Nano Energy 83 (2021) 105844

Contents lists available at ScienceDirect

Nano Energy

journal homepage: http://www.elsevier.com/locate/nanoen

Review

Towards smart cities powered by nanogenerators: Bibliometric and machine learning–based analysis

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ARTICLE INFO

Keywords:
Nanogenerators
Output performance
Bibliometric analysis
Machine learning
Principle component analysis
Environmental impacts

ABSTRACT

Nanogenerators have attracted particular attention during the last decade. A nanogenerator harness mechanical or thermal energy to produce electricity without any need for battery. In this paper, general descriptions of different types of nanogenerators, including piezoelectric, triboelectric, and pyroelectric, are presented. Next, bibliometric analysis and unsupervised machine learning–based analysis (principle component analysis) are carried out to determine the trends in this field of science. The current developments and directions for technology commercialization are briefly discussed. Additionally, the output performance and environmental consequences of active materials used in nanogenerators are analyzed by principle component analysis. The analysis reveals China's sensible investment in the nanogenerator field during the last five years. The number of articles published by Chinese scholars is over 1000 during 2015–2020 with a considerable distance from the USA. It is also deduced that European countries need to pay more attention to this field if they want to compete with the USA, China, and South Korea. Overall, due to the huge amount of waste thermal energy worldwide, more efforts and resources have to be focused and invested in developing pyroelectric nanogenerators. Moreover, there is a need to find low-cost materials having a favorable environmental profile to fabricate nanogenerators.

1. Introduction

The history of sensor dates back to 770–476 BCE in China, where a time observing device (sundial) was used. Then in 475–221 BCE, the direction indicating device (Sinan- a south-pointing ladle) was invented, which is considered as one of the noble inventions of China [1]. The primary concern with sensor technology is the power supply problem when used in real-world applications. The concept of self-powered sensors/systems based on "Nanogenerators" was coined by Wang and Song in 2006 [2]. A nanogenerator is a small electronic chip that uses Maxwell's displacement current as the driving force for converting mechanical energy available in the environment into electrical energy.

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https://doi.org/10.1016/j.nanoen.2021.105844
Received 18 December 2020; Received in revised form 28 January 2021; Accepted 29 January 2021
Available online 30 January 2021

The invention of nanogenerators was a revolution in self-powered nanotechnology. This discovery was indeed the starting point of the nano energy field and a novel solution to provide the required power for implantable biomedical devices, robots, wireless sensors, portable electronics, sensing systems of smart vehicles, intelligent transportation and so on without a need for batteries [2–6]. Fig. 1 depicts a schematic of the smart city in which daily life equipment and devices are empowered by nanogenerators, a dream that is achievable but needs much more financial support by the government and more scientific endeavors. Analysis of recent pre-granted publications by the United States patent and trademark office in the field of nano communication devices powered by nanogenerators reveals that devices, methods, and systems are being developed for medical applications including cancer immunotherapy [7], head injury detection [8] and preventing fertilization of an egg using the one or more nano-nodes [9]. Wang's group at Georgia Institute of Technology introduced and developed various nanogenerators that operate mainly based on three famous physical effects, including piezoelectric, triboelectric, and pyroelectric [10]. Here, a general description of each type of nanogenerator is presented.

1.1. Different types of nanogenerators

1.1.1. Piezoelectric nanogenerator

The first generation of nanogenerators worked based on the piezoelectric effect of ZnO nanowire arrays. In this type of nanogenerators, mechanical energy is converted to electrical energy by creating a strain field across nanowire arrays. The reason behind selecting ZnO nanomaterials to produce nanogenerators is their individual ability to act as an electromechanical element with semiconducting and piezoelectric properties [2]. In 2006, Wang and Song [2] introduced piezoelectric-based nanogenerators as the mechanical energy source to create direct-current electricity. The fundamental unit of this piezoelectric-nanogenerator is a ZnO nanowire. Fig. 2 illustrates a schematic diagram of the ZnO nanowire-based piezoelectric nanogenerator. It was revealed that ZnO-aligned nanowires could result in energy conversion efficiency up to 30%.

In recent years, the performance of piezoelectric-based nanogenerators has been modified through innovative integrations [11–13], and implementing advanced materials like molybdenum disulfide [14], cadmium sulfide and telluride [15,16], and gallium nitride [17]. Besides, the piezoelectric-based nanogenerators have been successfully implemented in energy harvesting [18], transport monitoring [19], and sensing applications [20,21].

1.1.2. Triboelectric nanogenerator

In 2012, Fan et al. [22] demonstrated that the friction between two or more different materials (for example, polymer-based materials) is not always damaging and destructive. However, if this effect called "triboelectric" is harnessed elaborately, it can produce electricity for wireless equipment through an inexpensive process. Fig. 3 illustrates the typical construction of a triboelectric nanogenerator. The nanogenerator has been made by inserting two polymer sheets with different materials (Kapton and polyester) on each other by keeping a small gap between them. The electricity can be generated by the deformation of the nanogenerator, as shown in Fig. 3.

Similar to piezoelectric nanogenerators, triboelectric nanogenerators are used in a wide variety of applications. However, the quantitative comparison of the output performance of these two nanogenerators reveals that the output performance of triboelectric nanogenerator is high compared to piezoelectric nanogenerators, and they have the potential to be used as flexible devices even at lower frequencies (less than 4 Hz) [23]. In the recent past, several works have been carried out on fabricating wearable devices using triboelectric nanogenerators. These works considered the movement patterns and characteristics of each body part for on-body electricity generation [24]. The structural design of wearable triboelectric nanogenerators provided in recent studies is illustrated in Fig. 4.

Several authors have also reported mechanisms/techniques to improve the output performance of triboelectric nanogenerators. For instance, Gao and coworkers [28] reported new mechanism using hot electron-hole pairs decaying from the surface plasmon resonance to boost the output power. They reported that this new mechanism could boost the output power by 4.5 times and at the same time reduce output impedance by 75%. Integrating two or more nanogenerators (hybrid nanogenerators) is another approach to increase the total electric power. The readers are referred to Zhang et al. [29], where the progress of hybridized nanogenerators has been critically reviewed. Overall, further research is desirable in this field to pave the way for multiple energy

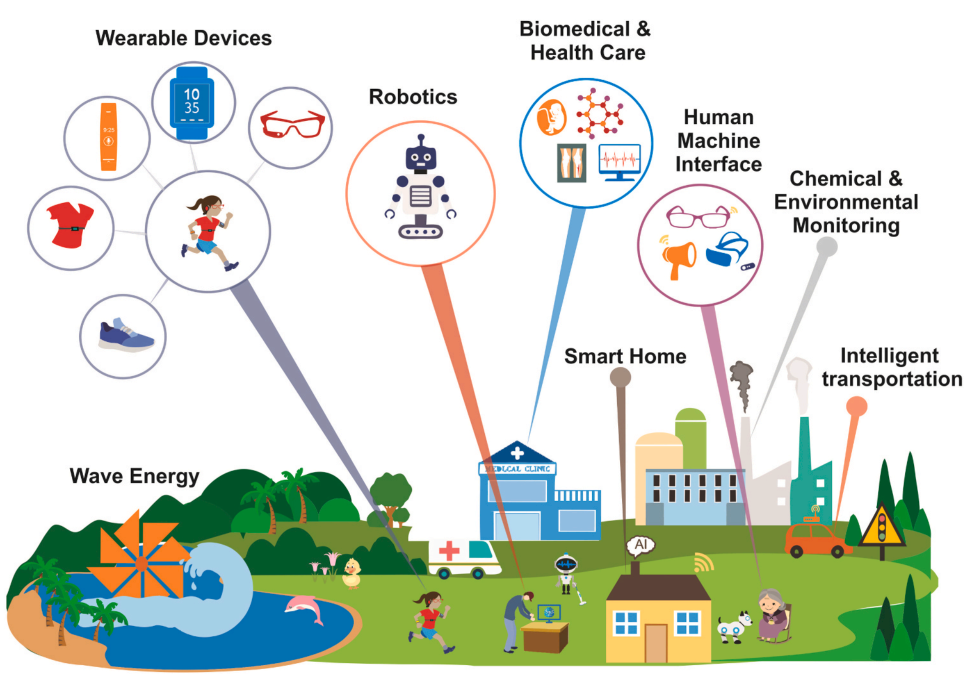

Fig. 1. A smart city powered by nanogenerators: a dream that is achievable but needs further support.

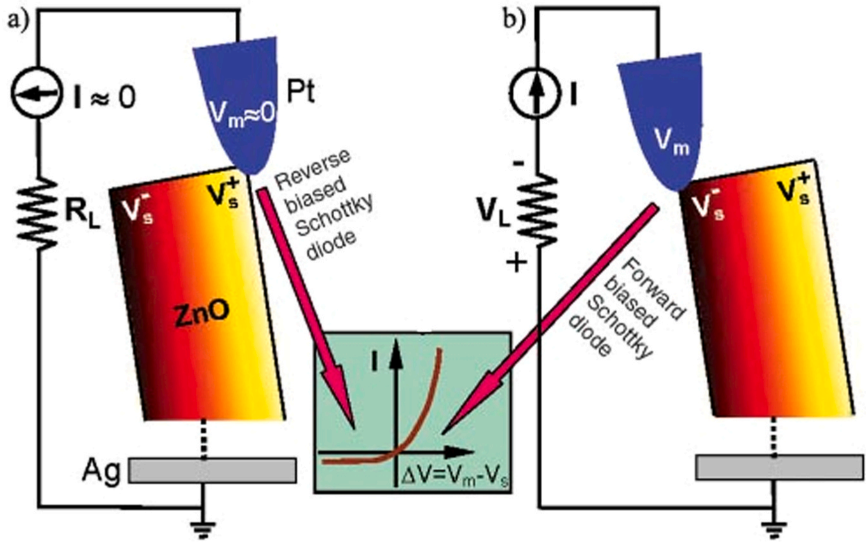

Fig. 2. Operation principle of ZnO nanowire-based piezoelectric nanogenerator: (a) The process of separation, maintenance of charges and buildup of potential and (b) The process of discharging the buildup potential and generation of electric current [2].
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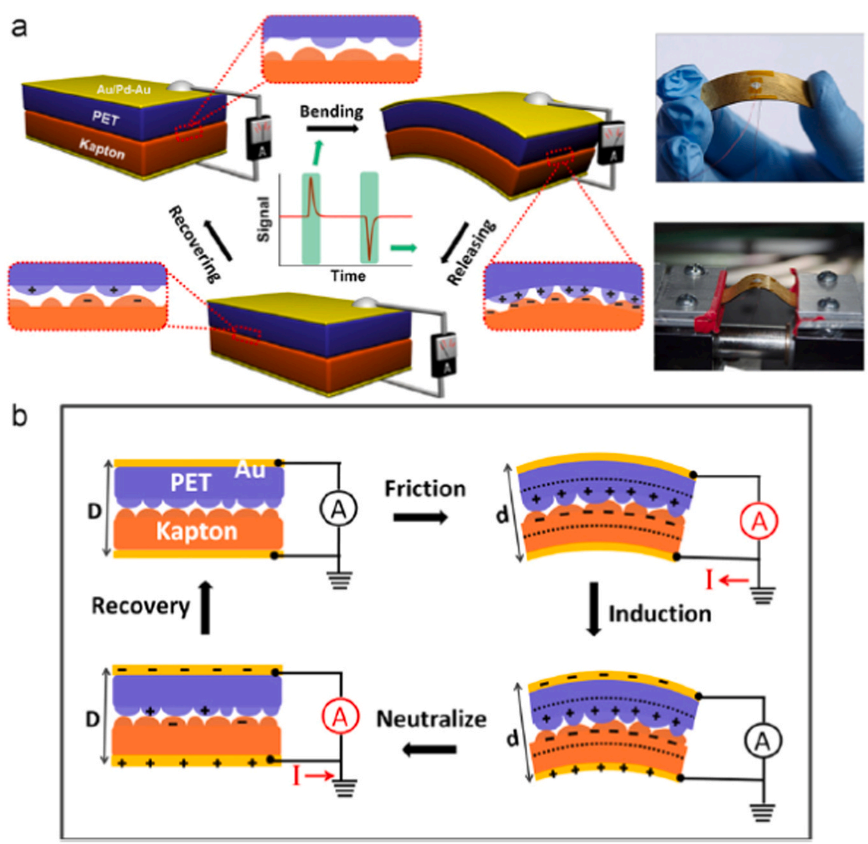

Fig. 3. Triboelectric nanogenerator: (a) Schematic of the generator structure and related measurement tests for output electricity and (b) Mechanism of performance [22].
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scavenging and extensive commercial applications of hybrid nanogenerators in the not-too-distant future.

1.1.3. Pyroelectric nanogenerator

As mentioned, in piezoelectric and triboelectric nanogenerators, the mechanical energy is converted to electrical energy; however, in pyroelectric nanogenerators, thermal energy is used to generate electricity [10]. Generally, the Seebeck effect employed to produce electricity in thermoelectric modules is not useful when the temperature is uniform in the environment. In such situations, the pyroelectric effect can be helpful for electricity generation. In 2012, Yang et al. [30] revealed that electricity could be generated due to time-dependent

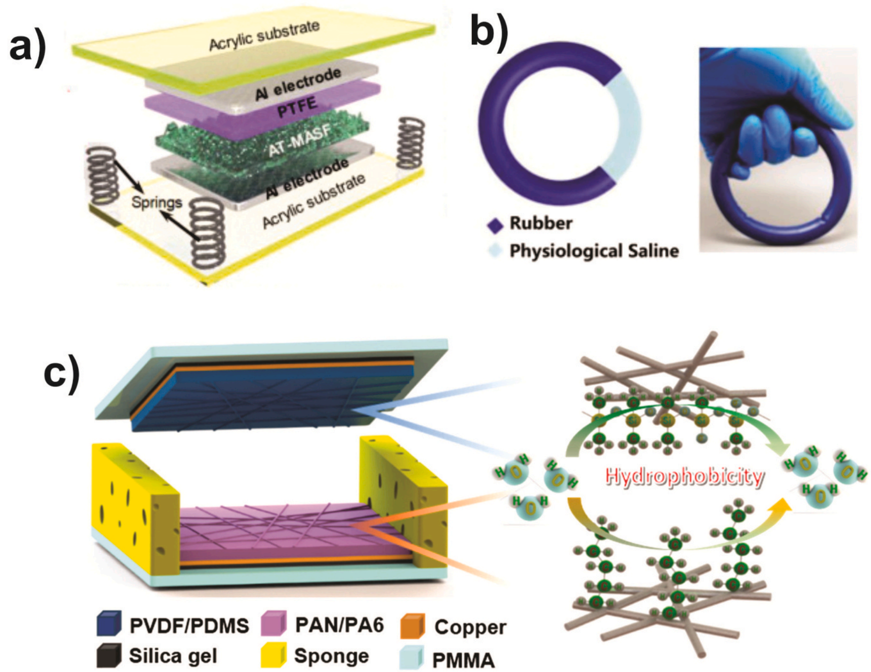

Fig. 4. Structural design of wearable triboelectric nanogenerators a) Structure of triboelectric nanogenerator based on microarchitectured silk cocoon films [25], b) Typical structure of the triboelectric nanogenerator band [26], c) Nanofibrous membrane-based triboelectric nanogenerator [27].
a) Reprinted with permission, LN: 4986311423393, b) Reprinted with permission, LN: 4986320061421, c) Reprinted with permission, LN: 4986320177987.

variations in the temperature of ZnO nanowire arrays. Fig. 5 depicts the schematic of the experimental set-up designed for electricity production by the pyroelectric nanogenerator. As shown in Fig. 5, the top and bottom of ZnO nanowire arrays are respectively in contact with silver (Ag) and indium tin oxide (ITO) electrodes to form the electric circuit. The variation of temperature with time produces electricity in the circuit.

In a recent study, different active materials like polyvinylidene fluoride or polyvinylidene difluoride films and lead zirconate titanate ceramic materials have been used for optimizing the performance of pyroelectric nanogenerator and estimating the electricity generation rate [31].

2. Bibliometric analysis of nanogenerators

Nowadays, bibliometric analysis is not limited to the library and information sciences, but it is a systematic approach to evaluating the progress in various branches of engineering and science [32]. A bibliometric study deals with both quantity and quality of published articles and books in a specified field, which can be determined through scientific databases such as Web of Science and Scopus. To measure the quality of published documents, the number of citations can be a criterion. Generally, analyzing publication and citation trends can provide the perspective of nanogenerator technology and its potential impact on daily life, particularly in the growth of future smart cities [33].

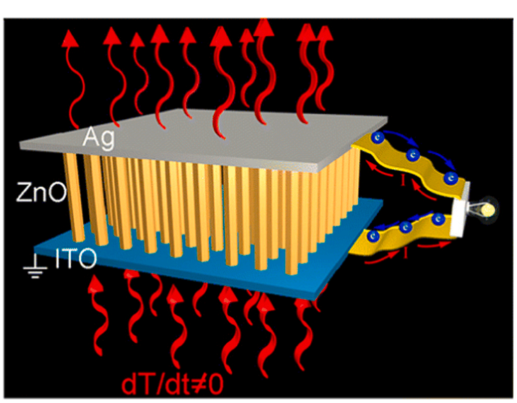

Fig. 5. Schematic of the experimental set-up for pyroelectric nanogenerators. Source: Nano Letters, Copyright © 2012, American Chemical Society [30].

2.1. Data collection and analysis

The present analysis is based on the Scopus database of Elsevier. According to Scopus factsheet of 2019, it indexes 23,500+ peer-reviewed journals [34]. Till 2007, the number of articles published was scarce in the field of nanogenerators. The first article on piezoelectric nanogenerator was published in 2006, and the other two types, namely triboelectric and pyroelectric nanogenerators, were proposed in 2012. After 2014, there was an exponential growth of publication in this field. Therefore, this study considers the period 2015–2020 for the bibliometric analysis. The retrieval experiments with different rules based on the Scopus database (2015–2020) are provided in Table 1. It is interesting to note that more articles have been published on triboelectric nanogenerators compared to piezoelectric nanogenerators. This shows the performance and viability of this nanogenerator in practical applications. On Scopus, 2324 articles were found for the keyword "nanogenerator" for the period 2015–2020. It is interesting to note that approximately 15% of articles did not explicitly mention the types of nanogenerators (i.e., piezoelectric, triboelectric, and pyroelectric) in their article title, abstract or keyword. Some of these articles have focused on applications like therapy of osteoarthritis [35], cancer/tumor therapy [36,37], self-powered tactile systems [38,39]. Furthermore, it should be noted that the 2323 articles belong to the source type journal, and one belongs to the book series titled "piezoelectric energy harvesting nanofibers" [40].

In this study, four types of analysis, such as co-authorship, co-occurrence, citation, and co-citation of the downloaded records, are performed. The fractional counting method is used for the analysis. The difference between full and fractional counting is that the same weight is

Table 1
Retrieval trails with different rules based on the Scopus database (2015–2020).

No	Retrieval trails	Results
1	TITLE-ABS-KEY ("nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	2324
2	TITLE-ABS-KEY ("triboelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	1647
3	TITLE-ABS-KEY ("piezoelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	645
4	TITLE-ABS-KEY ("pyroelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	38
5	TITLE-ABS-KEY ("piezoelectric" AND "triboelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	134
6	TITLE-ABS-KEY ("piezoelectric" AND "pyroelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	28
7	TITLE-ABS-KEY ("triboelectric" AND "pyroelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	15
8	TITLE-ABS-KEY ("piezoelectric" AND "triboelectric" AND "pyroelectric" AND "nanogenerator") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	14
9	TITLE-ABS-KEY ("nanogenerator" AND NOT "piezoelectric" OR "triboelectric" OR "pyroelectric") AND DOCTYPE (article) AND PUBYEAR > 2014 AND PUBYEAR < 2021	157

given for each co-authorship, co-occurrence, and co-citation in the full counting method, while the weight is fractionalized in fractional counting.

3. Machine learning for dimensionality reduction

In the present study, the unsupervised machine learning algorithm (principal component analysis) is used to classify and group the most influential authors, sources, and countries based on two variables (published documents and citations) for the period 2015–2020. Furthermore, the principal component analysis is used to categorize the technical and environmental performance of nanogenerators' active materials. The flow chart of principle component analysis is depicted in Fig. 6. In a principal component analysis, the data exploration is done using the two-dimensional graph of the first two principal components. The Minitab software is used to conduct the principal component analysis. The correlation type of matrix is selected to perform the analysis. From the analysis, the score plots of the first two principal components are used for discussion.

4. Results and discussion

4.1. Data statistics and aggregate analysis

According to the retrieval of collected data, the rising trend of publication is evident during 2015–2020, as shown in Fig. 7. According to this Figure, 175 articles were published in 2015. Even between 2015 and 2016, the total number of articles per year was less than 250. Besides, the number of published articles maintained a steady growth from 2015 to 2017. However, after 2017 one can see that there is an exponential growth trend. Based on the developed model, it is envisaged that the number of publications in this domain will at least double by 2030. Fig. 8 compares the document counts for the top 10 publication sources. Obviously, Nano Energy occupies the first place with a total of 706 documents. When comparing the total Nano Energy documents with the second-highest source (ACS Applied Materials & Interfaces) over the period 2015–2020, it can be observed that Nano Energy published five times more articles than the second-highest source. This trend reveals that researchers working on nanogenerators consider Nano Energy as a prospective journal to publish their work. One can also observe that the number of published documents was increased after 2017 in Nano Energy (Fig. 8). This shows that significant research developments/

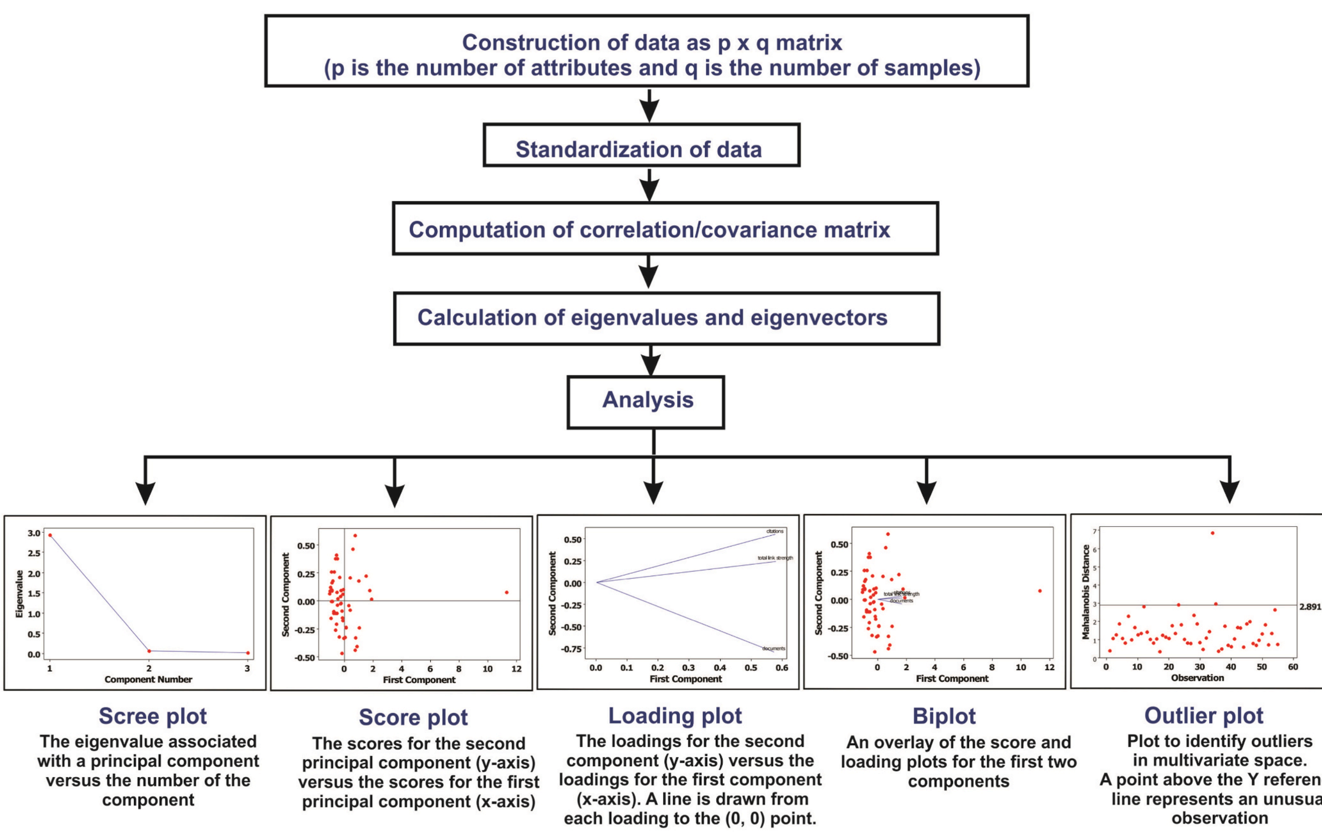

Fig. 6. Flow chart illustrating the steps involved in principal component analysis.

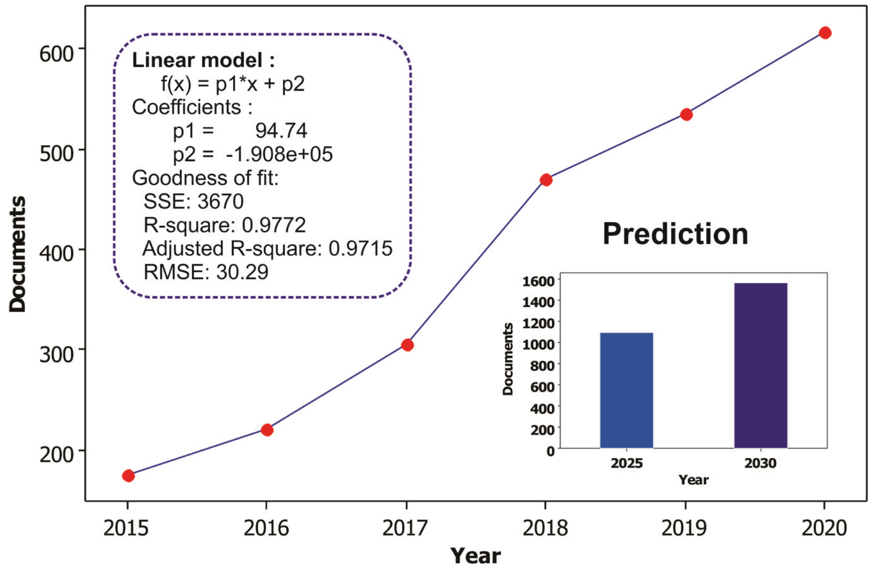

Fig. 7. The yearly published articles of nanogenerators in Scopus (2015–2020).

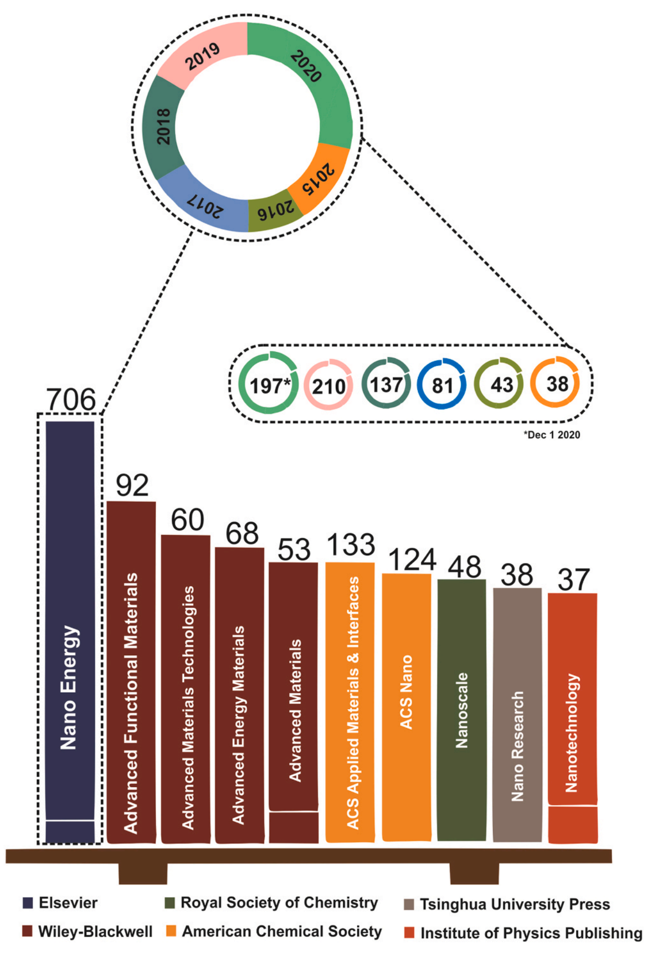

Fig. 8. Comparison of document counts among the top 10 sources.

improvements and fund sponsoring occurred from 2017 onwards towards nanogenerator's research. Fig. 9 shows the top 10 funding sponsors and affiliations found in the articles published in Scopus indexed journals during the considered period (2015–2020). It was inferred that funding organizations in China significantly support nanogenerator's research. For the period 2015–2020, 1017 articles report funding sponsor from the National Natural Science Foundation of China. Next, the National Research Foundation of Korea (299 articles) has funded nanogenerator's research. Surprisingly, no other countries funding agencies were seen in the top 10 sponsor list, other than sponsors from China and South Korea. Furthermore, Fig. 9 shows the top 10 affiliations involved in this research. Clearly, 7 out of 10 organizations/units are from China, two are from South Korea, and one from the United States.

Furthermore, analyzing the subject area of the published documents shows that 33% of the documents can be grouped under the subject area "Material Science". Fig. 10 shows the percentage distribution of documents by subject areas. Interestingly, nearly 2% of documents are grouped under the Multidisciplinary and other categories, including medicine, mathematics, business, management and accounting, pharmacology, toxicology and pharmaceutics, agricultural and biological sciences, psychology, and social sciences.

4.2. Co-authorship analysis

The co-authorship analysis determines the relatedness of the items based on the number of co-authored documents. The co-authorship analysis can be performed on three units, namely authors, organizations and countries. First, the co-authorship analysis of authors discloses that a total of 3961 authors were involved in nanogenerator's research during the period 2015–2020. Further analysis of data shows that more than 50 cluster groups were found in the co-authorship analysis. The influential authors in the cluster with their co-authorship link strength are provided in Fig. 11.

Furthermore, the co-authorship analysis of documents based on organizations reveals that 3636 organizations were involved in nanogenerator's research. Among different organizations, the Beijing Institute of nanoenergy and nanosystems, the Chinese academy of sciences and school of materials science and engineering, Georgia Institute of technology are the two leading organizations involved in co-authorship analysis. According to Scopus, these two organizations have published more than 200 articles and received more than 11,000 citations. Moreover, the co-authorship analysis based on countries reveals that 62 countries are involved in nanogenerators research during the considered period. The first five places are occupied by China (co-authorship link strength: 715), the US (co-authorship link strength: 576), South Korea (co-authorship link strength: 120), Singapore (co-

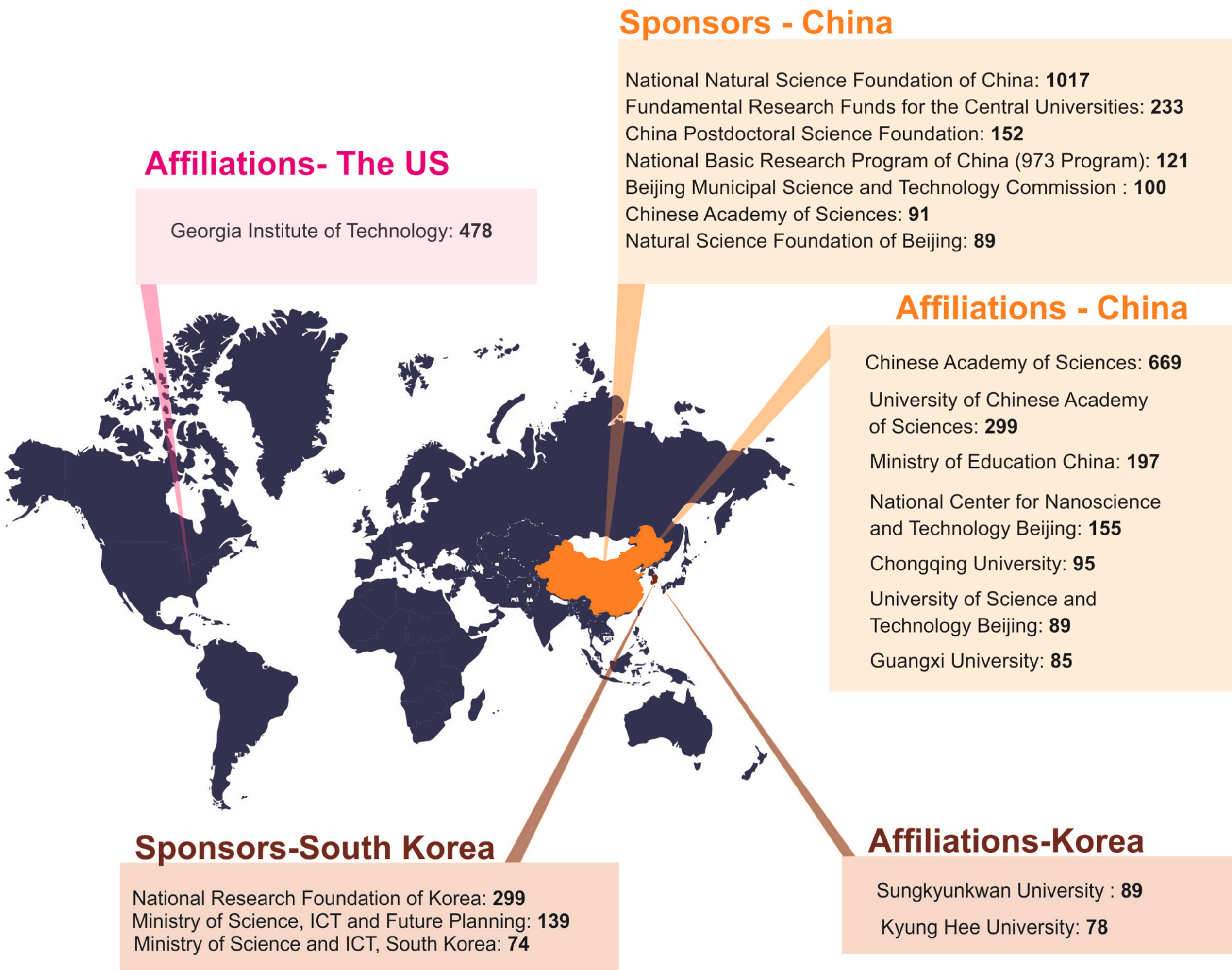

Fig. 9. Top 10 funding sponsors and affiliations in the nanogenerator field during the period 2015—2020 (The number represents articles published).

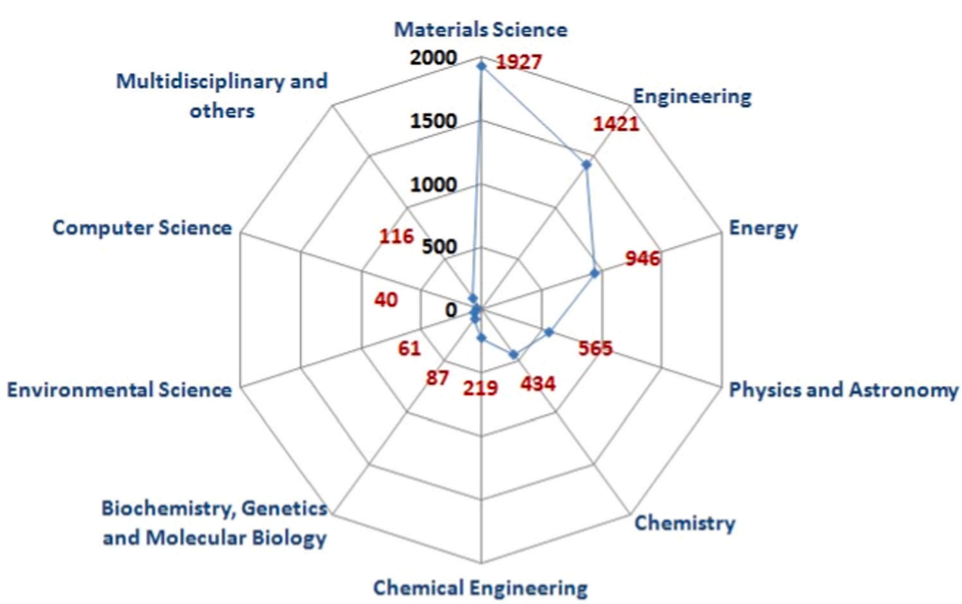

Fig. 10. Percentage distribution of articles in the field of nanogenerator by subject areas.

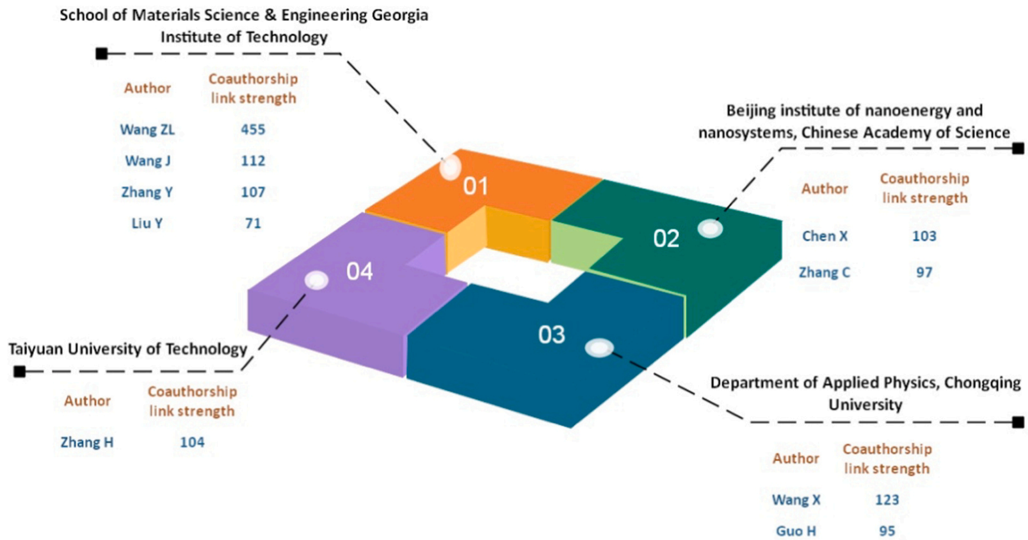

Fig. 11. Co-authorship link of influential authors in nanogenerator's research.

authorship link strength: 72) and Hong Kong (co-authorship link strength: 58). This trend reveals that most researchers from Asian countries do significant research collaborations in this field.

4.3. Co-occurrence (keywords) analysis

In academic research, keywords are a direct representation of the interests of researchers. In this work, the research hotspots are intuitively generated using the keyword visualization feature in VOSviewer. The minimum number of occurrences of a keyword in the collected data is set to 30. Meeting this threshold, 168 high-frequency keywords are observed, out of which 50 are shown in Fig. 12.

Each keyword is represented by a circle with a different size denoting its occurrence frequency (bigger size indicates the higher the occurrence frequency). Nanogenerators, triboelectricity and nanotechnology are three widely-used keywords. The occurrence and total link strength of these keywords are provided in Fig. 13. The authors also used "wearable technology" and "flexible electronics" keywords in their study. The analysis of the articles having these keywords reveals that recent studies are centered on the application of nanogenerators in the human lifestyle.

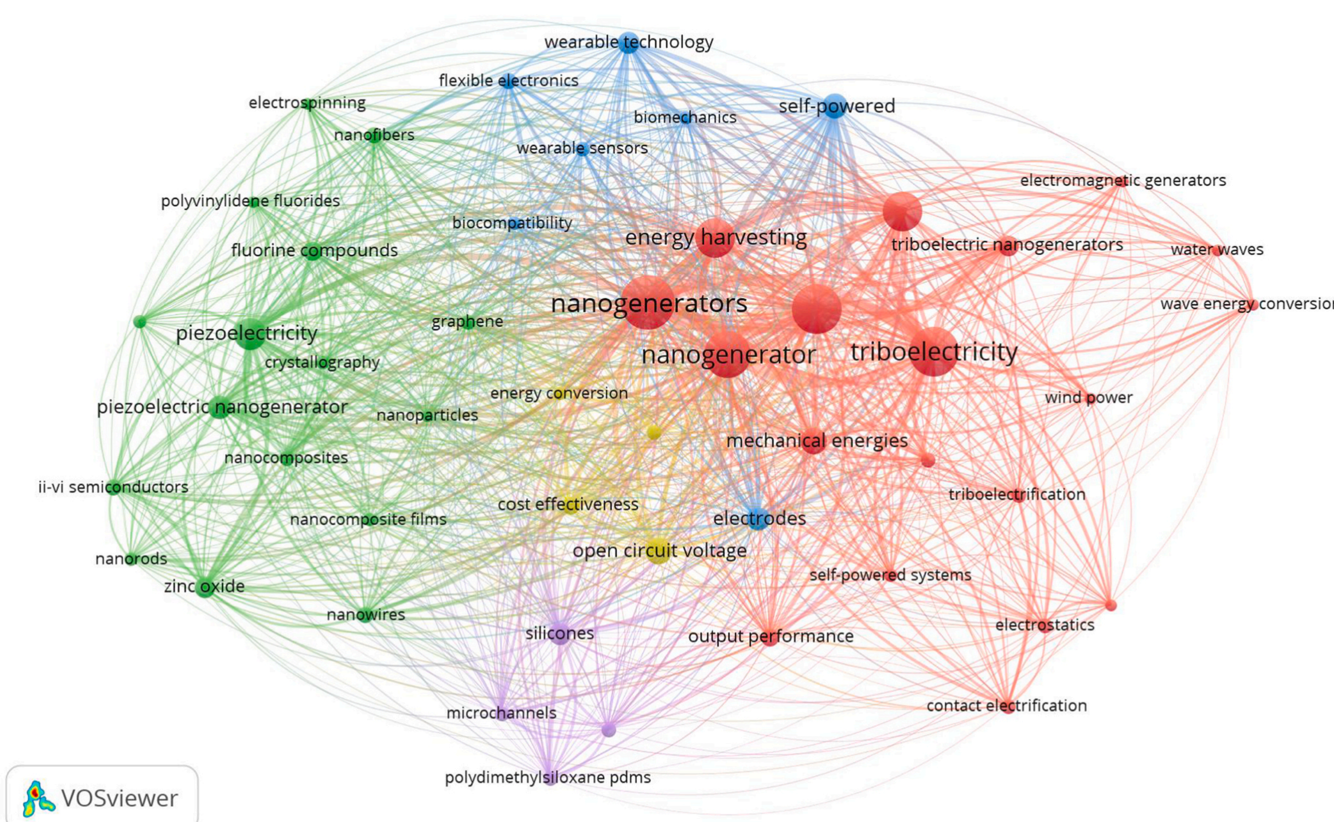

Fig. 12. High-frequency keywords in nanogenerator research.

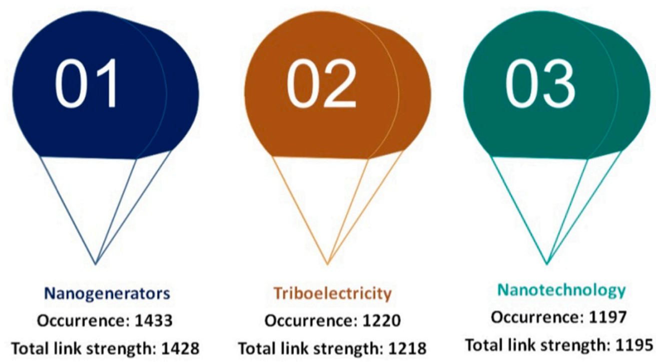

Fig. 13. Top three high-frequency keywords with the occurrence and total link strength.

Recently, He et al. [41] reported that textile-based composites could be successfully fabricated to detect human motions, which provides a potential opportunity in the area of self-powered flexible electronics.

Fig. 13 shows that nanogenerator is the high-frequency keyword with 1433 occurrences and total link strength of 1428 in the Scopus database from 2015 to 2020. Another highly-used keyword, "Triboelectricity", is linked with triboelectric nanogenerator because triboelectric nanogenerator constitutes a promising and high-performance technology for sustainable energy harvesting [42]. Furthermore, the analysis of keywords reveals that recently emerging application areas of nanogenerators are 3D printed devices [43,44], portable electronic devices [45] and blue energy [46].

4.4. Citation analysis

Citation analysis is the method of calculating the impact of an author, an article or a publication by counting the number of times that author, article, or publication has been cited by other works. In the present study, the citation analysis of documents, authors, sources and countries are analyzed. On the citation analysis of documents, 89% of articles published during the period 2015–2020 have received a least one citation. Moreover, 92 articles published during this period received more than 100 citations. The top 5 cited articles on nanogenerators during the period 2015–2020 are listed in Table 2.

Table 2
The Top-5 cited articles in the field of nanogenerators during the period 2015–2020.

Title	Year	Source	Ref.	Citations (as of Dec. 1, 2020)
A self-charging power unit by integration of a textile triboelectric nanogenerator and a flexible lithium-ion battery for wearable electronics	2015	Advanced Materials	[47]	393
Ultrastretchable, transparent triboelectric nanogenerator as electronic skin for biomechanical energy harvesting and tactile sensing	2017	Science Advances	[48]	371
Self-powered textile for Wearable electronics by hybridizing fiber-shaped nanogenerators, solar cells, and supercapacitors	2016	Science Advances	[49]	363
Single-layer MoS_2 nanopores as nanopower generators	2016	Nature	[50]	343
Nanopatterned textile-based wearable triboelectric nanogenerator	2015	ACS Nano	[51]	333

As noted from Table 2, the article titled "A self-charging power unit by integration of a textile triboelectric nanogenerator and a flexible lithium-ion battery for wearable electronics" published by Pu et al. [47] has received the highest citations of 393. The top-cited articles published during the period 2015–2020 majorly address the exploit of nanogenerators as wearable electronics. This discloses that wearable and flexible electronics are the emerging topics in sensor-based technology and depict the requirement of these devices in the coming years. Concerning the citations of top publication sources of this research, Nano Energy (Elsevier) stands first with 15,875 citations (706 articles). The second major source with the highest citations is the journal ACS Nano (7848 citations, 124 articles). The third (4125 citations, 53 articles) and fourth (3330 citations, 92 articles) major cited sources were from Wiley publications (i.e., Advanced Materials and Advanced Functional Materials).

The citation analysis of countries reveals that China stands first with 37,908 citations (1398 articles). Next to China, the United States is at second position with 26,425 citations (629 articles). The third, fourth, and fifth top countries are from Asia (South Korea, Singapore, and Hong Kong). The citations (articles) of these countries are observed as 9624 (477), 2408 (89) and 1856 (84), respectively. In the top ten list, India (2595 citations, 178 articles), United Kingdom (1203 citations, 63 documents), Taiwan (2141 citations, 58 articles), Canada (711 citations, 37 articles) and Australia (652 citations, 30 articles) were also seen.

4.5. Co-citation analysis

Co-citation coupling is usually used to establish the subject similarity of two documents. The co-citation analysis of cited authors, documents, and sources is performed herein for the period 2015–2020. The minimum number of citations is set to 20. The co-citation analysis of cited authors shows that 2566 authors out of 62611 authors meet the threshold. The co-citation network map of 100 most cited is shown in Fig. 14.

According to Fig. 14, Wang.Z.L is at the center with 28,928 citations and 23,652 total link strength because he is one of the specialized authors in nanogenerators. In the red cluster, the most important in terms of total strength link and citations is demonstrated by the group of authors formed by Wang.Y (3518 citations and 3422 total strength link), Zhang.Y (3281 citations and 3169 total strength link), Liu.Y (2801 citations and 2744 total strength link). The green cluster comprises principal authors Wang.J (2872 citations) and Guo.H (2686 citations). In the blue cluster, Chen.J is one of the influential authors. He is also the most citation-received author (6729) and exhibits high link strength (6367) next to Wang.Z.L. The co-citation analysis of documents shows that the three most cited references are Wang's work (ACS Nano, 7, (2013), pp. 9533–57 [52], Materials Today, (2017) 20, pp. 74–82 [53], Energy Environmental Science, 8, (2015), pp. 2250–2282 [54]). Furthermore, the co-citation analysis of sources reveals that Nano Energy, ACS Nano, Advanced Materials, Advanced Functional Materials, and Nano Letters are the most influential sources with co-citation link strength of 9931, 7584, 6521, 3481, and 3417, respectively.

4.6. Principal component analysis

For principal component analysis, the authors, sources and countries are sorted based on the minimum number of articles as ten and minimum citation as 1000. It is noteworthy that 55 authors, nine sources and eight countries meet the threshold. Fig. 15a shows the score plot of two principal components for most influential authors. Fig. 15a shows that the first principal component (PC1) accounts for 97.5% variation, and the second principal component (PC2) accounts for 2.5% variation. The plot shows that Wang.Z.L is at the extreme top right quadrant of the score plot. This is because all other authors have the Mahalanobis distance value less than 2.5, whereas the value was calculated as 6.7 for Wang.Z.L. This trend reveals that Wang.Z.L is the topmost influential

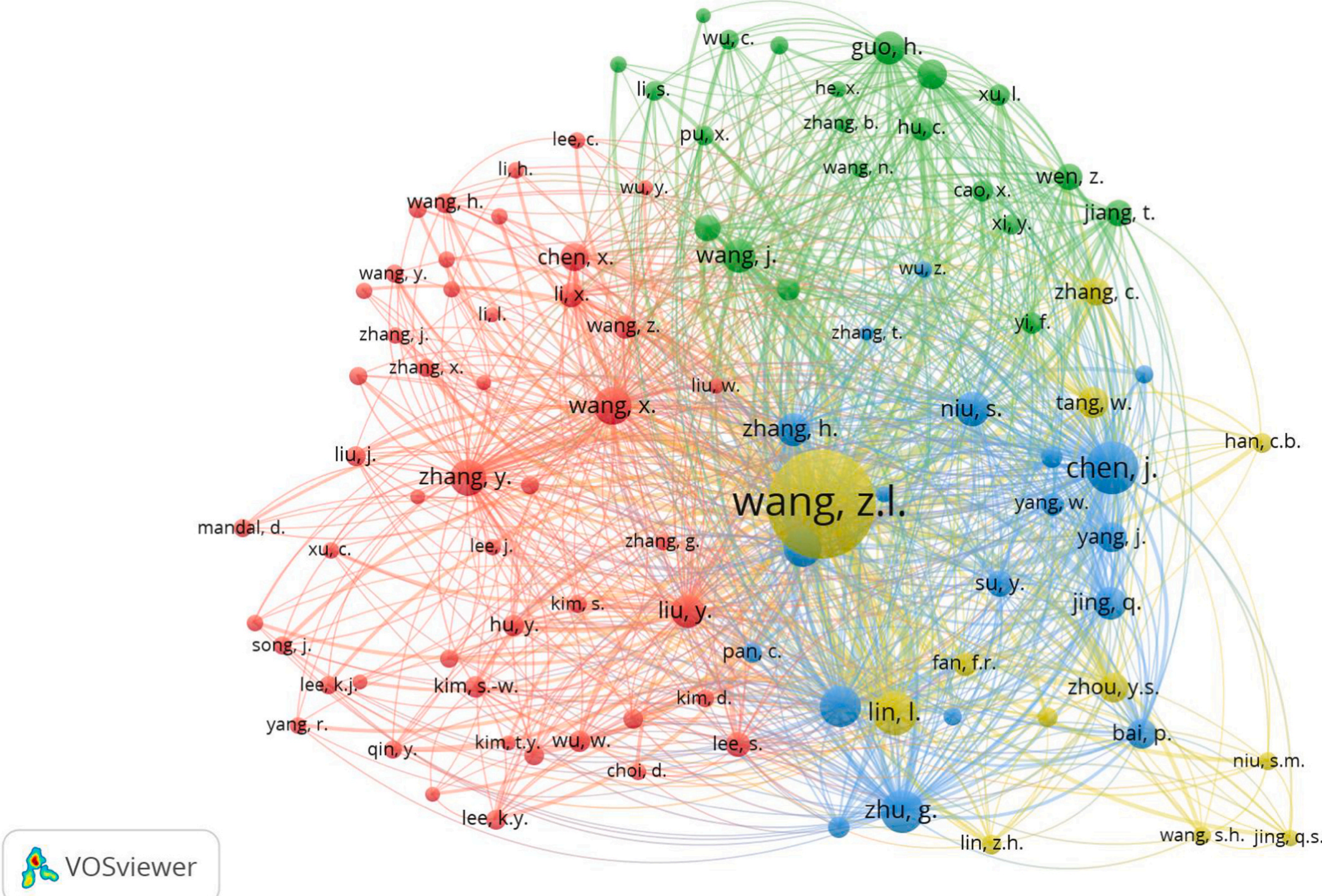

Fig. 14. Co-citation network map of 100 most cited authors in nanogenerator research.

author in the field of nanogenerators with greater positive scores. Moreover, Chen.J (University of California, Los Angeles), Guo.H (Chongqing University) and Zi.Y (The Chinese University of Hong Kong) are the next level influential authors in this field with higher positive scores.

Fig. 15b shows the score plot of two principal components for most influential sources (publications). This plot indicates that the first principal component (PC1) accounts for 97.2% variation and the second principal component (PC2) accounts for 2.8% variation. The score plot reveals that Nano Energy is in the top right quadrant with greater positive scores. This trend displays that most articles published by Nano Energy in the field of nanogenerators have received higher citations.

Next to Nano energy, ACS Nano is the most influential publication source with a higher positive score. In the top left quadrant, the journals (ACS Applied Materials & Interfaces, Nano Research, Advanced Energy Materials, and Advanced Functional Materials) exhibit similar performance based on both articles published and citations. Similarly, the two journals (Advanced Materials and Nature Communications) reveal that they exhibit close clustering.

Fig. 15c shows the score plot of two principal components for the most influential countries in the field of nanogenerators. In Fig. 15c), the first principal component (PC1) accounts for 98.2% variation, and the second principal component (PC2) accounts for 1.8% variation. The score plot displays that China is in the bottom right quadrant. This trend shows that China, the United States and South Korea are the most influential countries working in nanogenerators. In the left quadrant of the score plot, the countries the United Kingdom, Singapore, Hong Kong and Taiwan form a close cluster, revealing that they have a similar research performance in this field.

5. Analysis of current trends and direction towards technology commercialization

The analysis shows that research on self-powered sensors and systems based on triboelectric nanogenerators has been increasing in recent years. This is because of the several application domains, including wearable devices, robotics, chemical and environmental monitoring, biomedical, health care, and other smart applications. IDTechEx's recent report on the 2021–2040 smart city market indicates substantial revolutionary prospects for dramatically new smart city technologies. Trillions of dollars are expected to be invested in the installation of these technologies by 2041 [55]. The subjective estimation of new smart city technologies installation by 2041 is illustrated in Fig. 16.

It is evident from Fig. 16 that a significant share of smart city technologies is forecasted to be used in wearables and healthcare. This gives a hint that nanogenerators are going to play a crucial role in self-powering cities in the near future. Therefore, it is now the right time for smart device manufacturing industries to invest in these technologies. Notably, a few companies have already started developing these technologies for future smart cities. Fig. 17 illustrates some companies and their technologies for future zero-emission smart cities. Obviously, robotics will play an important role in smart vehicles and future transportation. Accordingly, future research work should be directed towards developing self-powered soft robots [56]. Moreover, the domain-specific challenges in the field of robotics need to be addressed. The ten grand challenges of science robotics are presented in Fig. 18. Of the ten challenges listed in Fig. 18, the first seven reflect underlying technologies that have a broader influence on all robotics application areas. The eighth and ninth challenges (social interaction and medical robotics)

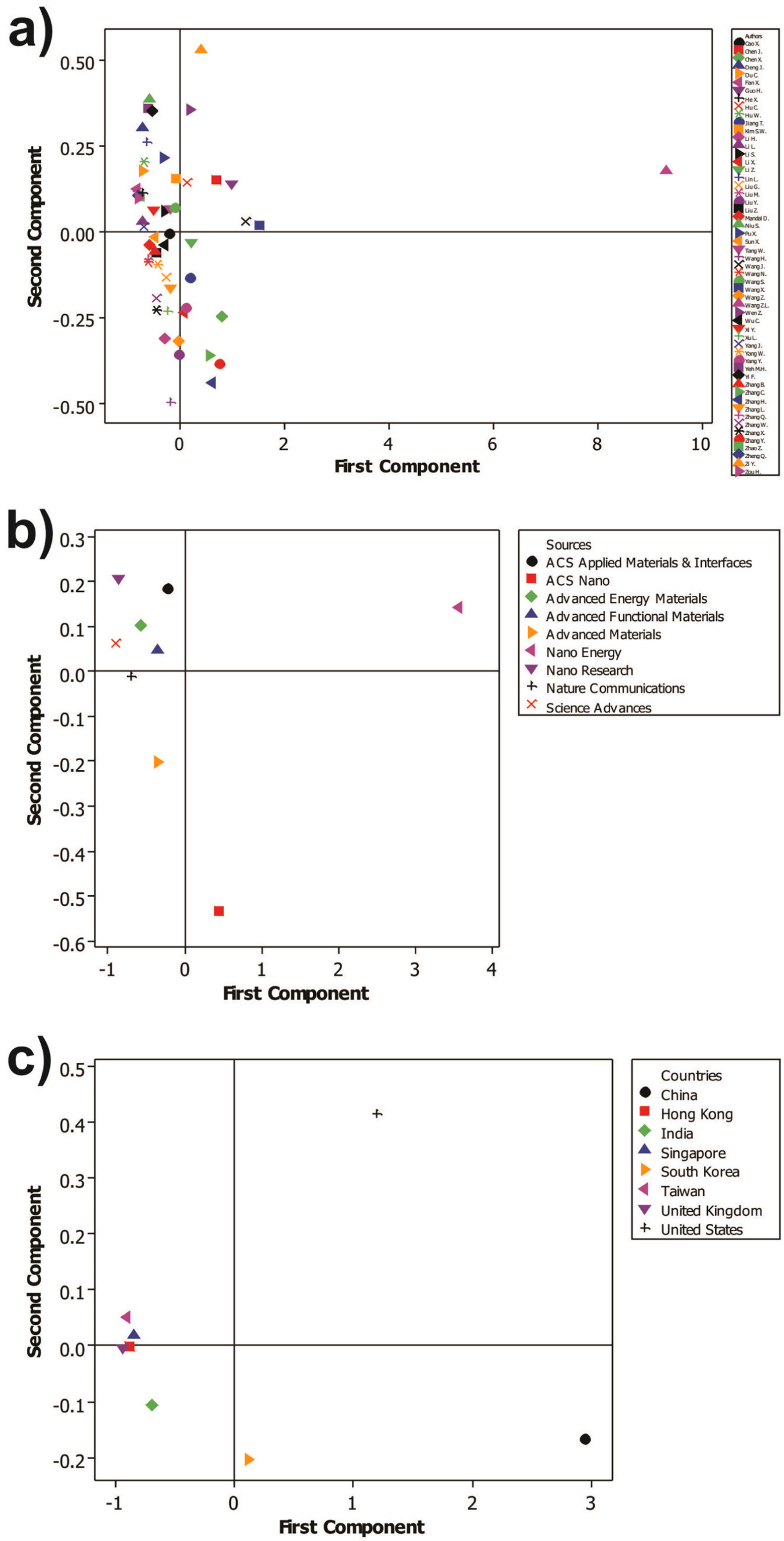

Fig. 15. Score plot of principal component analyses: (a) authors (b) publication sources and (c) countries.

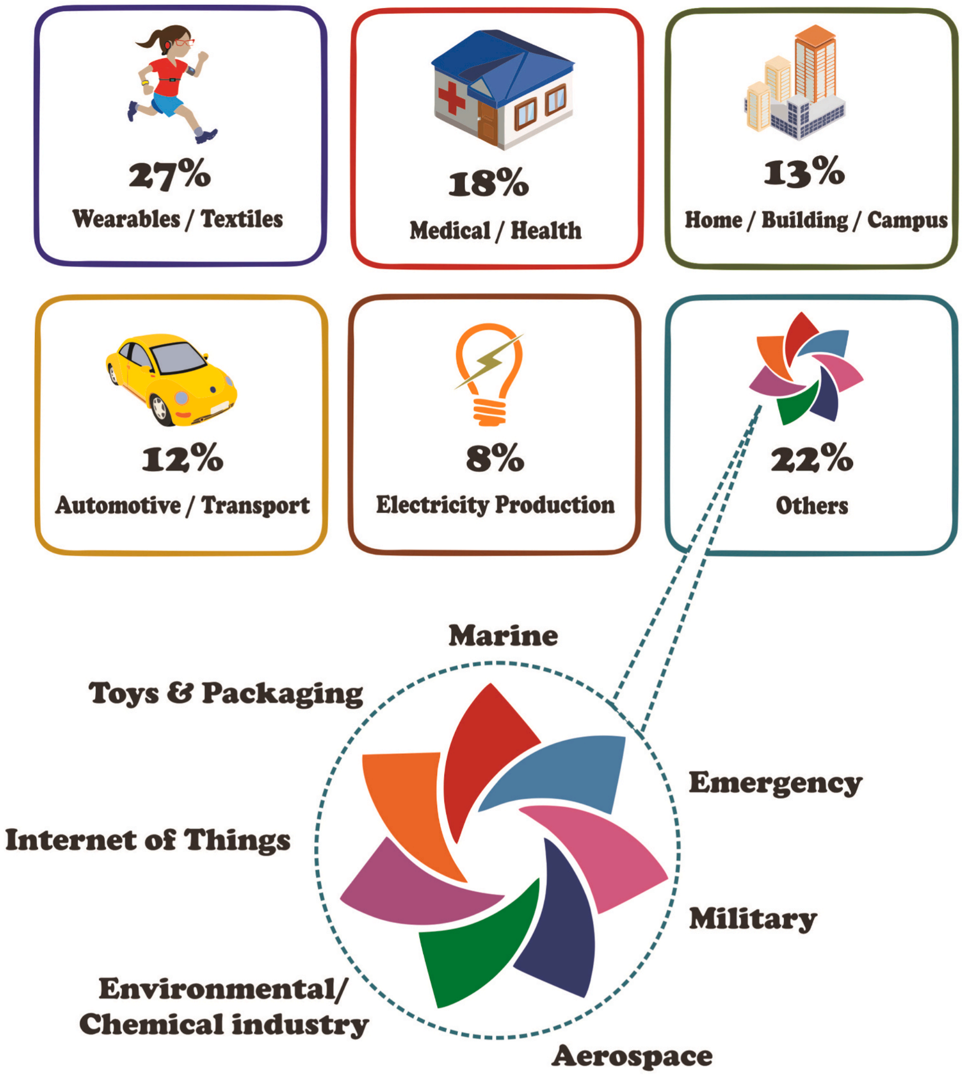

Fig. 16. Forecasted percentage share of smart city technologies by 2041.
Source: IDTechEx's Smart Cities Market report 2021–2041 [55].

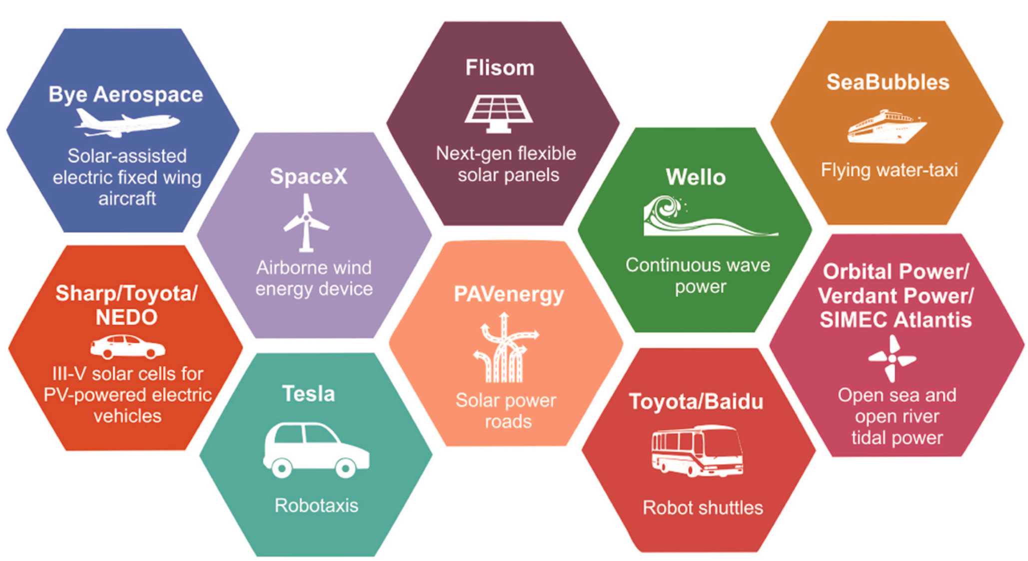

Fig. 17. Some companies and their technologies for future zero-emission smart cities.
Source: IDTechEx's Smart Cities Market report 2021–2041 [55].

Fig. 18. The grand 10 challenges of robotics.
Redrawn with permission from Science robotics, LN: 4996341310045 [92].

reflect the necessity of robotics in society and human health. The final challenge (robot ethics and security) relates to responsible innovation and how ethics and safety should be treated carefully as the technology is further advanced.

Although energy harvesting using self-powered sensors/systems is green and sustainable compared to battery technology, the commercial market of this technology is still in the nascent stage. This is because of several issues associated with this technology, including lower output power, less durability, and power management issues. Therefore, the development of high-performance self-powered sensors/systems is the primary challenge to be addressed in this field.

5.1. Triboelectric nanogenerators' performance

Nanogenerators' output performance primarily depends on several factors, including active materials used for fabrication and the active surface area. Accordingly, an attempt is made to analyze the output performance (open-circuit voltage and short-circuit current) of triboelectric nanogenerators. The output performance of triboelectric nanogenerators fabricated with different materials and surface area is tabulated in Table 3. The data from Table 3 is used to analyze the effect of active materials and surface area on the nanogenerators' performance. The score plot of the principal component analysis of the data is depicted in Fig. 19. As indicated in Fig. 19, nine different active material combinations can be found with higher positive scores in the top right quadrant. Besides, active materials with less surface area exhibit higher performance. This trend reveals that the nanogenerator's output performance is significantly influenced by the high-performance materials used to fabricate nanogenerators than the surface area. Therefore, future research should focus on finding high-performance active material with less environmental consequences to improve the nanogenerators' performance.

5.1.1. Environmental impact of polymer materials used in triboelectric nanogenerators

In recent years, polymer materials have become a key component of triboelectric nanogenerator technology. Although the nanogenerators' output performance depends on the generated charge, the nature of materials has a significant contribution to the development of high-performance nanogenerators aimed at meeting commercial power demand. The route for developing high-performance polymer material is depicted in Fig. 20. There are various methods, including tribosurface morphology, surface molecular fictionalization, and bulk composition modification, to modify the polymer materials used in nanogenerators and improve their performance [93]. Therefore, developing modified polymer materials can boost the performance of nanogenerators. However, the charge transfer process associated with the modified polymer materials and their life cycle assessment needs to be explored by future research works. The atmospheric emission profile of the commonly-used polymer materials in nanogenerators is provided in Table 4.

The principal component analysis of polymer materials' emission profile is performed to categorize the materials based on their environmental impact. The score plot of the analysis is provided in Fig. 21. The first and second principal components account for 98.4% of the variation. Based on the analysis, it is evident that polycarbonate exhibits high positive scores. This reveals that nanogenerators fabricated using polycarbonate significantly contribute to atmospheric pollution. It can also be seen from the score plot that two clusters exist. The first cluster is formed by Nylon 6 and 6–6, exhibiting their equal contribution to atmospheric pollution. Similarly, the most commonly used polymer materials (polyethylene, polypropylene, polyvinyl chloride, polydimethylsiloxane and polystyrene) exhibit a similar emission profile.

The analyses reveal that nanogenerators will impact human civilization in a broad sense and contribute to the energy requirements in a broader scope in the near future. Wang's research group reported that

Table 3
Contact area and output performance of triboelectric nanogenerators fabricated with different active materials.

Active material	Contact area, open-circuit voltage (V_{oc}) and short circuit current (I_{sc})/ density (J_{sc})	Ref.
$BaTiO_3$ nanoparticles with PDMS	Contact area: 1 cm × 1 cm V_{oc}: 13 V I_{sc}: 18 μA	[57]
Kapton, PVC and PET	Contact area: 1 cm × 1 cm V_{oc}: 18 V J_{sc}: 0.13 μA/cm^2	[22]
$BaTiO_3$@PDMS Film	Contact area: 1.2 cm × 1.2 cm V_{oc}: 60 V I_{sc}: 1 μA	[58]
Hydrogel	Contact area: 1.5 cm × 1.5 cm V_{oc}: 270 V I_{sc}: 11 μA	[59]
Cryogel (Cr-3t18)/PDMS	Contact area: 1 cm × 2 cm V_{oc}: 170 V J_{sc}: 17.1 mA/m^2	[60]
$ZnSnO_3$/PDMS	Contact area: 2 cm × 2 cm V_{oc}: 400 V I_{sc}: 28 μA	[61]
Ca-BZT/PDMS	Contact area: 2 cm × 2 cm V_{oc}: 550 V I_{sc}: 34 μA	[62]
Poly(tetrafluoroethylene) Nanoparticle Arrays	Contact area: 2 cm × 2 cm V_{oc}: 116 V I_{sc}: 33 μA	[63]
PTFE/PVA-LiCl	Contact area: 2 cm × 2 cm V_{oc}: 1345 V J_{sc}: 260 mA/m^2	[64]
$LiNbO_3$/PDMS	Contact area: 2 cm × 2 cm V_{oc}: 600 V I_{sc}: 50 μA	[65]
PDMS and Parylene C	Contact area: 2 cm × 2 cm V_{oc}: 1.6 V I_{sc}: 0.15 μA	[66]
Allicin grafted onto cellulose nanofibers (CNFs)	Contact area: 2 cm × 2 cm V_{oc}: 7.9 V I_{sc}: 5.13 μA	[67]
ZnO nanoflowers/PDMS/ MWCNTs	Contact area: 2.5 cm × 2.5 cm V_{oc}: 260 V I_{sc}: 11.21 μA	[68]
Inorganic CsPbBr3 perovskite	Contact area: 2 cm × 3 cm V_{oc}: 240 V J_{sc}: 4.13 μA/cm^2	[69]
Conductive copper foil and silicone paper	Contact area: 2 cm × 3 cm V_{oc}: 295 V I_{sc}: 120 μA	[70]
Two-dimensional Mxenes	Contact area: 2.5 cm × 5 cm V_{oc}: 650 V I_{sc}: 7.5 μA	[71]
PDMS/Al	Contact area: 2 cm × 7 cm V_{oc}: 17 V J_{sc}: 0.02 μA/cm^2	[72]
ZnO Nano flakes/PDMS	Contact area: 3 cm × 3 cm V_{oc}: 470 V I_{sc}: 37 μA	[73]
Polypyrrole (PPy),	Contact area: 3 cm × 3 cm V_{oc}: 48 V J_{sc}: 30 mA/m^2	[74]
Magnetic polymeric composite	Contact area: 3 cm × 3 cm V_{oc}: 233.4 V I_{sc}: 32.6 μA	[75]
Porous (CA)-(PEI)(CP and (LTV)	Contact area: 3 cm × 3 cm V_{oc}: 478 V I_{sc}: 6.3 μA/cm^2	[76]
(PVDF) (NF) with (PI)	Contact area: 3 cm × 3 cm V_{oc}: 800 V I_{sc}: 40 μA	[77]
Thermoplastic polymeric fabrics	Contact area: 3 cm × 3 cm V_{oc}: 101.6 V I_{sc}: 9.3 μA	[78]
Polyimide/ laser induced grapheme/PTFE/PDMS	Contact area: 3 cm × 3 cm V_{oc}: 168 V J_{sc}: 21.3 mA/m^2	[79]
PVDF-CsPbBr3	Contact area: 8.1 cm^2 V_{oc}: 104 V J_{sc}: 14.2 mA/m^2	[80]
Polypropylene (PP) nanowire array	Contact area: 4 cm × 4 cm V_{oc}: 1900 V I_{sc}: 19 mA/m^2	[81]
PCL/GO and Cellulose	Contact area: 4 cm × 4 cm V_{oc}: 120 V I_{sc}: 2.5 mA/m^2	[82]
CFRC lamina and office paper	Contact area: 4 cm × 5 cm V_{oc}: 150 V I_{sc}: 2.5 μA	[83]
Healable PDMS-PU	Contact area: 4 cm × 6 cm V_{oc}: 20 V I_{sc}: 1.9 μA	[84]
PDMS/PET	Contact area: 4.5 cm × 4.5 cm V_{oc}: 220 V I_{sc}: 40 μA	[85]
Smearing carbon/silicone grease and dielectric elastomers	Contact area: 9 cm^2 V_{oc}: 115 V I_{sc}: 3 μA	[86]
Wrinkled PEDOT: PSS Film	Contact area: 6 cm × 3 cm V_{oc}: 180 V I_{sc}: 22.6 μA	[80]
Hydrogel	Contact area: 6 cm × 6 cm V_{oc}: 383.8 V I_{sc}: 26.9 μA	[87]
PTFE/Ti/Al	Contact area: 7 cm × 2 cm V_{oc}: 334 V I_{sc}: 67 μA	[88]
Al/Ti/Kapton	Contact area: 7 cm × 2 cm V_{oc}: 296 V I_{sc}: 57 μA	[88]
Nanostructured polytetrafluoroethylene (n-PTFE)	Contact area: 9 cm × 5 cm V_{oc}: 30 V I_{sc}: 5 μA	[89]
Thermoplastic polymeric fabrics	Contact area: 10 cm × 10 cm V_{oc}: 403.7 V I_{sc}: 43.8 μA	[78]
Highly porous (PDMS)	Contact area: 10 cm × 10 cm V_{oc}: 3200 V I_{sc}: 94 μA	[90]
CNT thin films	Contact area: 12 cm × 12 cm V_{oc}: 870 V I_{sc}: 60 μA	[91]

55% instantaneous energy conversion efficiency could be achieved using triboelectric nanogenerators [94]. However, the instantaneous energy conversion efficiency of nanogenerators needs to be further boosted to a phenomenal level to increase its commercialization. Besides, the real potential of nanogenerators can be built by lowering material and manufacturing costs and improving their environmental performance compared to other energy harvesting technologies.

Furthermore, a successful self-powered smart city using nanogenerators can be built by addressing both technological challenges and policy issues. The utility of these self-powered systems during times of disaster and emergencies should be further explored. In this perspective, future research should focus on developing durable wireless sensor nodes powered by nanogenerators during emergencies or catastrophic events. Even though a large amount of literature is available to improve the nanogenerators' performance, the policy aspects of these systems have not yet been taken into account. Thus, future research should address the policy hurdles encountered during the commercial implementation of smart applications powered by nanogenerators.

6. Conclusions

In this paper, the fundamentals of three types of nanogenerators, including piezoelectric, triboelectric, and pyroelectric, are presented. Next, bibliometric analysis and unsupervised machine learning-based principal components analysis are performed on the published materials in the field from 2015 to 2020. Furthermore, the analysis of current trends, future direction for technology commercialization and nanogenerator's output performance analysis is presented. The main findings of this paper can be summarized as follows:

- China, the USA, and South Korea have the most articles and citations in this field, respectively.
- During the period 2015–2020, China has surpassed the USA in the number of published articles (> 2 times) and citations (> 1.4 times). One reason may be the investment of China government to attract Chinese elites in abroad (such as Z. L. Wang as the pioneer of this field) during recent years.
- If European countries want to compete with China and the USA in nanogenerators, they need to invest more in this field. Devoting prestigious fellowships and exchanging professors and researchers with China and the USA institutes can be a solution for the growth of European nations in the field of nanogenerators.
- By considering the most cited articles, it can be concluded that the articles addressing the emerging topics of the present era, such as artificial intelligence and the internet of things in sensor-based technology, have received more citations. Moreover, it was figured out that pyroelectric nanogenerators have attracted less attention than other types of nanogenerators, particularly triboelectric nanogenerators, although the ideas of both triboelectric and pyroelectric nanogenerators were given in 2012. Therefore, researchers should focus more on this topic since a huge amount of thermal energy wastes in industrial processes.

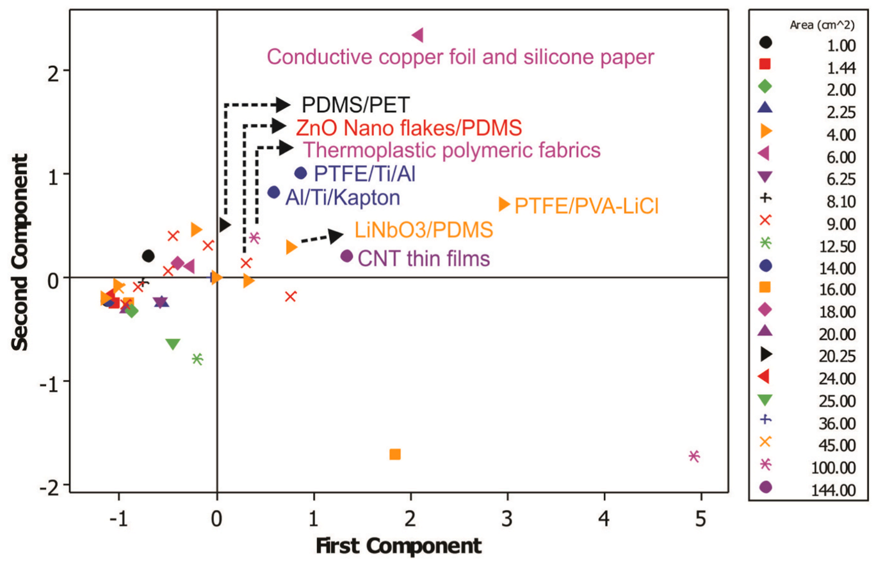

Fig. 19. Score plot of triboelectric nanogenerators performance (grouped based on surface area).

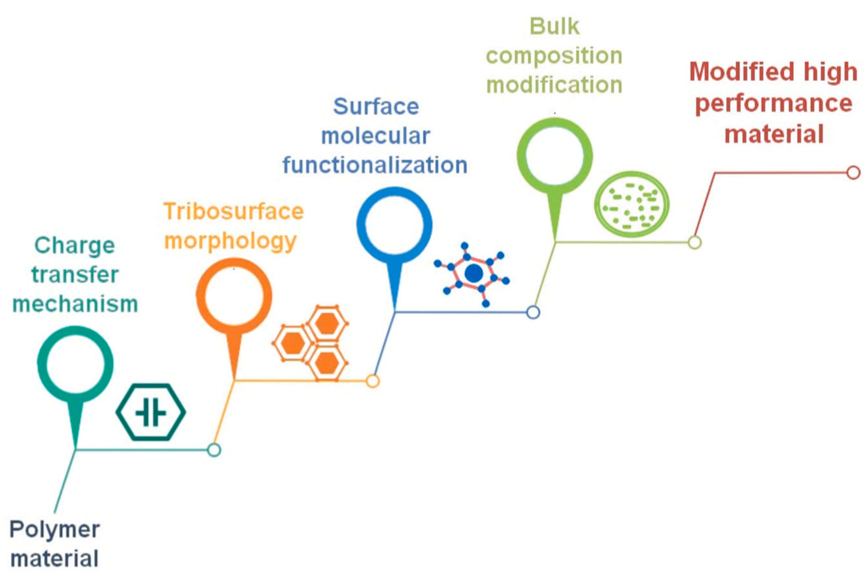

Fig. 20. Towards modified polymer materials to improve nanogenerators' performance [93].

Table 4
Emission profile of different polymer materials.

Polymer materials	Carbon dioxide, fossil (kg)	Carbon monoxide, fossil (kg)	Nitrogen oxides (kg)	Particulates, < 2.5 μm (kg)	Particulates, > 10 μm (kg)	Particulates, > 2.5 μm, and < 10 μm (kg)
Polyvinyl chloride (suspension polymerization)	1.08E-02	1.71E-05	5.30E-06	2.58E-06	2.22E-05	6.42E-06
Polyvinyl chloride (Emulsion polymerization)	9.83E-02	1.16E-04	1.59E-04	6.00E-06	1.08E-04	2.09E-05
Polycarbonate	7.29E-03	5.39E-06	1.21E-02	2.04E-03	2.61E-03	3.5E-03
Polyethylene (high density)	3.49E-02	6.72E-05	1.24E-05	–	5.89E-06	1.42E-06
Polyethylene (low density)	2.02E-02	1.71E-05	2.45E-05	–	3.29E-06	9.29E-08
Polystyrene (high impact)	5.17E-03	7.33E-06	5.63E-03	2.44E-04	3.12E-04	4.19E-04
Nylon 6	5.45	9.73E-03	1.86E-02	7.28E-04	9.31E-04	1.25E-03
Nylon 6 (gas filled)	5.27	8.66E-03	1.54E-02	1.08E-03	1.38E-03	1.85 E-03
Polypropylene	4.16E-02	1.59E-05	2.00E-05		6.62E-06	2.77E-06
Nylon 6–6	6.52	7.29E-03	1.35E-02	5.32 E-04	5.32E-04	9.15E-04
Nylon 6–6 (gas-filled)	6.03	5.99E-03	1.1E-02	8.5 E-04	1.09E-03	1.46E-03
Polydimethylsiloxane	2.52E-02					

Source: Ecoinvent ver 3.7 (2020).

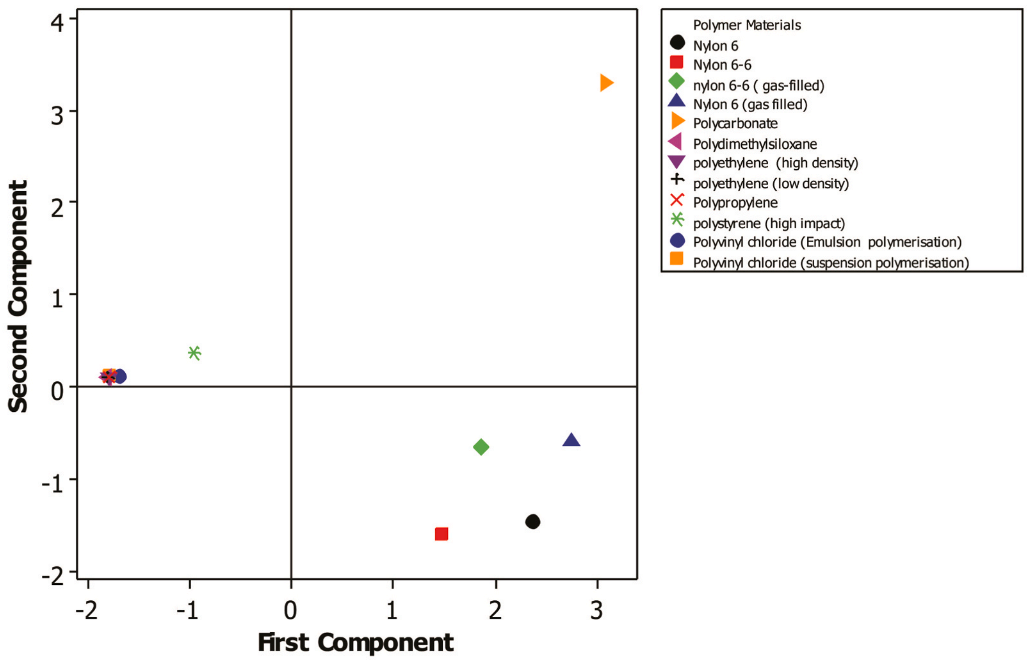

Fig. 21. The score plot of polymer materials' emission profile.

- Nano Energy (Elsevier) and ACS Nano are the most influential journals in the field of nanogenerators.
- The large-scale commerciality of nanogenerators depends on finding highly-active, low-cost, eco-friendly materials along with lower manufacturing costs and an encouraging environmental profile compared to other energy harvesting technologies.

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.

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