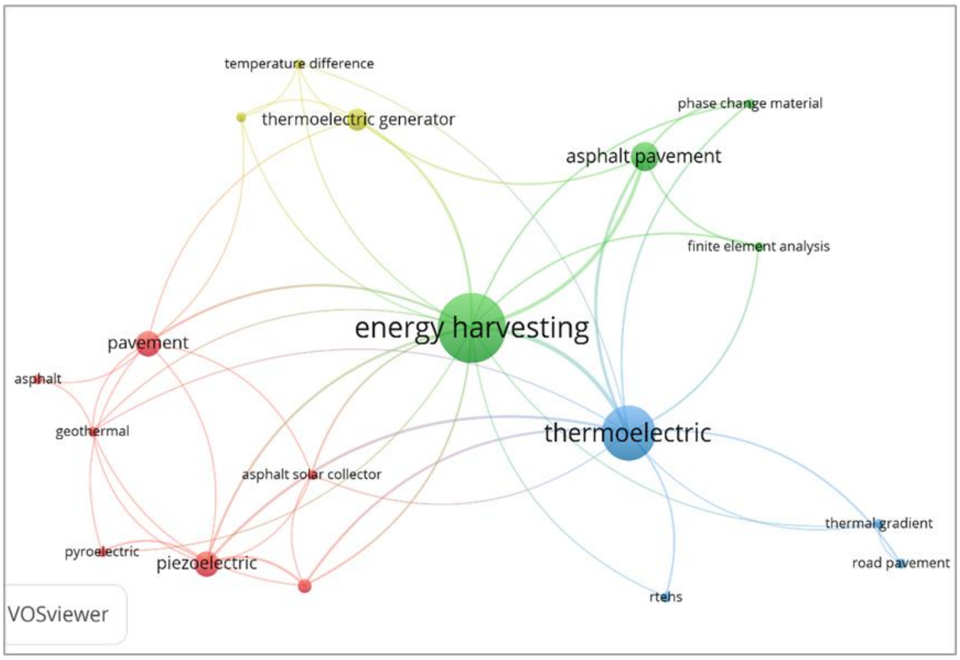

Figure 9. Co-occurrence mapping of author keywords.

Table 3. Top Six Author Keywords Summary.

Author Keyword	Links	Occurrences	Average Publications per Year
Energy harvesting	15	20	2018
Thermoelectric	12	15	2018
Asphalt pavement	5	7	2019
Pavement	8	6	2017
Piezoelectric	7	6	2018

4. Common Thermal Energy Harvesting Technologies

Roadway networks are one of the main essential transportation infrastructures which play a fundamental role in transporting goods and passengers. For example, the are a total of 6 million km and 4.7 million km of paved roads in the USA and China alone, respectively [58,59]. Besides their main function, roadways can be improved and developed into so-called smart pavement, which can support other functions and services, for example communication, pavement health monitoring, vehicle detection sensors, and wireless sensor networks [60,61]. However, all these extra services require a continuous electricity supply to keep them operating all the time, which is considered to be one of the critical challenges in the development of smart pavement. One should take into consideration that these paved roadways are exposed to a huge amount of solar energy throughout the year, especially in tropical countries [62,63], and that could be extracted as renewable energy [64–67]. From another perspective, temperature has critical effects on asphalt pavement behavior; plastic deformations may occur in hot weather, while cold weather results in brittle failure [68,69]. Therefore, harvesting thermal energy from pavements can help in all directions, i.e., producing renewable energy, keeping the pavement healthy, and reducing solar radiation.

Different technologies and techniques have been established and employed to harvest thermal energy from pavement throughout the past years. The most common technologies are (i) path solar collectors, (ii) thermoelectric generators (TEG), and (iii) pyroelectric materials systems. In the following section, a detailed description of these technologies is presented.

4.1. Path Solar Collectors (PSCs)

PSCs are pipeline systems embedded underneath the asphalt pavement to collect the heat through circulating fluids inside the pipes [70]. Later this hot fluid can be used to generate energy through a heat exchanger (Figure 10a) or TEGs (Figure 10b). Additionally, the collected hot fluid can be stored to be used for pavement de-icing in the winter season [71]. Generally, PSC systems consist of three main components, including (i) the pipe system, (ii) the storage tank or TEGs system, and (iii) the pumping system, as shown in Figure 10. Regarding the pipe network, durability and high heat conductivity are the main characteristics of the pipe material that were recommended [72]. The common materials that were used in the previous studies were polyethylene [73,74], copper [75], and steel [76,77].

The fluids that circulate inside the pipes are the primary carrier of the heat, and their thermal properties play the main role in the amount of collected heat. In the previous studies, two main fluids were used, including pure water [74,75], and pure air [76,77]. However, few studies investigated the efficiency of the water when mixed with other materials as a heat carrier. A mixture of water and ethylene glycol was used by Johnsson and Adl-zarrabi (2020) [73], while Mirzanamadi et al. (2020) [78] used a mixture of water and 42% propylene glycol. These materials enhanced the water so as to absorb more heat when compared with pure water.

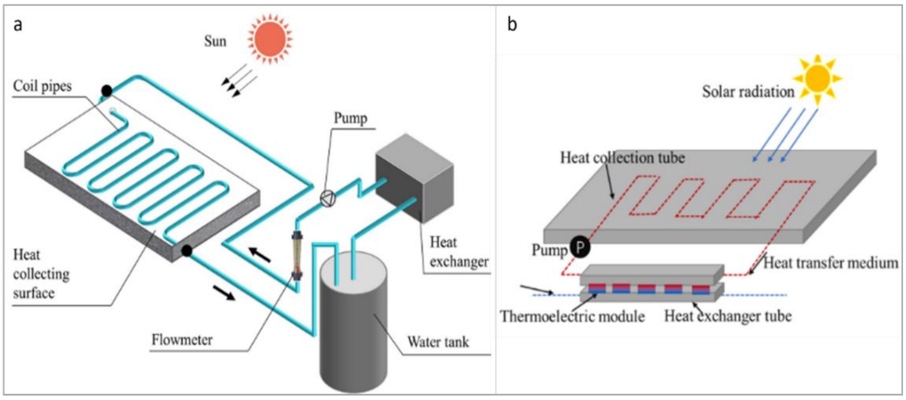

Figure 10. This 3D view illustrates the path solar collector system connected to (**a**) heat exchanger and (**b**) TEG modules [32,79,80].

As previously mentioned, that collected heat from the PSC system can be used in different ways to generate electricity, either through TEGs or heat exchangers. In addition, the PSC system brings more advantages to the pavement during the summer and winter seasons. In summer, a PSC system helps to decrease the temperature of the pavement, resulting in reducing heat island effects, while in winter, a PSC system can be employed to melt the snow and ice on the pavement by pumping hot fluid inside the pipes. Johnsson and Adl-zarrabi (2020) [73] conducted experimental and numerical studies to evaluate the efficiency of the PSC system in harvesting thermal energy and decreasing pavement temperature. An ethylene glycol–water mixture circulated in cross-linked polyethylene pipes with a diameter of 20 mm and a length of 140 m. It was reported that the surface pavement temperature was reduced by 10 °C, while the output power was 245 kWh/m^2. Baumgärtel et al. (2021) [81] carried out an experimental study to investigate passive geothermal heating and cooling system performance for pavements. Water was circulated inside PE-XA pipe with a length and diameter of 27 m and 25 mm, respectively. It was found that the pavement temperature was above 2 °C in winter, while in summer it was below 20 °C. On the other hand, the total power that could be extracted was 980 W/m^2. Chiarelli et al. (2017) and García and Partl (2014) [76,77] investigated the efficiency of the PSC system on reducing the pavement temperature by circulating air inside a steel-pipe network underneath the pavement. Chiarelli et al. (2017) [76] reported that the surface temperature of the pavement was reduced by 6 °C in summer, and it was increased by 2.1 °C in winter. García and Partl (2014) [77] reported that the pavement surface temperature was reduced by 10%. A detailed summary of the previous studies that have been published regarding pavement thermal energy harvesting using PSC systema is shown in Table 4.

Table 4. Summary of the Previously Published Studies Using the PSC system.

Paper Type	Software	Climatic Zone	Heat Collector	Heat Source	Pipe Length (m)	Pipe Diameter	Pipes Spacing (m)	Area m^2	Heat Collector Location	Output Power/Voltage	Surface Temperature Reduction	Ref.
Experimental and numerical	HyRoSim	Temperate	Ethylene glycol-water mixture circulated in cross-linked polyethylene	Sun	140	20 mm	0.050	70	62 mm	245 kWh/m^2	10 °C	[73]
Numerical	COMSOL 5.3	Temperate	42% propylene glycol-water mixture circulated in pipe	Heat flux	198	19 mm	0.305	55.51	89 mm	126 kWh/m^2/year	-	[78]
Experimental	-	Temperate	Water circulated in PE-XA pipe	Summer T_{in} < 20; winter T_{in} = 10 °C	27	25 mm	0.010	4	40 mm	980 W/m^2	Above 2 °C (Winter); below 20 °C (summer)	[81]
Experimental and numerical	Fluent	Subtropical	Water circulated in copper pipe	Infrared lamp	-	20 mm	0.010	0.09	70 mm	750 w/m^2	-	[75]
Experimental	-	Subtropical	Water circulated in high-density polyethylene (HDPE) piping	Hot water	360	0.025 m	0.600	200	500 mm	-	-	[74]
Experimental and numerical	Autodesk CFD	Temperate	Air moved through a stainless-steel pipe	Infrared heating element	-	65 mm	-	0.329	100 mm	-	6 °C reduction (summer); 2.1 °C increment (winter)	[76]
Experimental	-	Temperate	Air moved through a steel pipe		3 × 6	9 mm	0.001 V; 0.002 H	0.135	-	-	10% reduction	[77]

Overall, the PSC system shows good potential in terms of pavement thermal energy harvesting. Besides, it can bring more benefits to the environment and pavement by minimizing the heat island effects and reducing some thermal-related pavement diseases, such as rapid aging and rutting. Furthermore, the PSC system can be used as a de-icing system in winter by circulating hot fluid inside it. However, the PSC system required an external source of energy to power the pump that is one of the essential components of the system. Additionally, fluid leaking from the pipe underneath the pavement may occur, especially over the long-term and due to heavily loading.

4.2. Thermoelectric Generator (TEG) System

4.2.1. Theory and Principles

In 1821, T.J. Seebeck claimed that the temperature difference between two dissimilar electrical conductor or semiconductor materials results in an electric voltage difference. Later, this theory was called the Seebeck effect, which is the fundamental theory of thermoelectric generators (TEGs) [82,83]. Basically, TEGs consist of two thermoelectric materials, namely (i) P-type, which is the positive charge carrier, and (ii) N-type, which is the negative charge carrier. These thermoelectric materials are joined at their ends, as shown in Figure 11. By transforming temperature differences into electric voltage, these materials can generate energy directly from heat. Perfect thermoelectric materials should have high electrical conductivity (σ) and low thermal conductivity (κ). Low thermal conductivity means that, while one end of the thermoelectric materials gets hot, the other stays cool, increasing the system's efficiency and producing higher electric voltages [79,84]. Mathematically, the output power and voltage of TEGs can be evaluated using Equations (1) and (2) [17,85].

$$V = a\ (T_h - T_c) \tag{1}$$

$$P = Q_h - Q_c = I^2 R_l \tag{2}$$

where:

V is the voltage,
a is the Seebeck coefficient, which describes the magnitude of electron fluxes due to a temperature variation across that material,
T_h and T_c are the temperatures at the hot and cold ends of the thermoelectric materials,
P is the power.
Q_h and Q_c are the amounts of heat absorbed and released by the hot and cold TEG sides.
I is the current.

and

R is the TEG internal resistance.

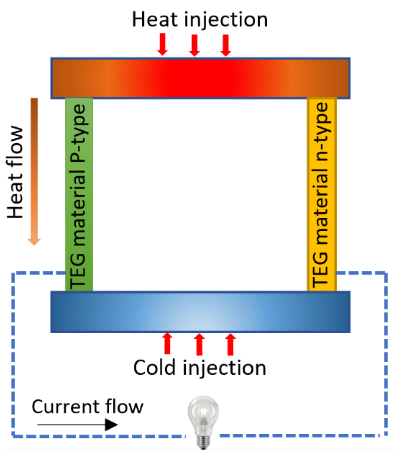

Figure 11. Schematic view of the thermoelectric materials and electric voltage producing process [17,84] (this drawing was created by the authors).

4.2.2. TEG Applications on Pavements

TEGs have been integrated into roadway pavement since 2006 to harvest the available thermal energy [79]. Since that time, several experimental and numerical investigations have been conducted to study TEG potential in generating electricity from roadways using different design approaches. A typical TEG system consists of three main components namely, (i) the heat collector, (ii) the thermoelectric generator module, and (iii) the heat sink (Figure 12a).

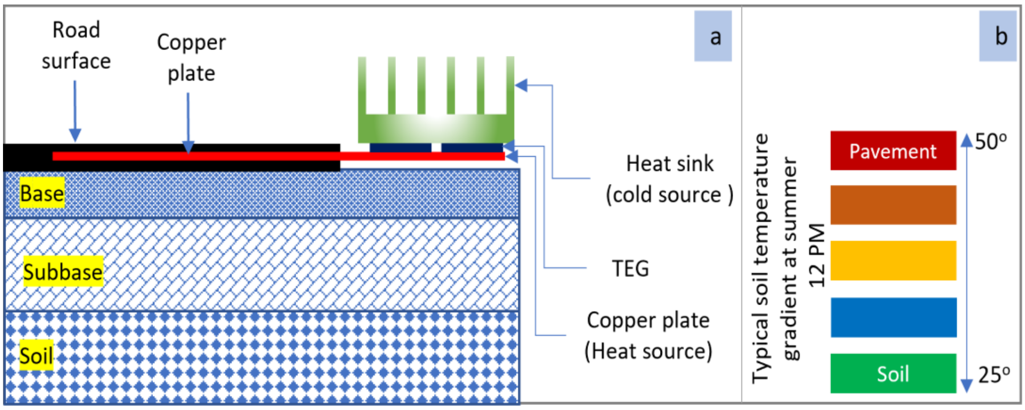

Figure 12. (**a**) Typical thermoelectric energy harvesting system in pavement [86,87] (**b**) temperature distribution in asphalt pavement [88,89] (this drawing was created by the authors).

The heat collector is an essential component that helps collect the thermal energy from the pavement and transfer it to the hot side of the TEG module. Based on the literature, the heat collector can be either solid or fluid (water circulated inside a PSC system, Figure 10a) with the condition that the selected material should have an acceptable thermal conductivity coefficient. The common solid heat collectors that have been used previously are copper [90–97] and aluminum [94,98–103] plates. However, some studies did not employ heat collectors to obtain energy from the pavement; instead, the TEG module's hot end was directly subjected to the heat source [104–107]. Regarding fluid heat collectors, one study has been published in this regard, in which the heat collector was water pumped inside a PSC system embedded underneath the pavement [87]. In terms of system efficiency, it was observed that the TEG systems that utilized solid heat collectors, such as copper or aluminum, produced higher electric voltages when compared with other methods. This was due to the high-temperature gradient that was generated between the hot and cold sides of the TEG modules.

Taking into consideration the thermal behavior of the asphalt pavement, defining the optimal location of the heat conductors is of utmost importance to reach the best performance. It was reported that temperature values differ with asphalt pavement depth as well as over time [86] as shown in Figure 12b. Based on the literature, different heat collector locations were tested; the locations ranged between 0.3 [100] and 7 [79] cm underneath the pavement surface. However, most of the previous studies reported that 2 cm underneath the pavement surface was the optimal location for the heat collector [91,92,95,98,99].

TEG modules are the main part of the TEG system, as they are responsible for converting the temperature gradient into electric voltage, as previously discussed in Section 4.2.1. In previous studies, varying numbers of TEG modules, ranging from 1 [100,105–107] to 19 [79], were studied at different configurations and sizes. Overall, it was observed that increasing the number of TEG modules resulted in increasing the generated electric voltage and vice versa [97,98]. Sharuddin et al. (2020) [92] carried out an experimental study to investigate the electric voltage output of a TEG system employed in asphalt pavement. Three different TEG module configurations were studied, including (i) 4 × 1, (ii) 2 × 2, and (iii) 4 × 1, as shown in Figure 13. Two heat collectors were used in this study, namely copper and aluminum, and three cooling methods were employed, including (i) ambient air, (ii) an aluminum heat sink, and (iii) a water tank. Based on the results, the 4 × 1 TEG configuration produced the highest electric voltage compared with other configurations, as shown in Figure 14b. On the other hand, the system that employed copper plates as heat collectors generated higher electric voltage compared with the system employing aluminum plates as heat collectors, with a voltage difference of 36.9 mV, as shown in Figure 14a. In terms of the cooling method, the water tank showed better performance when compared with other cooling techniques. The results showed that the obtained electric voltages using no cooling and a heat sink were 149 mV and 170 mV, respectively. On the other hand, an electric voltage output of 287 mV was obtained when employing a water tank as a cooling system [92].

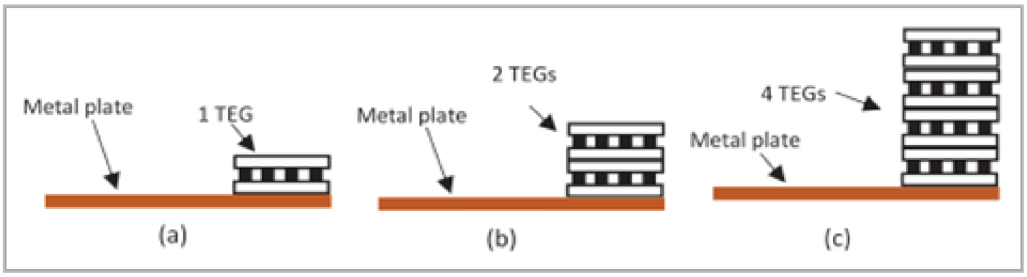

Figure 13. TEG module configurations; (**a**) 4 × 1, (**b**) 2 × 2, (**c**) 1 × 4 [92].

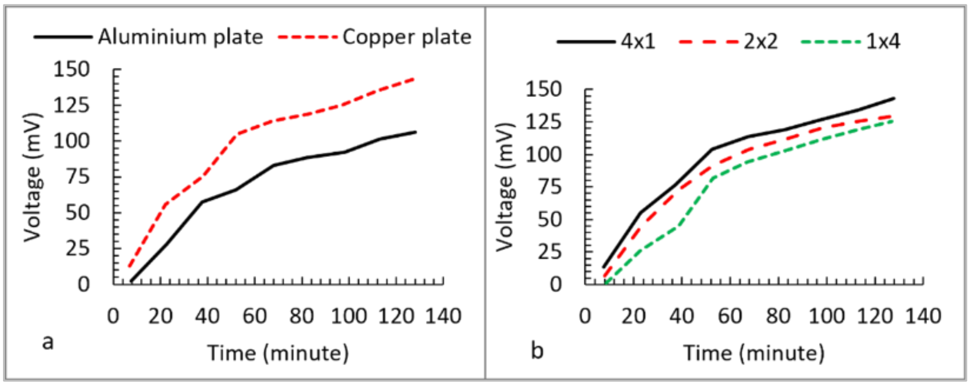

Figure 14. Output voltage vs. time (**a**) different materials, (**b**) different configurations [92].

The heat sinks are responsible for keeping the TEG module's cold side at a low temperature to maximize the temperature difference between the two TEG sides. Based on the literature, a water tank [92,94,102] and an aluminum [92,100,104,108] heat sink are the common methods that are used to keep the TEG cold side at a low temperature. In some cases, both materials were integrated in different combinations, such as an aluminum heat sink filled with water [95,96,98,99] or an aluminum heat sink filled with phase change materials (PCM) [90,91,93,97]. It was found that the integrated heat sinks provided better performance when compared with the pure techniques. A detailed analysis of the previous studies on implementing TEGs on harvesting thermal energy from pavement is introduced in Table 5.

Table 5. Summary of the Previously Published Studies Using the TEG System.

Paper Type	Software	Modeling Method	Heat Collector	PCM	No. of TEGs	Cold Source	Cold Source Insulation	Heat Collector Insulation	Ref.
Experimental + Numerical	ABAQUS	Transient	Copper plate, 0.15 mm thickness	Yes	2	Aluminum heat sink filled with PCM	Yes	No	[90]
Experimental	-	-	TEG hot side (direct contact)	No	Three configurations; (a) single model (1), (b) cascade module on module (2), (c) cascade side by side (2)	Aluminum heat sink	No	No	[104]
Experimental	-	-	Aluminum vapor chamber	No	3 setups; 1 TEGs; 2 TEGs; 3 TEGs	Aluminum heat sink filled with water	Yes	Yes	[98]
Experimental + Numerical	ABAQUS	Transient	L-shape copper plate	Yes	2	Aluminum heat sink filled with PCM	Yes	Yes	[91]
Experimental	-	-	copper and aluminum	No	Three setups; (a) 4 × 1, (b) 2 × 2, (c) 1 × 4	(a) No cooling, (b) aluminum heat sink, (c) water tank	No	Yes	[92]
Experimental	-	-	Aluminum vapor chambers	No	3	Water tank attached to vapor chamber and heat sinks	Yes	No	[99]
Experimental + Numerical	ABAQUS	Transient	Copper plate, 0.15 mm thickness	Yes	2	Aluminum heat sink filled with PCM	Yes	No	[93]
Numerical	COMSOL Multiphysics	Transient	Aluminum plate	No	1	Aluminum plate connected to aluminum rod	Yes	Yes	[100]
Experimental	-	-	TEG hot side (direct contact)	No	1	cooling sink	No	No	[105]
Experimental + Numerical	COMSOL Multiphysics	Transient	Aluminum plate	No	2	Aluminum plate attached to 2 aluminum rods	Yes	No	[101]
Experimental	-	-	Aluminum bars	No	Four TEGs (A, B, C, D); 1 each run	Cold reservoir	Yes	Yes	[102]
Experimental	-	-	Four straight heat pipes	No	8	Aluminum heat sink	No	No	[108]
Experimental	-	-	Copper plate	No	2	Water tank	Yes	No	[94]
Experimental + Numerical	ABAQUS	Steady state	Z-shape copper plate	No	(a) Two of 64 mm × 64mm; (b)Four 40mm × 40mm	Aluminum heat sink filled with water	No	Yes	[95]

Table 5. *Cont.*

Paper Type	Software	Modeling Method	Heat Collector	PCM	No. of TEGs	Cold Source	Cold Source Insulation	Heat Collector Insulation	Ref.
Experimental + Numerical	ABAQUS	Steady state	(a) Copper, (b) Aluminum, (c) and Steel (different shapes)	No	(a) Two of 64 mm× 64 mm; (b)Four 40 mm × 40 mm	Aluminum heat sink filled with water	No	Yes	[96]
Experimental	-	-	Direct sun	No	1	Aluminum plate and rod	Yes	No	[106]
Experimental + Numerical	COMSOL Multiphysics	-	Aluminum plate	No	2	Aluminum plate attached to cooling element cylindrical rod or a flat bar	Yes	No	[103]
Experimental + Numerical	ABAQUS	Steady-state heat	Copper plate	Yes	(a) 1 TEG, (b) 2 TEGs, (c) 3 TEGs, (d) 4 TEGs (one side), (e) 4 TEGs (two TEGs per side)	Aluminum heat sink filled with PCM	Yes	Yes	[97]
Experimental + Numerical	ANSYS/FLOTRAN	-	Water moves in a pipe network	No	19	Cold water passed through a heat exchanger	Yes	Yes	[79]
Experimental	-	-	TEG hot side (direct contact)	No	1	Unbound aggregates	Yes	Yes	[107]

Heat Source	Location of the Heat Collector	The Highest Temperature on the Surface	Temperature Difference °C	Output Power/Voltage	Pavement Type	Field Test	Ref.
Solar radiation simulator	3 cm	55	Design A: 15.1; Design B: 18.3	Design A: 24.95 mWatt; Design B: 27.35 mWatt	Asphalt	No	[90]
Heater	0	TEC-12705 configuration (b): 51.2; TEC-12708 configuration (b): 60.1; APH-127-10-25-S configuration (b): 61.335; TEG1-PB-12611-6.0 configuration (b): 54.3	TEC-12705 configuration (b): 23.6; TEC-12708 configuration (b): 27.6; APH-127-10-25-S configuration (b): 29.8; TEG1-PB-12611-6.0 configuration (b): 19.4	TEC-12705 configuration (b): 1.5; TEC-12708 configuration (b): 1.9; APH-127-10-25-S configuration (b): 2.4; TEG1-PB-12611-6.0 configuration (b): 0.26	No pavement	no	[104]
Iodine–tungsten lamp (lab); Sun (field)	2–3	75.5	30	0.564 v	Asphalt	Yes	[98]
Sun (field)	2–3	62	32.5	34.3 mW	Asphalt	Yes	[91]
Two 100 W bulbs	2	-	9	0.29 v	Asphalt	No	[92]
500 W iodine–tungsten lamp (lab); sun (field)	2	-	34.7	0.74 v	Asphalt	Yes	[99]

Table 5. *Cont.*

Paper Type	Software	Modeling Method	Heat Collector	PCM	No. of TEGs	Cold Source	Cold Source Insulation	Heat Collector Insulation	Ref.
Solar radiation simulator	3	55			Design A: 15.12; Design B: 17, Design C: 19.73, Design D: 18.28	Design A: 24.59; Design B: 27.19, Design C: 30.41, Design D: 27.94	Asphalt	No	[93]
Solar irradiance	0.3	48			11	N/A	Asphalt	NO	[100]
Halogen lamp	0	60			29	0.065 v	Concrete	No	[105]
LED light (lab), Sun (field)	0	61.12			23	0.95 v	Asphalt	Yes	[101]
Hot reservoir	-	-			A: 2.4; B: 16.7; C: 14.2; D: 16.5	A: 1.6; B: 6.9; C: 1.9; D: 1.5 mW	-	No	[102]
LED lamp (lab), sun (field)	NA	84.6			49.3	11.9 v	Asphalt	Yes	[108]
100 W incandescent light bulb (lab), sun (field)	-	-			-	DC1577A with MPPT: 4.2 mW; ECT310 without MPPT: 0.7 mW	Asphalt	Yes	[94]
Heated water tub	2	52.3			7.6	(a) 8 mW, (b) 11 mW	Asphalt	Yes	[95]
Heated water tub	2	52.3			7.6	14.3 mW	Asphalt	Yes	[96]
Filament lamp	0 (Asphalt pavement surface)	70			20	0.5 v; 300mW	Asphalt	No	[106]
Halogen lamp (lab); Sun (field)	0 (Asphalt pavement surface)	61.45			8.99	0.35 v	Asphalt	Yes	[103]
Solar simulator	2	65			47	47.14 mW	Asphalt	No	[97]
Hot water heated by gas boiler	7	60			35	3.6 W	Asphalt	No	[79]
Full spectrum lamp	5	61			15	63 mW/m2 (Asphalt); 39 mW/m^2 (concrete)	(a) Asphalt, (b) concrete	No	[107]

The potentials of the TEG system in harvesting pavement thermal energy are high when compared with other existing systems. Based on the literature, it was observed that the harvested electric voltage from the TEG system can be used to operate sensors or LED lights. Furthermore, the TEG system is an independent system which does not require any external source of energy to operate it, which makes it a more preferable system. Besides its advantages in producing clean and renewable energy, the TEG system increases the lifetime of the pavement by minimizing heat-related diseases and reducing pavement surface temperature. However, generating a high-temperature gradient between both sides of the thermoelectric generator module remains one of the main challenges inhibiting the wide usage of this system.

4.3. Pyroelectric Materials System

Basically, pyroelectric materials convert electromagnetic radiation energy, such as infrared, ultraviolet, microwave, X-ray, and terahertz into electric voltage [109]. Therefore, heating or cooling certain pyroelectric materials can help to produce a temporary voltage [110,111] making these materials a potential source renewable energy [112,113]. Pyroelectric materials can be utilized to harvest energy from different sources, such as solar energy harvesting [113,114], mechanical energy harvesting [115–117], magnetic energy harvesting [118–120], and thermal energy harvesting [121–123]. To date, several studies have been conducted to investigate the ability of pyroelectric materials in harvesting energy [124–126], while few studies have been published regarding pyroelectric material energy harvesting systems from pavements [18]. Xie et al. (2010) [127] investigated the feasibility of different pyroelectric materials, including PMN-PT, PZT, and PVDF to generate electric power experimentally. The implemented method was to generate electricity by rapidly increasing the temperature from 45 °C to 140 °C at 10 s. Based on the obtained results, it was found that PZT pyroelectric material produced the highest power value, with a total magnitude of 0.23 $\mu W/cm^2$. Batra et al. (2011) [128] simulated the availability of harvesting pavement thermal energy using pyroelectricity. It was found that using pyroelectric materials a potential technique to harvest electrical energy from pavements to power autonomous low-duty electric devices. Additionally, it was noted that triglycine selenate (TGSe) is an attractive candidate for energy harvesting from pavement when compared with other tested materials; this was attributable to the fact that it had a greater pyroelectric coefficient near ambient temperatures. Tao and Hu (2016) [129] conducted an experimental and analytical study to investigate the potentials of using hybrid piezo–pyroelectric effects to harvest energy from pavement. It was found that pure piezoelectric and pure pyroelectric effects generated around 68 mV and 8.7 mV electric voltage, respectively. Furthermore, under the same temperature profile, it was noticed that the algebraic sum of the individual effects of the piezoelectric and pyroelectric methods is equivalent to the hybrid effect. Moreover, different ferroelectric materials were compared in terms of different aspects, including energy harvesting capacity. Finally, PVDF-TrFE/CNT nanocomposites were recommended as a good material to be utilized in harvesting both thermal and mechanical energy from pavement [129].

In general, all of the thermal energy harvesting technologies that have been discussed in this study showed the ability to generate enough power to operate the needed instruments, such as sensors, cameras, and pavement health detection devices that may be installed along the roadways. However, solid-state thermoelectric generator systems (TEGs) showed the best performance in terms of electric voltage outputs when compared with other technologies. Moreover, TEGs are independent systems that do not require any external power to the operate system. On the other hand, the TEG's solid-state system has some limitations, such as it cannot be used as a de-icing system during winter seasons, and it requires frequent maintenance because its heat collector is embedded at about 2 cm from the pavement surface. The path solar collector system (PSC) has the advantage of being used in summer and winter. In summer, PSCs can be utilized to store the heat or generate electricity through a heat exchanger or TEG module, while in the winter, hot water can be pumped through the pipe system to melt the snow and ice. However, in some conditions, PSCs need an external power source to run the pump that is used to circulate the fluid inside the pipes. This disadvantage puts restrictions on implementing PSCs in pavement in remote areas. Integrating systems (PSC–TEGs) may help to overcome this issue because the TEG can provide the required energy to run the pump. The efficiency and electric voltage output of a pure pyroelectric material system is low and insufficient. Thus, the pyroelectric material system is usually integrated with the piezoelectric system for better performance. Finally, all the discussed technologies have promising advantages for the environment, such as providing new renewable energy sources, decreasing fossil fuel uses, reducing heat island effects, and reducing greenhouse gas emissions.

5. Future Directions

Based on the literature, some recommendations for future studies are proposed as follows:

- The output electric voltage is one of the most essential parameters that can be used to judge any developed technology. Therefore, increasing the power output is of the utmost importance. TEGs' power generating efficiency can be enhanced by increasing the temperature gradient between the hot and cold sides. Thus, heat collector plates should be insulated, and different designs and materials of heat collectors should be investigated. On the other hand, PCM should be employed to increase the heat sink's efficiency, which can help to provide a low temperature to the TEG's cold side. Further, future studies should focus more on studying the effects of increasing the number of TEG modules under different configurations.
- More studies on the PSC system should be conducted to enhance its efficiency. This can be achieved by investigating different fluids to be circulated in the pipe system since only water and air were investigated. Furthermore, insulation systems have not been employed yet to prevent heat leakage during the fluid circulating process.
- Integrated systems should be investigated more, especially those involvging PSC and TEG systems. TEG systems have some limitations in the winter season, such as that it cannot be used as a de-icing system; on the other hand, the PSC system required external power to operate the pump. Thus, integrating these systems may help to increase efficiency.
- Long-term investigations of the effects, efficiency, and maintenance requirements of these technologies are needed to ensure that these systems are sustainable, workable, and commercialized.
- Pavement durability and performance should be investigated after implementing these harvesting technologies under real traffic loads to evaluate the stress concentrations among the pavement components.
- Most of the previous studies focused solely on implementing thermal harvesting technologies from asphalt pavement, while studies regarding concrete pavement are limited and insufficient. Thus, we recommend the study of the potential of harvesting thermal energy from concrete pavement.
- The thermal conductivity of both concrete and asphalt pavement should be enhanced by modifying the mixture content by adding specific materials which have the ability to increase the pavement's thermal properties.

6. Summary and Conclusions

In this study, the existing technologies that have been utilized to harvest pavement thermal energy were explored and highlighted. To achieve the study objectives, a systematic review and bibliometric analysis were performed to analyze the previously published studies from the year 2006 through August 2021. Based on the designed keywords, a total of 713 publications were collected from WoS, Scopus, and ScienceDirect; among the total collected articles, only 47 publications were considered after several filtration stages. Based on the literature, three common technologies were recognized, namely the path solar collector system (PSC), the thermoelectric generator system (TEG), and the pyroelectric materials system. Among these three methods, the TEG system was found to be the most frequently used technology, with a percentage value of 66.7%, while the PSC system scored second with a percentage value of 22.2%. The pyroelectric materials system scored third, with a percentage value of 5.4%. Furthermore, it was noted that TEG and PSC systems could be integrated and used in one system; however, the studies in this regard are not sufficient. Two main objectives were recognized as being behind the huge growth in pavement thermal energy harvesting studies in the recent years, including (i) helping the environment by reducing heat island effects, developing new renewable energy sources, and decreasing fossil fuel usage, and (ii) producing electric energy to support the essential sensors and devices that should be placed along roadways for smart pavement. Overall, it was noted that the existing techniques may achieve these objectives. It was observed that implementing thermal energy harvesting technologies on pavement helped to decrease the surface temperature by an average value of 10 °C. On the other hand, it was noted that all techniques generate sufficient electric voltage to operate sensors, LED lights, and microprocessors that can be installed along the highways. The promising uses and advantages of harvesting roadway pavement thermal energy have encouraged the research community, commercial entities, and governments to deeply investigate all feasible means of this technology. From an economic perspective, the capital cost of these technologies is not high when compared with other alternatives; however, evaluating the economic efficiency of these technologies is needed to ensure that wider distribution will reduce their unit cost, especially once these techniques are implemented on a wider scale. However, this study has some limitations, including considering only thermal energy harvesting technologies from pavements, not railways and pedestrians, focusing on publications within three databases (WoS, Scopus, and ScienceDirect), and considering the period between 2006 and August 2021.

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