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PIEZOELECTRIC AS AN ALTERNATIVE ENERGY SOURCE FOR SMART CITIES: AN EXPLORATORY APPROACH

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Abstract: Electricity is fundamental for the development of cities, but at the same time, it represents one of the biggest costs. In this scenario of intense use of electric energy, whose supply can be one of the biggest bottlenecks for industries, piezoelectric emerges as an alternative for energy generation and creation of autonomous systems in different spaces, such as highways, sidewalks, parks, and other public spaces, enabling the implementation of the guidelines of a smart city. The objective of this work is to explore the characteristics of this energy source. Therefore, a systematic literature review was carried out using the Methodi Ordinatio methodology. The results show that piezoelectric materials contribute to urban improvement, sustainability, real-time monitoring, health areas, population comfort, urban mobility, and numerous other areas that can help make a city smarter.

Keywords: Piezoelectric. Power generation. Sustainability. Smart Cities.

1 Introduction

For hundreds of years, there have been records of cities built to provide comfort and mobility for the population. As time passes, technology advances, and people's lifestyle changes; new points are considered in this planning. Thus, in the 21st century, more emphasis was placed on the concept of Smart City that emerged in mid-1991 and can be defined as a geographic location managed by people in a centralized way, supplied with natural and technological resources to provide quality of life to its residents and gradually reducing the negative impacts with high efficiency (Pagani, Soares, da Luz, Zammar & Kovaleski, 2019).

This concept is broadly connected with the seventh Sustainable Development Objective (SDG), which deals with ensuring access to sustainable energy at an affordable price, and with the ninth SDG which refers to promoting industry and fostering innovation (UN, 2019). Several alternative energy

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sources are studied and implemented in numerous areas, exploring the potentials of each location, and seeking to fit into the two SDGs mentioned.

In this context, the piezoelectric that until then had its use limited to sensors, microphones, and semiconductors, started to receive more attention in the early 2000, when they started to carry out more studies to convert the energy of vibrations into electrical energy (Anton & Sodano, 2007). From 2007, the piezoelectric gained more strength with the studies of Zhong Lin Wang (Zhu et al., 2017). This type of material was discovered by the French physicists Pierre and Jacques Currie in 1880 (Hannan et al., 2014). A piezoelectric is a material that can convert the mechanical stress, applied to it, into electrical energy (Wang, Jasim & Chen, 2018).

Piezoelectric can have different arrangements, shapes, and even be made of different materials, depending on their purpose, and can also present different levels of energy generation (Anton & Sodano, 2007). Piezoelectric materials can be found in different forms, such as ZnS, NaClO3, Lead Zirconate Titanate (PZT), and Polyvinylidene fluoride (PVDF).

Due to the characteristic of accumulation of electric charge generated by mechanical stress, piezoelectrics become an alternative for energy generation, currently, the literature points out that its main use is for small scale generation, also called microgeneration, that is, to feed sensors, LEDs and the like (Ibn-Mohammed et al., 2016). The search for energy efficiency encourages the study of different ways of obtaining clean and sustainable energy. With this premise, the purpose of this work is to explore what is in the literature and be able to answer the following question: How can studies on piezoelectric materials serve as an energy alternative in a Smart City? In addition to its general objective, this research seeks specifically:

- Research means of energy harvesting with an emphasis on piezoelectricity.
- Collect data on publications about piezoelectric and smart cities.
- Correlate the use of piezoelectrics for purposes that meet the requirements of a smart city.

The growth of research on the subject shows that there is still a lot to discover and research within such subjects, making its importance for the academic environment clear, since this work serves as a reliable reference bank, made through the review of systematic literature following Methodi Ordinatio, therefore, it is stated that the articles used are relevant. Equitably, this work also has an impact on society, bringing to the discussion a topic still little known in Brazil, showing alternatives that can meet needs, generate comfort, and even savings.

2 Theoretical Background

This section presents the theoretical foundations and concepts presented in this study, structured in two subsections: Piezoelectric in smart cities and Possible piezoelectric applications for Smart Cities.

2.1 Piezoelectric in smart cities

A Smart City needs to reconcile the use of technology to provide an efficient urban perimeter, bringing well-being and convenience to its population in a sustainable manner, besides must seek to reduce distances, create integrated systems, promote a sustainable economy, guarantee access to leisure among countless other factors (Macke, Sarate & de Atayde Moschen, 2019; Calvillo, Sánchez-Miralles & Villar, 2016). The characteristics and definitions of smart city are broadly linked with the Triple Bottom Line (TBL) concepts, directly attending to environmental, social, and economic factors, since studies show a strong correlation involving these themes and a growing number of researches involving the terms: economy, urban management and technology and innovation (Franco et al., 2021).

In the case of a Smart City, it is relevant to address topics such as the Internet of Things (IoT), Smart Homes, sensors, and controllers almost everywhere. The advantage of IoT is to make the integration and connection between things fast and wireless, allowing communication and monitoring improvements mainly (Alvi et al., 2015). About remote management, the person can have real-time control of their expenses (electricity, water, and gas), in addition to sensors in several places in the house to guarantee energy savings and practicality (Chan et al., 2008).

The Internet of Things could also provide smart parking. Sensors with 5G technology would easily be able to show free parking spaces around the city, taking the time needed to find a space to be reduced, improving traffic and urban mobility (Al-Turjman & Malekloo, 2019). In this theme, for small sensors, the piezoelectric can dispense with the use of batteries, for other cases, it can make the battery's autonomy become much longer, thus, making the use of wireless technologies possible (Anton & Sodano, 2007).

Sustainability is a very relevant topic when it comes to a Smart City. The complexity of replacing fossil fuel challenges researchers to explore new methods of energy generation that are renewable, sustainable and green (Lee et al., 2016), which is conceptualized as an alternative and sustainable source at the same time, being one that has zero or minimal environmental impact and comes from renewable sources (Midilli, Dincer & Ay, 2006)

Currently, it is not only the generation of sustainable energy that is in focus, but the debate still covers hybrid methods of harvesting, starting to pay more attention to terms such as cogeneration and energy recycling (Wang et al., 2018). Energy recycling is an expression used in terms of efficiency and losses. In this scenario, we seek to take advantage of the energy dissipated in one generation method through another method. It is important to note that, like the concept of regular recycling, firstly, it seeks to reduce consumption, as well as its reuse (Glavič & Lukman, 2007).

In addition to technological and innovative solutions, a smart city depends essentially on the human factor. It is necessary to acquire a sense of community and be less technocentric, after all, a Smart City is only made possible through the active participation of the population in political, scientific, and cultural debates (Macke et al., 2019). A systematic literature review, combining the concepts of Smart City with the Sustainable Development Goals proposed by the UN (2015) demonstrates both have the objective of the well-being of the planet and people (UN, 2020; Pagani et al., 2019).

2.2 Possible piezoelectric applications for Smart Cities

In terms of the benefits of using piezoelectric, we can emphasize the reduction of visual and noise pollution compared to other methods of power generation. While a wind generator changes the landscape around it and generates a high level of noise, the piezoelectric can be used in pavements, sidewalks, poles, and other places without generating noise and even without modifying too much the visual landscape around you (Wang et al., 2018).

In Seoul, South Korea, a system for power harvesting of people's movement using piezoelectric blocks similar to the common blocks has been used. These blocks have several layers of piezoelectric, thus being able to optimize the harvest of vibration generated by the movement, serving to power LEDs and even the traffic light, the work these researchers still considers the real conditions of daily life, such as climate, temperature, a mass difference of pedestrians, in addition to other factors. Another benefit is that since the blocks are the same dimensions as the most common blocks in Seoul, the cost for the replacement and implementation of the piezoelectric system would be lower (Song et al., 2019).

Piezoelectric can also be used for power harvesting through its use on streets, highways, and roads, where there is considerable vehicle traffic. Thus, the force exerted by the movement of the cars on the road is capable of generating electrical energy. Since the road network of several countries is extremely extensive, it is interesting to think that it is possible to take advantage of part of this space for the generation of sustainable energy (Zhao, Xiang & Shi, 2020).

Several studies are proposing piezoelectric formats and ordering on traffic routes. Cao et al. (2018) shows that 100m of pavement with a piezoelectric transducer can produce up to 963.99 J of energy in a day with normal average traffic, which is enough to charge the battery of approximately 35 cell phones.

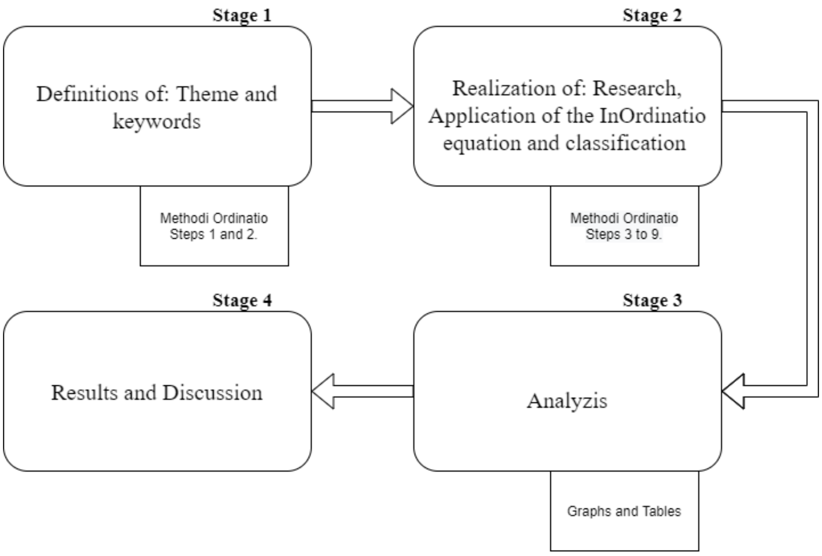
That material can be used to attach to the knee of human beings, allowing them to harvest the energy from the person's movement when walking. It is important to point out that, for applications related to the human body, piezoelectrics synthesized from flexible polymers and even nanotechnology is normally used, with their use intended for small energy demands and normally for health purposes (Kuang et al., 2017).

3 Materials and Methods

There are several methodologies for systematic literature review, since the 1970s, authors have been publishing their methodologies, each one meeting certain demands (Pagani, Kovaleski & de Resende, 2017). This work was done following the Methodi Ordinatio, uma revisão sistemática de literatura que leva em consideração o ano de publicação, número de citações e fator de impacto das revistas das obras. As etapas da metodologia de pesquisa são descritas na Figura 1.

Figure 1

Methodology steps



Source: Pagani et al. (2017).

Figure 1 divides the methodology into four stages with different activities, in addition to describing them in detail according to their sequence. In addition to the procedures following Methodi Ordinatio, the following activities were also carried out:

- The content of the articles was analyzed.
- Relevant information was gathered for the elaboration of graphs and tables.

- The information available in the databases was analyzed with the search for keywords.
- There was a discussion and clarification of the facts.

The research was based on the following four steps:

a) The theme and keywords were defined. The combinations used with each combination is specified in Table 1.

Table 1

Keyword Combinations for Analysis

Combination number	Combinations
1	*"piezoelectric*" AND "smart cities"*
2	*"piezoelectric*" AND "park*"*
3	*"piezoelectric*" AND sustainability*
4	“piezoelectric*” *AND “solar energy”*
5	"*piezoelectric**" *AND* "*green energy”*

Source: Elaborated by the authors (2021).

b) Articles were collected in Scopus and Web of Science databases, devido à padronização de resultados e a riqueza de materiais na área de engenharia. Posteriormente aplicou-se um processo de filtragem removendo duplicatas, eliminando livros e conferências e filtragem pelo título e abstract não correlatos. Em seguida foi aplicada a equação In Ordinatio para classificação do portfolio (Pagani, Kovaleski & de Resende, 2017). Por fim limitou-se aos 50 artigos com a classificação mais alta

c) Bibliometric analysis of the portfolio articles and content analysis was performed.

d) Graphs were prepared and results discussed.

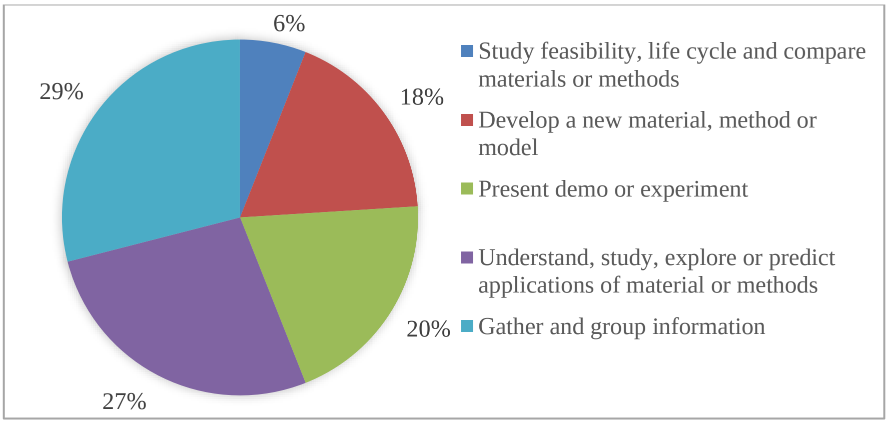
4 Results

This section will show the treatment of the results obtained by analyzing the content of the articles and grouping the important information. For this stage, it was restricted to the first 50 articles of the Methodi Ordinatio ranking and it was possible to generate graphs showing: the most present institutions, the objectives of the articles, the methodologies, the materials, and the problems and solutions found.

The first important information taken from the content of the articles is about the institutions present in these studies. Researchers linked to numerous institutions produce scientific articles on piezoelectric, smart cities, the internet of things, power generation, and related areas. The Georgia Institute of Technology (Georgia Institute of Technology, in free translation) leads among the institutions with publications about piezoelectrics, being present in 10 of the 50 articles taken into consideration. The other institutions, which had no recurrence in more than one article, add up to 22 publications. Another piece of information of great significance is related to the objectives of these works. It is possible to group them into 5 larger groups according to the similarities in their objectives and subjects covered, as shown in Figure 2.

Figure 2

Main objectives of the articles



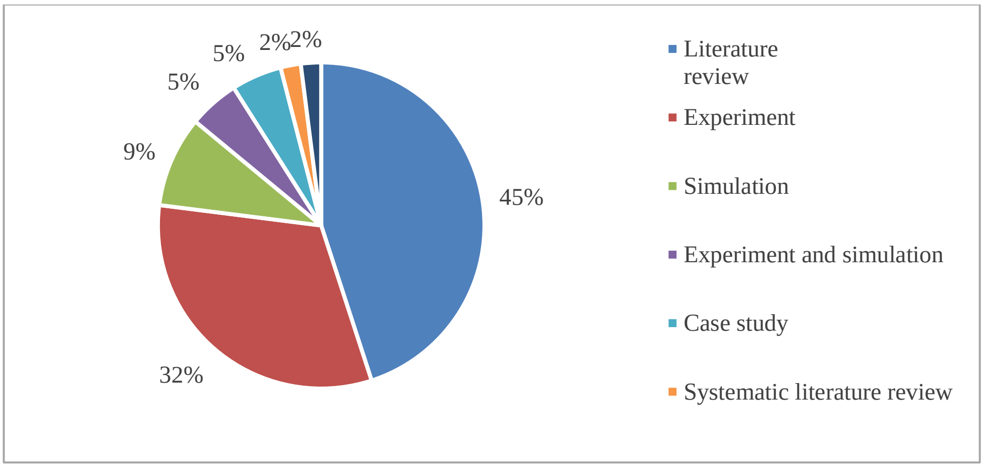
Source: Elaborated by the authors (2021).

Most of the selected articles (29%) have their objectives related to gathering and grouping information about piezoelectric materials, energy harvest, and smart cities, while only 6% aim to study the feasibility, life cycle, or compare materials or methods.

In addition to the information already analyzed above, another important aspect taken from the articles is the methodology employed, whether they are literature reviews (simple or systematic), experiments, simulations, case studies, or combinations between these methods.

Figure 3

Main methodologies used in the construction of the studies



Source: Elaborated by the authors (2021).

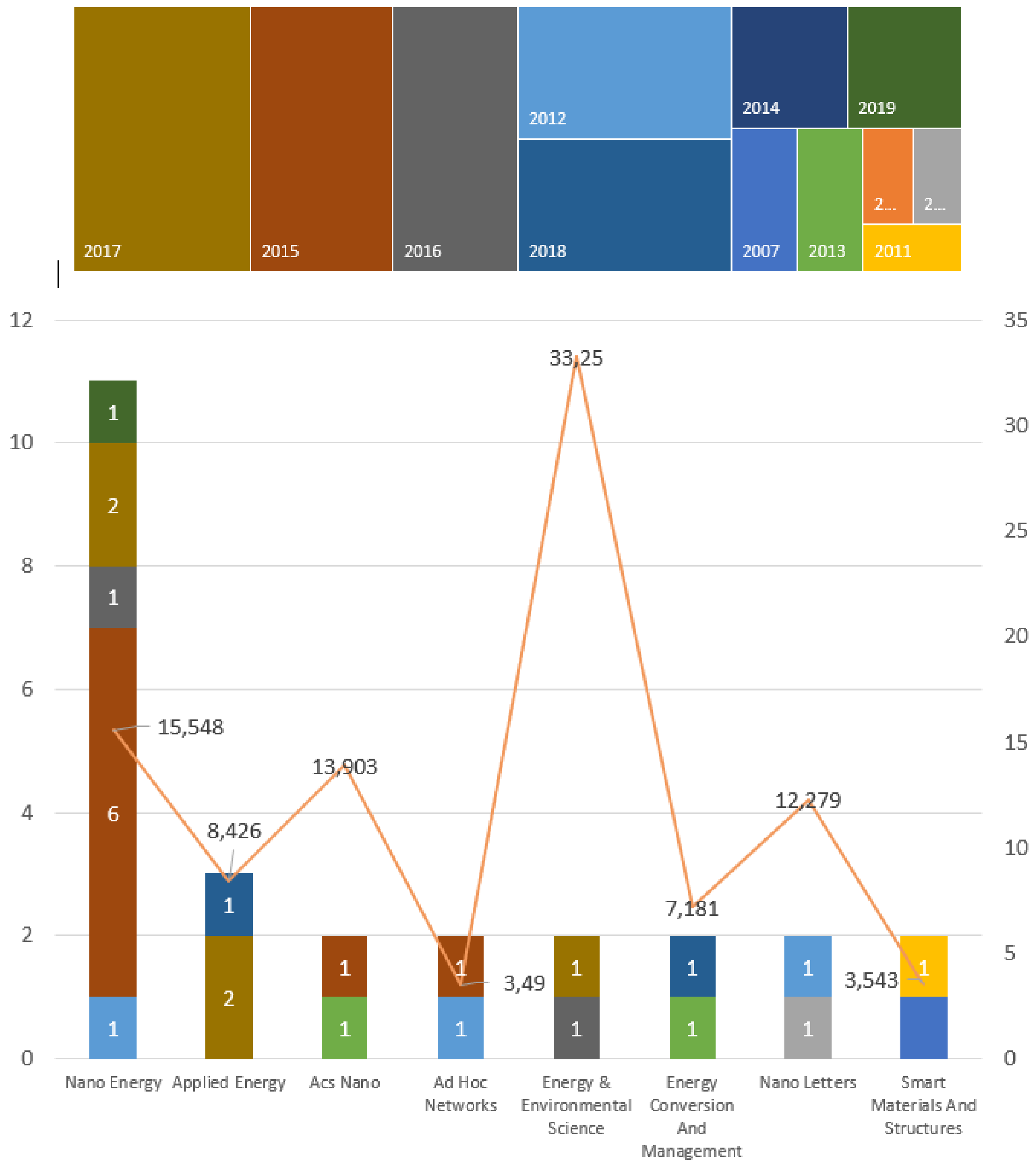
Figure 3 shows that most articles are simple literature reviews and only one occurrence of systematic literature review. Experiments are also very present, on two occasions it is accompanied by simulation. Experiments and simulations are also present, sometimes occurring both in the same article, although in only 5% of the articles. Case studies, on the other hand, are a minority, showing that little is exemplified on the subject.

As a multidisciplinary area, research on piezoelectric or smart cities can cover several Knowledge areas. As expected, due to the theme of this article, the largest number of publications is related to engineering. Also, there is a high number in Materials Science, due to studies related to the properties of the piezoelectric, its structure, and production. Not least, it is worth noting that despite a small percentage, results were obtained in the areas of Biomedicine, Chemistry, and Administration, showing the versatility of relations with piezoelectric.

The journals with the most articles were Nano Energy with 11 publications and Applied Energy with 3 articles. The most prestigious was Energy & Environmental Science, which has an Impact Factor of 33.25. Figure 4 presents a graph of the number of publications per year and the Impact Factor of journals that had more than two articles considered in this study, also shows the number of articles per year.

Figure 4

Number of articles per year and journal and Impact factor



Source: Elaborated by the authors (2021).

There are countless types of piezoelectric, some articles deal with a specific material, others of more than one type, addressing piezoelectric in general, there are also those that deal with other themes and materials.

Table 2

Comparison between piezoelectric types

Material Type	PZT	PVDF	ZnO
Description	Lead zirconate titanate is a ceramic piezoelectric, ideal for power harvesting	Vinylidene fluoride is a flexible piezoelectric polymer	Typically used in nanorods, nanowires, and semiconductor films
Advantages	Greater capacity to harvest energy	Flexible and versatile	Semiconductor properties
Disadvantages	The most probability to break	Less capacity energy harvest compared to PZT	Less capacity energy harvest compared to PZT
References	Anton & Sodano (2007), Wang et al. (2018)	Anton & Sodano (2007), Wang et al. (2018)	(Lee, Gupta & Kim, 2015).

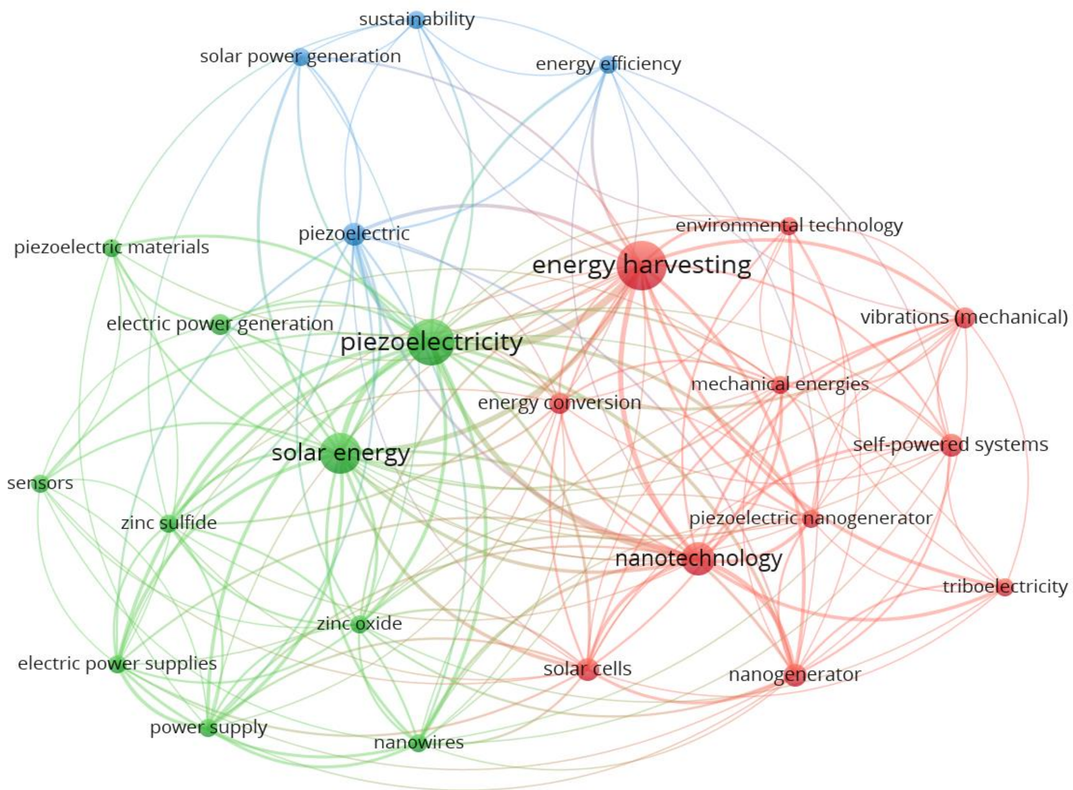
Source: Elaborated by the authors (2021).

Table 2 shows a comparison between the main types of piezoelectric shown in the portfolio of selected works, providing a brief description of their use, advantages, and disadvantages.

Keywords with four or more occurrences were considered for the creation of the keyword network, which resulted in three clusters. Figure 5 shows the keyword co-occurrence networks for the 50 articles.

Figure 5

Keywords Network



Source: Elaborated by the authors (2021).

The most frequent keywords were energy harvesting (22), piezoelectricity (20), solar energy (16), and nanogenerator (11).

5 Discussion

In the first decade of the 21st century, publications were more focused on energy harvesting with piezoelectric materials, as the years went by, themes began to emerge involving energy harvest methods using nanotechnology and hybrid methods. Until mid-2015, publications deal with piezoelectric materials with small-scale use, such as sensors, most of the time, but towards the end of the decade, more works are already being done dealing with macro-scale energy harvest.

The advancement of technology has enabled the exploration of these areas of study so that in more than one article it is clear that nanotechnology and hybridization of methods optimize energy harvest.

The largest and most significant publications occur in the United States of America, followed by China and South Korea. Real examples and applications in South Korea.

Still, on the publications, it is shown that most of the works talk about various types of piezoelectric during the study, this is because most of the articles are literature reviews, because of that they group and gather diverse information about various types of materials, draw comparisons and specify their use. This also justifies the few cases of examples showing use in real locations.

The piezoelectric study is a promising area. Even though there are sometimes reports that its efficiency is low when it comes to energy generation, the literature shows that the combination of different forms of harvesting and generation in a single hybrid device can alleviate or even solve this problem (Lee et al., 2015). The direct relationship between piezoelectric materials and smart cities is seen in only a few articles. But reviews on specific smart energy use, charge, and supply are common (Liang et al., 2020).

Estudos propõe diferentes formatos e aplicações de materiais piezoelétricos, desde monitoramento de estradas, captação de energia em rodovias por passagem de veículos dentre inumeras outras (Cao et al., 2021). Em termos de benefícios do uso do piezoelétrico, pode-se enfatizar a diminuição da poluição visual e sonora em comparação a outros métodos de geração de energia. Enquanto um gerador eólico altera a paisagem à sua volta e gera um nível elevado de ruído, o piezoelétrico pode ser empregado em pavimentos, calçadas, hastes e outros lugares sem gerar ruídos e até mesmo sem modificar demasiadamente a paisagem visual em sua volta (Wang et al., 2018)

But understanding the definition of a smart city and its guidelines and comparing them with the proposal and use of piezoelectric materials, the relationship between these two themes becomes clear. Even though most authors do not specifically mention smart cities for the use of piezoelectric, Table 3 exemplifies this correlation.

Table 3

Correlation between guidelines of a smart city with Piezoelectric applications

Smart City Guidelines	Piezoelectric application
Sustainability	It is not a fossil fuel (Ahmed, 2017). Clean Energy (Orrego et al., 2017). Reuse of energy (Ahmed, 2019).
Comfort to the population	Reducing or not using batteries (Chen et al., 2017), (Lee et al., 2015). Monitoring sensors (Ahmed, 2016).
Urbanism	Reduction of visual and noise pollution (Wang et al., 2018). Optimizing the use of public spaces and buildings (Chen, 2019).
Health	Greater integration and monitoring (Alavi et al., 2018). Prostheses (Hannan et, al., 2014).
Economic and energy factors	Optimization of energy harvesting (Lee et al., 2016).

Source: Elaborated by the authors (2021).

É válido apontar that piezoelectric alone, as the main and independent source of energy, proves to be a very expensive option and with a low capacity for producing electricity in comparison with other methods, such as photovoltaic panels (Wang et al., 2018). This is one of the reasons why it is common to see it combined with a flexible photovoltaic panel, supercapacitor, or another simultaneous energy conversion system (Adendorff et al., 2015).

The main advantage of using piezoelectric materials is the possibility of easy combination with other means of power harvesting and generation, making the system hybrid and optimizing the use of energy. This procedure reduces costs and provides less demand for the use of batteries, ensuring sustainability (Lee et al., 2015).

6 Conclusions

Energia solar e eólica normalmente são a primeira opção em termos de debate sobre energia limpa e sustentável. This work shows that there are more ways to harvest and generate green energy, in addition to expanding the horizons of the use of piezoelectric materials.

Through the analysis of the systematic review, it was possible to correlate the use of piezoelectric materials with the definitions and requirements of a smart city, showing that they can be used to provide wireless and battery-free (self-powered) technologies, in addition to serving to incorporate technologies of capturing hybrid energy, combined with thermal, wind or photovoltaic methods, optimizing energy harvesting.

Therefore, these materials contribute to urbanism, sustainability, real-time monitoring, in health areas, with the comfort of the population, with urban mobility, and in countless other areas that help make a city smarter.

Observado a análise of keywords in the databases and the content of publications, we see that it is a multidisciplinary theme and that emerging countries are standing out in this area of research. However, Brazil does not have major contributions to this topic, and it is a challenge for Brazilian researchers to gain space in magazines with a high impact factor.

For future work, economic feasibility studies are suggested, analyzing the costs of implementing piezoelectric materials, generation capacity, and return on investment time. Hybrid Harvesters models were very present among the analyzed articles, so a hybrid model could also be compared with a simple one to detail the gains about each other.

In addition to the economic aspect, it is also suggested the analysis of the life cycle and environmental trace of these materials, to prove if it can be considered a model of green and sustainable energy, showing its advantages and disadvantages, and comparing them with other methods of generation and obtaining energy. And not least, analyze the social aspects and impacts and how they could influence people's lifestyles.

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