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Elucidating the dynamics of salinity gradient energy research

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ABSTRACT

This study uses bibliometric methods, machine learning, and data analysis to examine Salinity Gradient Energy (SGE), a renewable energy source derived from saline water sources of different concentrations such as seawater, waste brines and mining industries. SGE's use of advanced membrane processes efficiently extracts energy from the difference in salinity between different waters. Based on the dataset collected up to January 22, 2024 that contains 1270 articles, the following in-depth analysis sheds light on the SGE scientific progress, trending topics, strong collaborations, current trends, dominant authors, influential articles, important affiliations, basic statistics, common words, sentiments, and emotions to reveal the quality, quantity, and impact of the domain. Since the first SGE paper published in 1976, SGE research has attracted considerable attention from researchers over the last 20 years. Reverse Electrodialysis (RED) and Pressure Retarded Osmosis (PRO) are identified as the leading energy harvesting technologies. However, in recent years, the number of research studies on RED has increased. Institutions from China and the USA contributed more to the SGE progress. "Ion current rectification" is the trending topic of 2023. Sentiment and emotion scores revealed researchers' optimistic and neutral views on SGE technologies.

1. Introduction

Salinity Gradient Energy (SGE), also known as Blue Energy, Osmotic Energy, or Salinity Gradient Power, may be traced back to 1954 with the idea reported by Pattle R.E. in his letter entitled "Production of Electric Power by Mixing Fresh and Salt Water in the Hydroelectric Pile" published in Nature [1]. At that time, Pattle envisioned the development of an electromagnetic force higher than electrode polarization voltages by alternating layers of fresh water and salt separated by alternating basic and acidic membranes (i.e. anion and cation exchange membranes). This early revelation pointed to an untapped reservoir of energy, paving the way for further research studies.

In general, a wide variety of techniques, ranging from traditional to innovative approaches, have been proposed to exploit energy from salinity gradients, both on a laboratory, pilot, and industrial scale. These processes can be divided into two main categories based on their operating principles: those that employ membrane separation and those with other mechanisms operating without membranes. The first group consists of Forward Osmosis Electrokinetic (FO-EK) [2], Pressure Retarded Osmosis (PRO) [3], Reverse Electrodialysis (RED) [4], Nanofluidic Reverse Electrodialysis (NRED) [5], Capacitive Reverse Electrodialysis (CRED) [6], Microbial Reverse Electrodialysis (MRED) [7] and Thermo-osmotic Energy Conversion (TOEC) [8], while the second group includes Reverse Vapor Compression (RVC) [9], Electric Double Capacitor (EDLC) [10], Hydrogel Swelling and Shrinkage (SSH) [11],

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List of abbreviations

AccMix	accumulator mixing
$AGCD_C$	average global citations per document value of the collection
$AGCD_{It}$	average global citations per document value of an item
$AGCD_{C_y}$	average global citations per documents published in a corresponding year
AF	articles fractionalized value of an author
$ANGCD_{C_y}$	average normalized GC per documents published in the corresponding year value of the collection
$ARGC_{It}$	average relative global citations value of an item
cAD_C	co-authors per document value of the collection
$CAGR_C$	compound annual growth rate of the collection
CAPMIX	capacitive mixing
CRED	capacitive reverse electrodialysis
DAA_C	documents average age value of the collection
DAA_{It}	documents average age value of an item
DO	diffusio-osmosis
EDL	electric double layer
EDLC	electric double layer capacitor
FO-EK	forward osmosis electrokinetic
GC	global citations
GC_i	global citations of an item
GC_{It_i}	global citations of document i of an item
GCY_i	global citations per year of a document
HG	hydrocratic generator
IcA_C	international co-authorship
ICR	ion current rectification
LC	local citations
MEB	mixing entropy battery
ML	machine learning
MCP	multiple country publications
MRED	microbial reverse electrodialysis
NLP	natural language processing
NRED	nanofluidic reverse electrodialysis
PRO	pressure retarded osmosis
RED	reverse electrodialysis
$RGC_{It_{i_y}}$	relative GC of document i from an item published in a corresponding year
RGC_{i_y}	relative global citations of document i published in a corresponding year
RVC	reverse vapor compression
SGE	salinity gradient energy
SSH	hydrogel swelling and shrinkage
TCY	times cited per year
TENGs	triboelectric nanogenerators
TM	text mining
TOEC	thermo-osmotic energy conversion
VOS	visualization of similarities

Mixing Entropy Battery (MEB) [12], Hydrocratic Generator (HG) [13], and Triboelectric Nanogenerators (TENGs) [14]. Capacitive Mixing (CAPMIX) [15–18] can operate with and without membranes.

During the last decade, PRO and RED have stood out as the most promising industrial technologies for SGE [19]. In PRO, freshwater flows across a semipermeable membrane into a pressured saline solution to produce mechanical energy, which is eventually converted into electricity in a hydroelectric turbine [20]. On the other hand, to directly generate electrical energy, RED employs alternating cation-exchange and anion-exchange membranes promoting selective ions passage from highly saline streams to low salinity water [21]. Thanks to the substantial development in membrane materials and processes, these approaches have been improved over time. As reported by Loeb & Norman (1975) [22], Loeb's pioneering work in PRO provided the platform for future advances. Various strategies for improving SGE efficiency have been adopted, including using nanofluidic technology, as demonstrated by Siria et al., in 2013 [23], which has greatly improved SGE efficiency. Specifically, since 2010, a significant surge in SGE research has been spurred by the worldwide demand for sustainable energy options. Its continuous and dependable power supply distinguishes SGE from intermittent energy sources such as solar or wind.

Significant advances in several countries exemplify the recent global interest in sustainable energy technologies. For instance, in the Netherlands, considerable progress has been made in RED technology. This is described in detail by Post et al. (2008) [24]. Moreover, pilot scale demonstration activities have been performed in Italy with installed power of 1 kW [25], and long-term operation with real brines [26]. Concurrently, China has made notable advances in membrane performance and overall system efficiency, as documented by Yanjun Fu et al. (2019) [27]. This emerging field continues to expand with recent research efforts. Joost Veerman et al. (2022) [28] published a comprehensive review of current advances in ion exchange membranes (IEMs) for RED applications, meticulously examining the various design strategies followed in the development of novel high-performance membranes. In addition, there is a growing focus on developing hybrid systems, as highlighted recently in these two research studies [29,30]. These systems represent innovative approaches to optimizing energy production by synergistically combining SGE systems with other renewable energy and desalination technologies. Finally, SGE technologies have been also proposed in closed-loop operational schemes for the conversion of low-grade heat into electricity, via the so-called Salinity Gradient Heat Engines [31,32], and for energy storage applications [33]. It is worth mentioning that very recently EU has officially included Osmotic Energy in the list of Renewable Energy sources, after completion of an exhaustive report published in 2024 on the potential of Osmotic energy in the EU [34]. In conclusion, SGE is emerging as an increasingly important component of renewable energy research. Its low environmental effect and long-term viability highlight its promise as a future energy alternative, particularly in coastal locations.

SGE literature analysis through bibliometric methods and machine learning (ML) can help advance this renewable energy field of research. Bibliometric analysis is a statistical technique that evaluates the publishing and citation patterns of scientific literature and the influence of academic papers. In addition, it is frequently used to evaluate the output and effect of research groups or institutions to discover trends in specific research disciplines [35,36]. One can find various bibliometric software tools in the literature that can be used to analyze scientific literature from many databases [37–42]. Biblioshiny (Bibliometrix package in R programming language) is a sophisticated open-source tool for bibliometric analysis and application developed in 2017 [43,44]. VOSviewer is a bibliometric analysis program developed over 20 years to visualize networks based on co-citation, bibliographic linkage, or co-authorship [45–47].

Using natural language processing (NLP) approaches, bibliographic and bibliometric analysis is becoming an increasingly common means of examining the dynamic character of scientific development [48]. NLP, a subfield of artificial intelligence (AI), enables computers to understand and process human language for various text-related tasks [49,50]. It can help researchers interpret and evaluate vast amounts of information in continuously increasing study domains [51]. Combining NLP with ML significantly improves text-based data processing. ML algorithms extract patterns from large datasets to predict outcomes and have become common in fields like engineering, medicine, and marketing [52–56].

Text mining (TM) seeks to extract and analyze significant insights or patterns from irregular and unstructured texts in an automated and efficient manner [57]. The frequency of words in a given article text is represented graphically by a word cloud [58]. The branch of research that evaluates people's views, sentiments, assessments, and attitudes regarding specific things and their qualities conveyed in written language is called sentiment analysis [59]. Various ML classification algorithms have significantly improved NLP as ML has risen in popularity [60,61]. The classification task in supervised ML attempts to predict the proper label of incoming data [62]. Zero-shot models, which include zero-shot classification of text data, image data, etc., are able to handle a wide range of operations without the need for labeled data [63,64]. In text analysis, zero-shot classification is used to label a text (paragraph, sentence, etc.) without any training. Zero-shot text classification models have started to find their place in text mining areas such as automated abstract screening, topic, event, emotion, and sentiment classification [65–67].

The present study employs powerful data mining approaches such as bibliometric methods, ML, and text mining. Integrating these methodologies presents a complete and systematic review of SGE research studies, covering key issues, trends, problems, collaborations, etc. Hidden insights and information that typical literature reviews and bibliometric tools may miss, have been detected. This study will help to enhance, broaden, and empower SGE technologies. Additionally, it will provide a significant new perspective on SGE research, helping academics, policymakers, and practitioners to better understand and harness this promising renewable energy source.

2. Data and methods

The dataset used for the bibliometric and ML analysis was collected from the Scopus database on January 22, 2024. This database is one of the biggest curated abstract and citation databases, with extensive worldwide and regional coverage of scientific publications (journals, conference proceedings, books, etc.). Furthermore, rigorous quality assurance mechanisms constantly monitor and enhance all data items in Scopus. Scopus provides complete author and institution profiles derived from powerful profiling algorithms and manual curation, assuring excellent precision and recall and richer metadata records of scientific papers [68,69]. The conducted filtration process was; source type as a "journal", document type as "article", publication stage as "final", language as "English", publication year up to "December 31, 2023 (up to 2024)", and article title, abstract, keywords as follows: "battery mixing", "blue energy", "capacitive double layer expansion", "capacitive electrode response", "capacitive mixing", CAPMIX, "concentration difference energy", "concentration gradient battery", "concentration gradient driven energy harvesting", "diffusion-osmosis", FO-EK, "high and low ionic concentrations", "nanofluidic energy conversion", "osmotic diffusion", "osmotic energy", "osmotic power", "osmotic pressure difference", "reverse electro dialysis", "reverse electrodialysis", "salinity energy", "salinity gradient energy", "salinity gradient power", "salt power", "SaltPower", "electric double-layer capacitor", "gradient energy", "pressure retarded osmosis", "salinity gradient" + "power", and "salinity gradient" + "energy". Because of the use of so many keywords, many articles other than those related with SGE subject appeared in the dataset. Thus, dataset was screened manually to filter out, resulting in 1270 articles.

Scientific mapping programs, Biblioshiny (version 4.1.4) and VOSviewer (version 1.6.20), were employed to visualize bibliometric networks. The basic calculations used in bibliometric analyses are reported in the following paragraphs.

The total number of times an author, an article, or a journal has been cited in the bibliographic database is known as the global citations (GC) (refers to Total Citations (TC) in Biblioshiny). On the other hand, the local citations (LC) quantify the number of citations of other authors for a certain article inside the collected dataset [58,70].

The compound annual growth rate ($CAGR_C$) (denoted as annual growth rate in Biblioshiny) of the collection is defined as [71]:

$$CAGR_C\ (\%) = \left(\left(\frac{nd_{C_l}}{nd_{C_f}} \right)^{\frac{1}{\left(y_{C_l} - y_{C_f}\right)}} - 1 \right) 100 \tag{1}$$

where y_{C_f} indicates the first year of the dataset, y_{C_l} indicates the last year of the dataset, nd_{C_f} indicates the number of articles from the first year of the collection, and nd_{C_l} shows the number of articles from the last year of the collection.

The co-authors per document (cAD_C) value of the collection is written as [58]:

$$cAD_C = \frac{na_C}{nd_C} \tag{2}$$

being nd_C is the total number of documents in the dataset and na_C is the total number of authors in the dataset (repeated author names are included).

The documents average age value of the collection (DAA_C), or an item (author, journal, or country) (DAA_{It}) (denoted as average publication year in VOSviewer) is defined as [72]:

$$DAA_C = \frac{1}{nd_C} \sum_{C_i=1}^{C_n} a_{C_i} \text{ or } DAA_{It} = \frac{1}{nd_{It}} \sum_{It_i=1}^{It_n} a_{It_i} \tag{3}$$

where the age of document i in the collection is denoted by a_{C_i}, which can be estimated $(y_C - y_i)$, y_i is the publication year of the document, and y_C is the year that the collection is downloaded. a_{It_i} denotes the age of the document i of the item, which can be calculated as $(y_C - y_{It_i})$, y_{It_i} is the publication year of the document i of the item, and nd_{It} denotes the number of documents of the item.

The average global citations per document value of the collection ($AGCD_C$) or an item ($AGCD_{It}$) can be calculated using the following equation [72] (denoted as average citations in VOSviewer and average citations per doc in Biblioshiny):

$$AGCD_C = \frac{1}{nd_C} \sum_{i=1}^{nd_C} GC_i \text{ or } AGCD_{It} = \frac{1}{nd_{It}} \sum_{It_i=1}^{It_n} GC_{It_i} \tag{4}$$

being the global citations of document i in the collection appear by GC_i, and the global citations of document i of an item are given by GC_{It_i}.

The average global citations per documents published in a particular year (in year y) of the collection $\left(AGCD_{C_y}\right)$ (denoted as average citations per year or mean total citations (TC) per article, MeanTCperArt, in Biblioshiny) is defined as [73]:

$$AGCD_{C_y} = \frac{1}{nd_{C_y}} \sum_{i_y=1}^{nd_{C_y}} GC_{i_y} \tag{5}$$

In this equation, nd_{C_y} represents the total number of documents in the collection in that particular year and GC_{i_y} represents the global citation of document i published in year y from the dataset.

The average normalized global citations per documents published in the corresponding year, $\left(ANGCD_{C_y}\right)$ of the collection (denoted as mean TC per year, MeanTCperYear, in Biblioshiny) is calculated as [74]:

$$ANGCD_{C_y} = \frac{AGCD_{C_y}}{a_{C_y}} \tag{6}$$

in here, a_{C_y} denotes the age of any document utilized in the $AGCD_{C_y}$ equation.

The document's global citations per year (denoted as TC per year in Biblioshiny) (GCY_i) is written as [69]:

$$GCY_i = \frac{GC_i}{a_{C_i}} \quad (7)$$

being GC_i is the total number of global citations of the document *i*.

One may compute the relative global citations of document *i* published in year y (RGC_{i_y}) (denoted as normalized *TC* in Biblioshiny) as in Eq. (8) [75]:

$$RGC_{i_y} = \frac{GC_{i_y}}{\sum_{i_y=1}^{nd_{C_y}} GC_{i_y} \Big/ nd_{C_y}} \quad (8)$$

where the global citation counts of a document *i* published in a certain year (y) is represented by the variable GC_{i_y}.

The average relative global citations $(ARGC_{It})$ value (denoted as average normalized citations in VOSviewer) of an item (author, journal, or country) is defined as [76]:

$$ARGC_{It} = \frac{1}{nd_{It}} \sum_{i=1}^{nd_{It}} RGC_{It_{i_y}} \quad (9)$$

where $RGC_{It_{i_y}}$ represents the global citations of document *i* of the item published in year *y*.

The international co-authorship (IcA_C) ratio of the collected dataset is calculated as [77]:

$$IcA_C\ (\%) = \frac{MCP}{n}\ 100 \quad (10)$$

where *MCP* is the multiple country publications (publications having affiliations from at least two different countries) in the collection.

The articles fractionalized (*AF*) value of an author is calculated as follows [78]:

$$AF = \sum_{i=1}^{m} \frac{1}{d_i} \quad (11)$$

where *m* is the number of documents of an author and d_i denotes the number of co–authors in the corresponding documents.

The *h*-index is a metric of the number *h* of publications of a researcher or a journal that have been cited at least *h* times [79]. The *m*-quotient (denoted as *m*-index in Biblioshiny) is calculated by dividing the *h*-index of an item (author, journal or country) by the total number of years from the item's first publication and it can be calculated as in Eq. (12) [80].

$$m - \text{index} = \frac{h - \text{index}}{Y_{fi} - Y_{xi}} \quad (12)$$

where Y_{fi} is the final year of publication and Y_{xi} is the initial year of publication of an author or a journal. However, the Biblioshiny package uses y_C instead of Y_{fi} to calculate the *m*-index of an item.

When we rank a set of articles in descending order by number of citations, the *g*-index is the largest number of times the top *g* articles have received at least g^2 citations in total [81].

A word cloud technique was used to identify the most important words within the collection. Before using the word cloud approach, the text was cleaned up using Orange Data Mining Tool (https://orangedatamining.com/) in a pre-processing stage that included stop word removal, lowercase conversion, accent removal, URL removal, tokenization, and lemmatization. The emotion analysis was performed in Python using J. Hartmann's emotion-english-distilroberta-base pre-trained model, which can be found in the Hugging Face website (https://huggingface.co/). The model is an optimized DistilRoBERTa-based checkpoint. It divides the data into seven emotional categories: fear, joy, disgust, sadness, neutral, anger, and surprise. The sum of the scores of all emotions equals one, and the emotion with the higher score relatively expresses the emotion of the sentence. For the zero-shot text sentiment classification, Facebook's bart-large-mnli architecture was employed in Python. After training on the Multi Natural Language Inference dataset, this model serves as a checkpoint for the bart-large model. For the sentiment analysis, three classes were depicted: positive, negative, and neutral. The total of all sentiment scores equals one, and the emotion with the greater score reflects the statement's sentiment more effectively [65,82,83].

3. Results and discussions

Bibliometric datasets measure and analyze scientific outputs in various dimensions (number of publications, number of citations, *h*-index, geographical distribution, collaboration network, keywords, topics, journals, authors, and institutions). However, before considering the nuances, understanding the basic statistics of the dataset is substantial. The fundamental information of the collection provides a quick overview of the current state of the SGE domain, which can be found in Table 1.

The SGE collection starts with two consecutive articles published in 1976 by Journal of Membrane Science entitled "Production of energy from concentrated brines by pressure-retarded osmosis. I. Preliminary technical and economic correlations" and "Production of energy from concentrated brines by pressure-retarded osmosis. II. Experimental results and projected energy costs" [84,85]. The first one, focused on preliminary technical and economic correlations of SGE, was reported by Loeb S.; while the second one, more oriented to experimental results and projected energy costs of SGE, was reported by Loeb S., Van Hessen F., and Shahaf D. These two first articles played important role for the initial development of PRO since both theoretical and practical aspects of SGE were thoroughly discussed. As summarized in Table 1, the total number of journals that published SGE papers is 258. This high number of sources publishing SGE proves that this area is recognized as an important branch of science by many journals. The compound annual growth rate (*CAGR*) of these sources is found to be 9.76 %, which indicates the increase of number and quality of SGE research and publications. Besides, the *CAGR* indicates that the SGE field is interesting, innovative, and overall valuable for the scientific community. The average age of the collected articles is 6.17 years, while the average citations per article is 42.82. The value of the article's average age indicates how young the published articles are and how recently they have been published. The high number of citations clearly reveals the SGE domain's impact in other research fields or the same SGE field. The total number of authors (2658) shows that many researchers are interested in SGE. Among the high number of SGE authors, 31 authors published their SGE papers as single authors (i.e., without co-authors), while the number of single-authored articles is 50. On the other hand, it was found that the average number of co-authors per article is 5.17, which indicates

Table 1
Primary details of the SGE dataset.

Information	Value
Timespan[a]	1976:2023
Sources (Journals)	258
Compound Annual Growth Rate $(CAGR_C)$ *(%)*	9.76
Document Average Age (DAA_C)	6.17
Average Global Citations per *Document* $(AGCD_C)$	42.82
References	39455
Keywords Plus	6144
Author's Keywords	2183
Authors	2658
Authors of Single-authored Documents	31
Single-authored Documents	50
Co-Authors per *Document* (cAD_C)	5.17
International co-Authorships (IcA_C) *(%)*	26.77

[a] In Scopus database R.E. Pattle, 1954 [1] is tagged as a "Letter" not as an "Article" so this document is not included in the analysis.

that the number of authors of the articles is relatively high. The rate of international co-authorship is 26.77 %, implying that the SGE subject's international cooperation is low The annual SGE scientific production together with the average citations per article published in the corresponding year metrics $(AGCD_{C_y})$, which is the ratio of the sum of the citations of the articles published in the corresponding year to the number of articles published in the corresponding year, and the normalized average citations per article published in the corresponding year $(ANGCD_{C_y})$ metrics in which $AGCD_{C_y}$ value is normalized by dividing the age of articles published in the corresponding year, are good ways to output the scientific research numbers and to study the impact of the SGE field. The results are plotted in Fig. 1.

Fig. 1(a) indicates the annual publication of the SGE articles and as it can be seen, the number of SGE articles has increased significantly over time, especially after 2012. For instance, while 25 articles were published in 2012, this number doubled in 2013 (i.e. 51 articles). Therefore, 2013 can be considered the breakthrough year for the interest in SGE research. Moreover, the enhanced number of published articles in the last decade indicates that this field has become a more popular and important research area within the worldwide scientific community. The number of published articles has also seen some fluctuations over time. For example, no articles were published between 1983 and 1985, 1987–1989, and 1993–1997.

From Fig. 1(b) $(AGCD_{C_y}$ value$)$ we can say that articles published in different years have different impacts. For instance, the articles published in the years 1977, 1980, 2000, 2003 and 2006 are less cited, whereas the articles published in 1976, 1981, 1998, 2002, 2007, 2008, and 2009 are highly cited or, which is the same, are impactful. It is clear that the 2 articles published in 2007 received quite a good number of citations (i.e., an average of 338 times). It must be pointed out that the increasing number of published articles, especially after the year 2012, has resulted in a reducing average number of citations received by articles published in the corresponding year. From Fig. 1(c) it can be seen again that the articles published in 2007 received the highest $ANGCD_{C_y}$ with an average of 18.78 per year, while the $ANGCD_{C_y}$ metric of the articles published in the following years decreased.

The page count (i.e. how many pages each article is), reference count (i.e., how many references each article includes), and global citations count (i.e., how many times each article is cited) values of the collected SGE articles are analyzed in term of basic statistical parameters, and the results are given in Fig. 2.

When the statistics of the number of pages of the published SGE articles were analyzed, a significant difference between the minimum and maximum number of pages (i.e., min. = 2; max. = 39) was detected with a standard deviation of 3.98. Fig. 2 indicates that the average number of pages of a typical SGE article is 9–10. The higher this value is, the more references to the article are being used and the more extensive research has been conducted. According to Fig. 2, the articles about SGE generally use between 20 and 55 references. When the global citations were examined, it was found that there were articles with very high citations (877) as well as articles without citations in the dataset. The most common number of citations is 0. This indicates that there are a large number of recently published papers, which have not received any citations yet. The calculated standard deviation of the number of citations of the SGE articles is 75.22. These results show that the citation values of the articles have an extensive range and are variable.

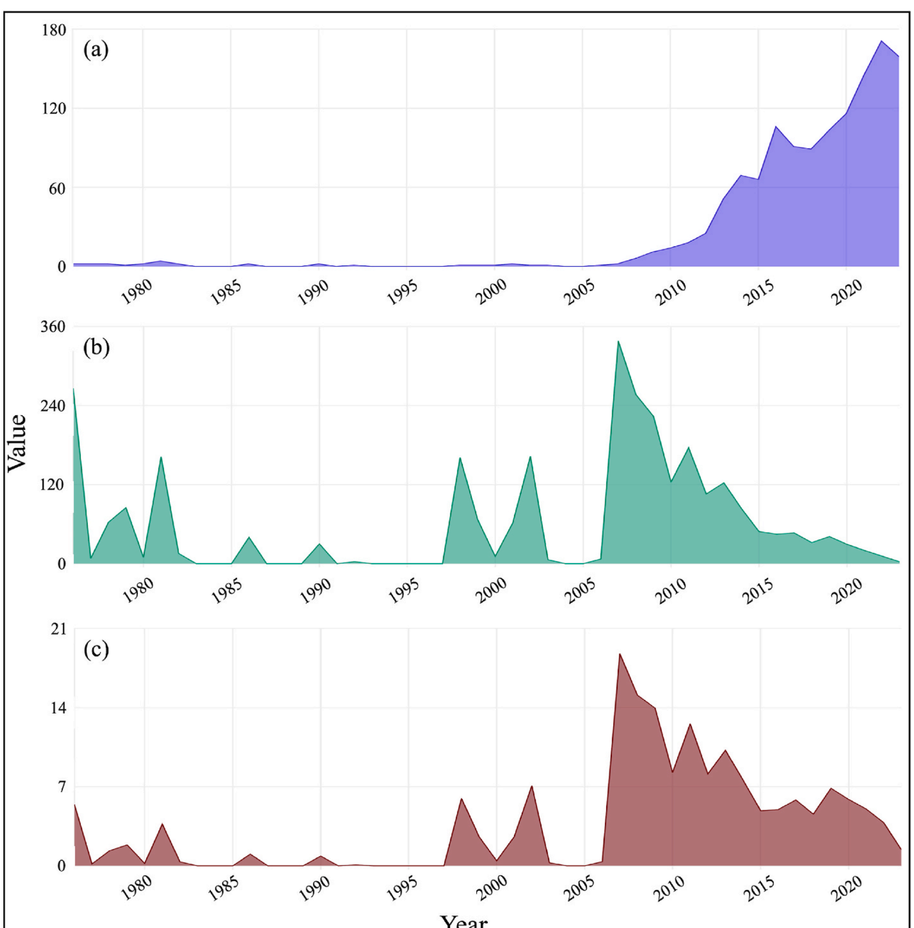

Fig. 1. Annual publications **(a)**, average citations per document published in the corresponding year $(AGCD_{C_y})$ **(b)**, and average normalized citations per document published in the corresponding year $(ANGCD_{C_y})$ **(c)** in SGE research domain.

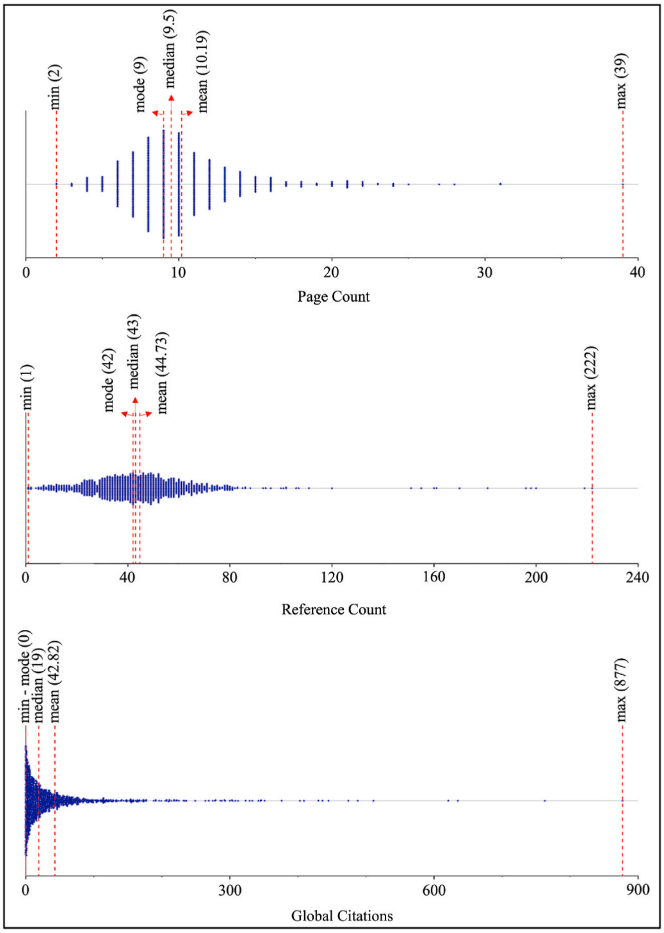

Fig. 2. Basic page count, reference count, and global citations count statistics of the collected SGE dataset.

A systematic effort was made to classify and quantify the proposed SGE technologies. This first involves categorizing SGE technologies based on their operating principles and mechanisms and assessing their performance and applicability in the SGE context quantitatively. Such an analytical approach is instrumental in outlining current SGE technologies' landscape. It facilitates a deeper understanding of their capabilities and contribution to the SGE field. The systematic classification of these technologies identifies specific methods as subsets of broader categories, thereby enhancing the understanding of their technological lineage and interrelationships. Under the umbrella of RED technology, MRED, NRED, and CRED are categorized. At the same time, within the Accumulator Mixing or Accumulator-mediated Mixing (AccMix) technology, MEB and CAPMIX are recognized as subsets [86,87]. This structured classification not only allows for a more nuanced understanding of each of the technologies but also emphasizes the interconnectedness and potential overlap in the operation and application of these technologies within the broader field of SGE harvesting. In conclusion, SGE is emerging as an increasingly important component of renewable energy research. Its low environmental effect and long-term viability highlights its promise as a future energy alternative, particularly in coastal settings. The resulting upset graph can be seen in Fig. 3.

The horizontal graph in Fig. 3's bars labeled "Set Size" indicate how many times each technology's name appears in the overall collection. Purple rectangles and lines in the "Group" field indicate the non-intersecting (stand-alone) or intersecting (hybridization or comparison) technology, and the corresponding number of articles in the Group field. The number of articles based on the Group field is displayed in the vertical bars at the top. The comparative analysis in Fig. 3 identifies RED and PRO as leading technologies in SGE research, with RED referenced 487 times and PRO 375 times. The RED principle involves strategically flowing water at alternating salinities through a carefully arranged stack of selective ion exchange membranes between an anode and cathode. This arrangement creates an electrical potential difference (i.e. electromotive force) between the cathode and anode, accompanied by an "oriented" migration of cations and anions in solution across the membranes. Such a mechanism culminates in the generation of an electric current in the same direction of the generated electromotive force. The

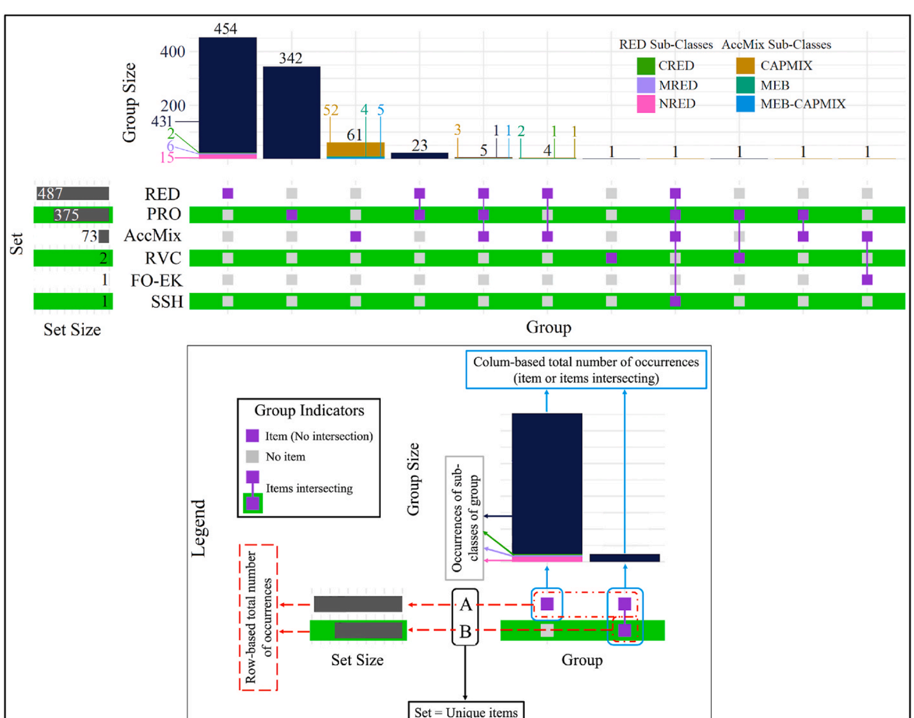

Fig. 3. The energy harvesting technologies used in SGE applications.

potential of RED in energy harvesting is significantly enhanced at the sites where seawater and river water converge. The pronounced salinity gradient can be exploited to optimize energy harvesting. This observation underscores the potential of RED technology to enhance salinity gradient energy harvesting efficiency and provides a compelling case for its application in regions with natural salinity gradients [88]. Fig. 3 shows the prevalence of various hybrid adaptations of RED technologies. These include mixed RED (MRED), nanofluidic RED (NRED), and capacitive RED (CRED). Notably, with 15 citations in the literature, NRED emerges as the most discussed technology. NRED is characterized by using ion-track etching techniques for the fabrication of nanochannels with charged nanopores. This innovation exploits nanoscale fluid dynamics' unique properties to improve ion transport efficiency across membranes. In this kind of membrane, the electric double layer (EDL) is produced adjacent to the charged nanopore surface, where co-ions are rejected and counter ions are attracted and therefore, the membrane is selective for cations or anions depending on the surface charge types. Because of the membrane's larger ionic flow and lower fluidic resistance, NRED greatly outperforms traditional membrane-based RED devices [89–91]. MRED has been mentioned in 6 papers. This technology can obtain electrical energy from salt gradients and chemical energy from organic waste. It is a hybrid system combining microbial fuel cells and RED. In an MRED system, spontaneous reactions at the electrodes are driven by exo-electrogenic bacteria at the anodes or oxygen reductions at the cathodes, which release energy. This technology surpasses the constraints of the two individual processes and has benefits in terms of power and efficiency enhancement [4,7]. CRED is only mentioned in 2 articles in the collected dataset. It is a combination of RED and capacitive electrodes. Utilizing capacitive electrodes prevents redox reactions and permits the use of many membrane cells between a single set of electrodes. The capacitive electrodes of a CRED system are kept from becoming saturated by periodically switching the feed fluids and inverting the electric current's direction. In large-scale operations, salinity gradients can be used to generate steady electricity by regulating the capacitive electrode charge/discharge cycles in CRED [92,93]. RED technology was also mentioned together with PRO in 23 articles and with AccMix in 4 articles. There are 5 articles in which the three technologies RED, PRO, and AccMix were mentioned, and there is one publication involving the four technologies RED, PRO, AccMix, and SSH. PRO is the second most mentioned energy harvesting technology in the SGE domain (375 published articles). This technology involves the transport of water through a semipermeable membrane from low salinity (e.g. fresh water) to high salinity solutions (e.g. seawater), driven by the osmotic pressure difference. A higher pressure is kept in the saline compartment than in the fresh water one, which "retards" the water flux, but allows to convert this flux in a generation of "pressure energy". This higher-pressure stream generated at the seawater side is used to operate the blades of a hydroelectric turbine to create mechanical and then electrical power [94,95]. AccMix is the third most studied energy harvesting technology in the collected dataset, with 73 published articles. AccMix works by alternating the flow of high-concentration and low-concentration solutions through the internal channel of an electrochemical capacitor (or chemical battery), which transforms the chemical potential of the salinity gradient into electrical energy [96]. AccMix is the general name of two sub-technologies, CAPMIX and MEB [87]. CAPMIX technology strategically modulates high and low-salinity feed solutions in a channel in contact with carbon electrodes. This allows the two solutions to exchange ions ("mix") in a controlled manner, while generating an electrical current through an external circuit connecting the two electrodes. The process generates electricity in an efficient and environmentally sustainable manner by using the difference in salinity to induce charge/discharge cycles of the electrodes, thus generating a change in electrical potential eventually leading to generation of electricity [97,98]. CAPMIX technology further may be divided into many subgroups based on the electrode materials, device topologies, and modes of operation. These subgroups include soft electrode (SE), capacitive energy extraction based on double layer expansion (CDLE), and capacitive energy extraction based on Donnan potential (CDP) [98]. CAPMIX technology is the dominant method within the AccMix group since it has been considered in 52 articles. However, in the whole dataset AccMix technology was encountered in 60 articles. MEB is a kind of battery whose anodic and cathodic electrodes allow it to charge when flushed with fresh water and discharge when flushed with seawater. Using battery electrodes and redox processes, MEB produces a voltage increase caused by a change in electrode potential in solutions with varying concentrations [12,99]. MEB energy harvesting technology has been mentioned in 4 articles in the AccMix group. In the whole dataset MEB was encountered in 11 articles. MEB and CAPMIX both were mentioned in 5 articles in the AccMix group. However, in the whole dataset MEB and AccMix were considered in 6 articles. Other technologies such as Reverse Vapor Compression (RVC), SSH, and Forward Osmosis Electrokinetic (FO-EK) [2,9,11,100] have been considered in very few research studies (i.e., few articles) because these are either recently discovered or are simply inefficient for energy harvesting.

In the RVC process, two water streams of different salinities evaporate under vacuum in separate chambers, creating different vapor pressures. The chamber containing the lower salinity water is in equilibrium at a higher vapor pressure, thus generating a vapor flow into the chamber containing the higher salinity water, characterized by a lower vapor pressure. By placing a turbine between these two chambers, energy is recovered. This method provides a sustainable means of energy recovery that elegantly captures the energy potential inherent in salinity gradients [87]. SSH represents a novel and compelling energy-harvesting technology using poly(acrylic acid) hydrogels as the base material. These hydrogels have the unique property of expanding in fresh water and contracting in salt water, enabling energy harvesting through mechanical expansion and contraction processes without the need for membrane systems [11].

FO-EK is a hybrid energy harvesting system essentially composed of two sub-modules: forward osmosis (FO) and electrokinetic unit (EK). Based on the FO principle, this technology generates a suction force using a salinity gradient to cause a hydrodynamic flow in the FO sub-module. Thus, electric energy is produced via a porous glass included in the EK sub-module in the form of EK streaming potential and streaming current. Without the requirement of an external pressure input, the SGE is converted into electric energy using the suggested power-generating approach [2,86].

There are also some SGE energy harvesting technologies that were not identified in our dataset because either these are not SCI papers or no SGE related SCI article has been published yet, but these have been proposed by different sources. One of them is hydrocratic generator (HG). Although HG technology was patented in 2001 by Finley, W., Pscheidt, E. [101], and two non-SCI articles were published [13,102], it was not introduced to the scientific community as an SCI indexed journal. However, in the SGE field it is classified as an energy harvesting technology in some SCI journals [103–106]. For these reasons, it is necessary to provide information about HG technology, although it is not included in our classification. By eliminating the need for membrane integration, the HG has a remarkable ability to recover energy over a wide range of environmental conditions. The HG system strategically introduces freshwater into the lower inlet of a vertical tube with a series of apertures. This configuration allows seawater to enter through these apertures, causing a swelling response in the hydrogel materials at a variety of salinity levels. Then, it efficiently captures the energy released by these swelling and deswelling processes. This approach demonstrates HG's potential to harness salinity gradient energy without the complexity and limitations associated to those membrane technologies [87]. Similarly, the Electric Double Capacitor (EDLC) technology proposed by Brogioli D. in 2009 [107], was not introduced as a SGE related SCI paper in Scopus database. Since some researchers classified EDLC as an energy harvesting technology in SGE [86,108], it is worth to mention.

EDLCs are cleverly designed to convert temperatures and concentrations gradients into alternating electrical current. This conversion occurs by forming two electrically double layers (EDLs) of opposite charge when a constant voltage is applied across the EDLC electrodes. Electric current is then generated by the migration of ionic charges between these two EDLs. This mechanism highlights the sophisticated ability of EDLCs to take advantage of variations in the environment and convert them into an useable form of electrical energy with a high degree of efficiency [10]. Besides Jiao et al. (2022) [86] suggested faradaic pseudo-capacitor as a class of SGE energy harvesting technology, but to our understanding this technology can only refer to special materials used in AccMix method. Diffusio-Osmosis (DO) is a transport mechanism, which is critical for facilitating osmotically-induced electrical currents from salinity gradients [23]. This transport phenomenon is also considered as an energy harvesting technology class by some researchers [108–110]. Thermo-osmotic energy conversion (TOEC) was proposed as an innovative technology for renewable energy production based on salinity gradient energy [111]. TOEC is a thermo-osmosis process in which water vapor is transported through a porous and hydrophobic membrane (i.e., at least one layer is hydrophobic) due to the transmembrane temperature and osmotic pressure from an atmospheric pressure feed side to a higher hydrostatic pressure permeate side (both heat and mass transfer occur simultaneously through the membrane). A hydro turbine depressurizes the generated permeate for electricity production [112]. For TOEC process, the hot feed source (i.e., low-grade heat or liquid temperature below 100 °C) can be taken from industrial waste heat geothermal wells or solar thermal collectors [113–115]. Although TOEC is centered on using heat as a thermal energy source, it can be integrated with a salinity gradient for more efficient energy harvesting or to create engineered salinity gradients. The combination of TOEC and salinity gradient creates complementary mechanisms that can be used synergistically to enhance energy production and storage [8,19,116,117]. TOEC technology can also be used with seawater desalination. A study by Xiao et al. (2023) [118] found that the this technology may reduce RO water production costs by at least 28 %. More SGE technologies can be found in the literature (i.e. mechanochemical turbine [119], dialysis cassettes [120], hydro-voltaic cells [121]), but the research on these topics is scarce, and published experiments have shown low power generation outputs, making it difficult to judge their practicality [19] thus these technologies are excluded from our classification process. SGE researchers are continuously exploring various methods to improve energy harvesting performance. One promising approach is the structural nanopores in membranes. Energy conversion based on nanochannels has gained more interest as an advanced nanotechnology research field. When a solid surface is brought into contact with an ionic solution, it becomes charged because of dissociation and adsorption by the solid material. The EDL is created when the co-ions are excluded and the counterions are absorbed to the charged surface. When the concentration difference is applied at both ends of the nanopore, the ions are transported in the gradient direction, and the electrical energy is harvested by the huge net charge density [122]. The SGE conversion in nanochannels tailored in membranes with different geometric shapes has become a hot research topic due to advances in nanofabrication technology. It is noteworthy that a good power production capability has been established using geometrically asymmetric nanochannels [123]. The studies based on nanoporous membranes emphasize various aspects of SGE systems. These include analyzing the effects of the geometrical parameter dimensions of channels [124], proposing and evaluating the charged conical nanopores [122] and examining the impact of the shape and surface charge of staircase nanochannels [123]. Such research significantly contributes to understanding how the design parameters of nanochannels and nanopores influence the performance of these systems.

The yearly publications of the three most used SGE energy harvesting technologies (RED, PRO, AccMix) are plotted in Fig. 4.

As can be seen in Fig. 4, the number of publications on energy harvesting technologies in the SGE field has always been limited until 2005 when PRO technology attracted the attention of scientists together with RED. These two technologies came into severe competition for years. On the other hand, AccMix technology has been an energy harvesting method that started to be studied since 2010. PRO was the more popular SGE energy harvesting technology for many years (from 2012 to 2018), thanks to the extraordinary developments in membrane engineering technologies, it suddenly lost its popularity. A significant number of articles (65) were published in 2016, and since then, interest in PRO faded drastically. In contrast, RED technology has continued to attract the attention of the SGE scientific community with determined steps until it has become the main energy harvesting technology during the last 5 years. RED's ability to directly convert salinity gradients into electricity provides it with distinct advantages over PRO in harnessing energy from salinity gradients. RED's direct approach increases energy yield and efficiency, unlike PRO, which requires an indirect mechanical conversion process. This direct conversion method also increases RED's operational reliability and reduces maintenance requirements by mitigating problems such as membrane fouling. With no moving parts, RED has a mechanical simplicity that contributes to its sustainability by making use of the perpetual resource of salinity gradients [125]. Moreover, RED features allow its use also at extreme conditions of salinity gradients, such as using saturated brines, to maximize the energy potential in open [126,127] and closed loop [128,129] applications. As a result, compared to PRO's indirect methods, RED's direct conversion of energy from salinity gradients positions it as a superior and more efficient technology for renewable energy production. In 2022, the number of articles published on RED reached 71, the highest number of articles ever published in one year. In the last year (2023), the number of RED-related publications was 62. Compared to PRO and RED, AccMix technology, which reached its highest publication value with 13 articles in 2014, after being presented to the scientific community with the first paper published by La Mantia et al., in 2011, entitled "Batteries for efficient energy extraction from a water salinity difference" [130], could not continue its trend and did not attract much attention.

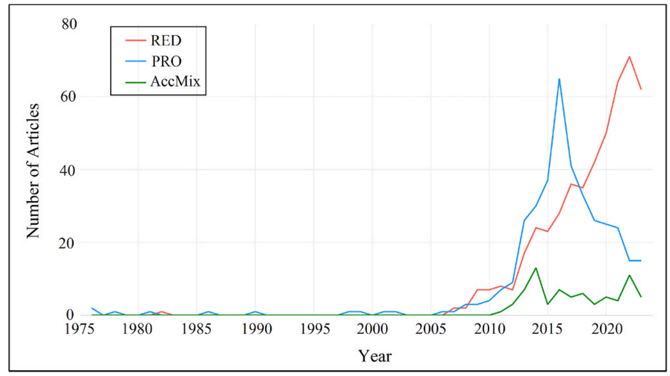

Fig. 4. Yearly publications of the three main SGE energy harvesting technologies groups (RED, PRO, AccMix).

Another important analysis concerns the distribution of published articles by countries, showing the extent to which these energy harvesting technologies have been differently developed in countries worldwide. This type of research helps recognize those countries more active in a specific SGE technology. VOSviewer was employed for the execution of the analysis and the resulting map is illustrated Fig. 5.

As can be seen in Fig. 5(a), the top 5 countries conducting SGE research using RED are China (149), USA (76), the Netherlands (75), Italy (64) and South Korea (60). Fig. 5(b) shows the country-based distribution of PRO technology. In this case USA is the leader contributing with 81 papers, followed by Singapore (69), China (49), South Korea (45) and Australia (26). Fig. 5(c) presents the distribution of the AccMix technology by countries, showing how USA ranks first with 19

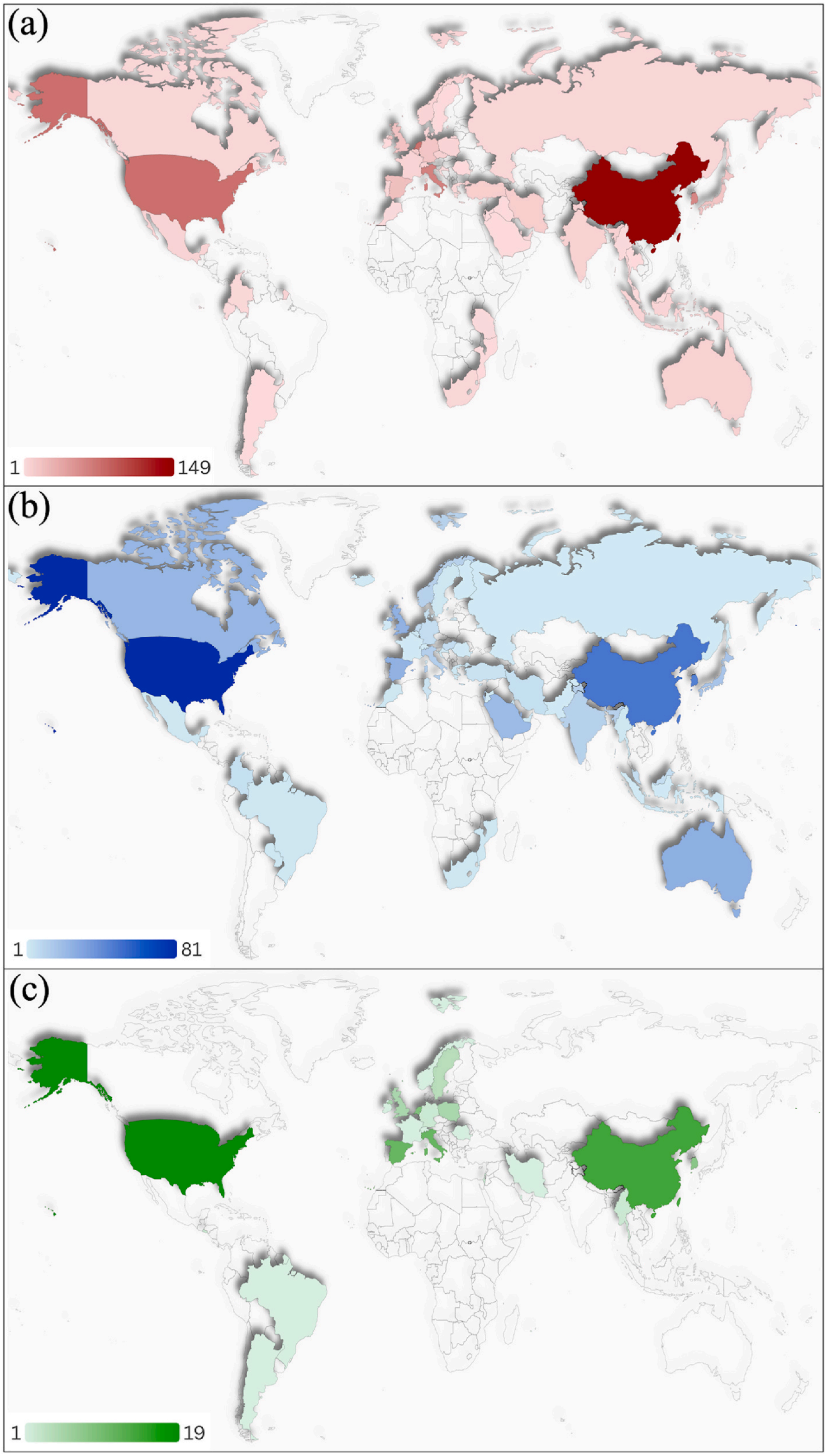

Fig. 5. Distribution of published paper on SGE harvesting technologies by country **(a)** RED, **(b)** PRO and **(c)** AccMix.

papers, followed by China with 14 papers, Italy, and Spain with 11 papers and the Netherlands with 9 papers. Considering all SGE energy harvesting technologies, it is observed that Chinese researchers are more interested in RED technologies, while USA researchers have been more interested in PRO and AccMix.

These results suggest that looking at the distribution of publications on SGE energy harvesting technologies by continent rather than by country will help us take a broader perspective, gain a more holistic understanding, understand policy and strategy development issues, make comparisons, and identify trends. Table 2 summarizes the

Table 2
Distribution of the considered SGE energy harvesting technologies by continent.

Continent	Number of papers		
	RED	PRO	AccMix
Africa	9	9	0
Asia	279	275	29
Australia	7	26	0
Europe	263	115	52
North America	86	106	21
South America	5	9	2

distribution of the SGE technologies by continents.

According to Table 2, it is evident that scientists from Asia have published more papers on PRO and RED energy harvesting technologies (275 and 279, respectively) than scientists in other continents. European and North American researchers have published almost the same number of papers dealing with PRO technology (115 and 106 respectively). However, European scientists are very close to Asian scientists in the number of publications on RED technology (263 articles). Regarding AccMix technology, most studies were carried out in Europe (52). Asia comes second with 29 articles and North America third with 21 articles. As shown in Table 2, the number of papers published by Australian, African, and South American researchers on SGE energy harvesting technologies is very low.

One of the main objectives of bibliometric analysis is to reveal the most active and influential scientists in a given domain. In the field of SGE, the Top 20 researchers were identified based on the highest number of published articles and their indices, and the obtained results are summarized in Table 3.

Considering the top authors in each column of Table 3, Jiang L. (Technical Institute of Physics and Chemistry, Beijing, China) is detected as the author who published the most significant number of articles in the SGE field (i.e., 79 articles), although he is not the author with the earliest career (i.e. first year of publication 2010). He is also the author with the highest *g*-index (72). Besides, Jiang L. is the most cited author (i.e., his articles have received 5233 citations). Although Wen L. (Technical Institute of Physics and Chemistry, Beijing, China) is one of the authors who published his first article quite late (2015), he occupied the second rank in Table 3 with 46 published articles. It must be pointed out that, based on the fractional number of articles, Chung T-S. (National University of Singapore, Singapore, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia) is on the top (i.e., 13.87 articles fractionalized). This value indicates that Chung T-S. has published with fewer co-authors than other researchers. In addition, Chung T-S. is the author with the highest *h*-index (34) and *m*-index (2.833). Saakes M. (Wetsus, European Centre of Excellence for Sustainable Water Technology, Leeuwarden, Netherlands) and Nijmeijer K. (Eindhoven University of Technology, Eindhoven, Netherlands) are the authors with the oldest careers, as both published their first articles in 2009. In general, we can say that Jiang L. and Chung T-S. stand out in terms of both the number of published articles and the number of citations, they have good rankings in both the *h*-index and *g*-index, and they perform quite well in the *m*-index.

Social structures in a scientific field refer to the set of relationships formed by researchers, institutions, organizations, journals, groups, and networks involved in the field. These are factors that influence the production, exchange, evaluation, and impact of scientific knowledge and determine the communication, cooperation, competition, norms, culture, and identity of the related scientific community. To understand the social structure of SGE authors, a co-authorship analysis using VOSviewer was conducted, and the obtained results are plotted in Fig. 6. Note that to improve the legibility of the figure, the minimum number of documents of an author value is set to 13 and unconnected items are filtered out.

In Fig. 6, the node size (vertex) is directly proportional to the number of articles of the item. A larger node indicates more articles and vice versa. The thickness of the edge (link) shows the connection (the degree of co-authorship) between two nodes. The thicker edge between two nodes means more co-authored publications and vice versa. Fig. 6 shows that there are 8 social structures (scientific teams). The smallest of these

Table 3
Top 20 SGE authors based on the number of published articles.

Author	Number of Articles	Articles Fractionalized (*AF*)	First Year of Publication	Global Citations (*GC*)	*h*-Index	*g*-Index	*m*-Index
Jiang L.	79	9.44	2010	5233	39	72	2.600
Wen L.	46	5.32	2015	2573	28	46	2.800
Chung T-S.	43	13.94	2013	2866	34	43	2.833
Micale G.	43	7.38	2012	2122	29	43	2.231
Wang Y.	43	9.17	2010	1458	20	38	1.333
Cipollina A.	39	6.57	2012	2035	28	39	2.154
Tamburini A.	38	6.54	2012	1837	27	38	2.077
Saakes M.	34	7.86	2009	3765	25	34	1.563
Kon X-Y.	33	3.51	2015	1958	21	33	2.100
Li X.	33	6.86	2013	1208	16	33	1.333
Liu Z.	33	6.42	2013	820	17	28	1.417
Nijmeijer K.	29	6.98	2009	3591	26	29	1.625
Chen Y.	28	6.32	2013	792	16	28	1.333
Wang S.	25	3.52	2011	471	11	21	0.786
Kim H.	24	3.3	2012	426	11	20	0.846
Logan B. E.	24	6.55	2011	1895	22	24	1.571
Wang H.	24	3.54	2014	1105	16	24	1.455
Zhang Y.	24	4.47	2012	663	14	24	1.077
Zhu X.	22	4.73	2013	769	15	22	1.250
Xu S.	21	3.43	2017	318	10	17	1.250

Low — **High**

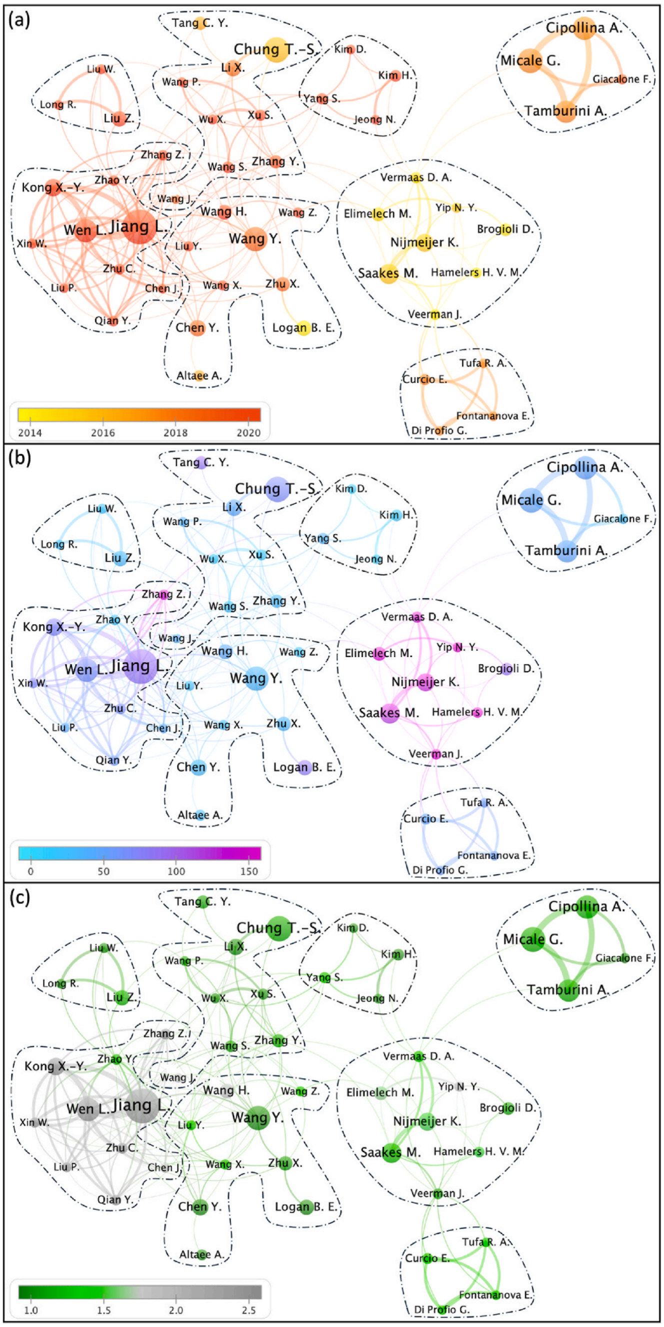

Fig. 6. Co-authorship analysis of authors **(a)** documents average age (average publication year) (DAA_{It}), **(b)** average global citations per document ($AGCD_{It}$), and **(c)** average relative global citations ($ARGC_{It}$) (weights = documents, min. number of documents of an author = 13, clusters with single item are removed).

include 3 scientists, while the largest structure has 10 scientists. Fig. 6(a) indicates the average publication years (DAA_{It}), of the researchers, with yellow being the oldest and red being the most recent. When cluster-based assessments are made, the cluster with the oldest articles (DAA_{It} value of 2014.59) is the cluster led by Saakes M., while the social group with the newest studies in the field of SGE is the cluster headed by Jiang L. (2020.52). When the average global citations per document ($AGCD_{It}$) value in Fig. 6(b) is analyzed cluster-wise, the cluster with the highest average global citations per document value is the social network led by Saakes M. (132 global citations per document), while the social structure with the lowest $AGCD_{It}$ value is the cluster of 4 members including Kim H. with a value of 22.47. To eliminate the problem of differences in citation counts due to the age of a document and to interpret the impact of a document more accurately, the average relative global citations metric ($ARGC_{It}$), which considers the number of years of publication, is more descriptive. This parameter first divides the citations of articles written by an author in each year by the total citations of articles written in the corresponding year and then takes the sum and averages this value with the number of the publications of the author. This type of normalization corrects the misconception that older documents obtain more citations than more recent ones [76,131,132]. Fig. 6(c) indicates the average relative global citations ($ARGC_{It}$). The cluster lead by Jiang L. is at the top, which has an average $ARGC_{It}$ value of 2.49 and the cluster headed by Kim H. is at the bottom with an average $ARGC_{It}$ value of 0.76.

When social links are analyzed individually, the authors with the highest number of links (co-occurrence of authors) are Micale G. - Tamburini A. and Jiang L. - Wen I. with 36 co-publications. The author with the lowest average publication years (DAA_{It}) value is Hamelers H. V. M. with 2013.67, while the author with the most recent articles is Liu P. with 2021.08. The scientist with the highest global citation value per document is Yip N. Y. (161.86) and Kim. D. at the bottom of the list with 15.54. In the $ARGC_{It}$ metric, Zhang Z. comes first with a value of 3.84, while the lowest value of this metric belongs to Kim D. with 0.49.

VOSviewer was also used to identify the most active and collaborative countries in SGE research. The results are presented in Fig. 7. To improve the readability of Fig. 7, the minimum value of the number of articles published in a country was set to 15, and the unconnected items were filtered out.

In Fig. 7, the most significant node corresponds to China, which is the country most active in SGE technology research and has the highest number of publications (429) in the collected dataset. The USA ranks second with 218 publications, and South Korea with 127 published articles. Although China has the most significant number of internationally collaborated articles (total link strength of 135), the USA has the most connections to different countries (20 links). The most extensive connection was found between China and the USA (40 co-authored articles), and between China and Australia (22 co-authored articles). Additionally, one of the important points that draws attention in Fig. 7 is the groupings of countries, forming 5 clusters. While Israel has social connections with 4 countries, it includes a cluster on its own. Fig. 7(a) shows the average publication of the countries in which the more the color scale of the countries in the clusters shifts to yellow, the less up to date their documents are. China has paid attention to SGE research in recent years (2020.48). Although USA ranks second in the number of published articles, their articles are becoming older than those of China (2016.11). Besides, the cluster led by China has more recent SGE research studies (cluster average 2018.46).

Fig. 7(b) expresses the countries' $AGCD_{It}$ values. France, The Netherlands, and Belgium received high average citations per article values indicated with pink color and with values of 110.47, 101.41, and 90.09, respectively. China is number one in terms of number of publications, but it is not at the top regarding the average citations per article (30.36). On the other hand, USA appears to be more balanced than China in terms of published articles and average citation per article metrics (64.17). Fig. 7(c) indicates countries' $ARGC_{It}$ values. The top 3 in this metric are France, Germany, and Saudi Arabia, with values of 1.93, 1.88, and 1.72, respectively. The countries dominating the SGE area are understood to be in good values regarding the average normalized citation. The country left behind in this metric is Spain, with an average normalized citation of only 0.46, showing less research interest devoted to SGE technology research. However, this country is promoting the use of renewable energy, sustainability, and circular economy. This is partly attributed to the relatively little or no government funding allocated to this type of SGE research study.

Knowing the leading journals of a scientific field can be useful for accessing up-to-date knowledge exchange and quality information about a subject of interest [133]. Bibliometric methods offer unlimited

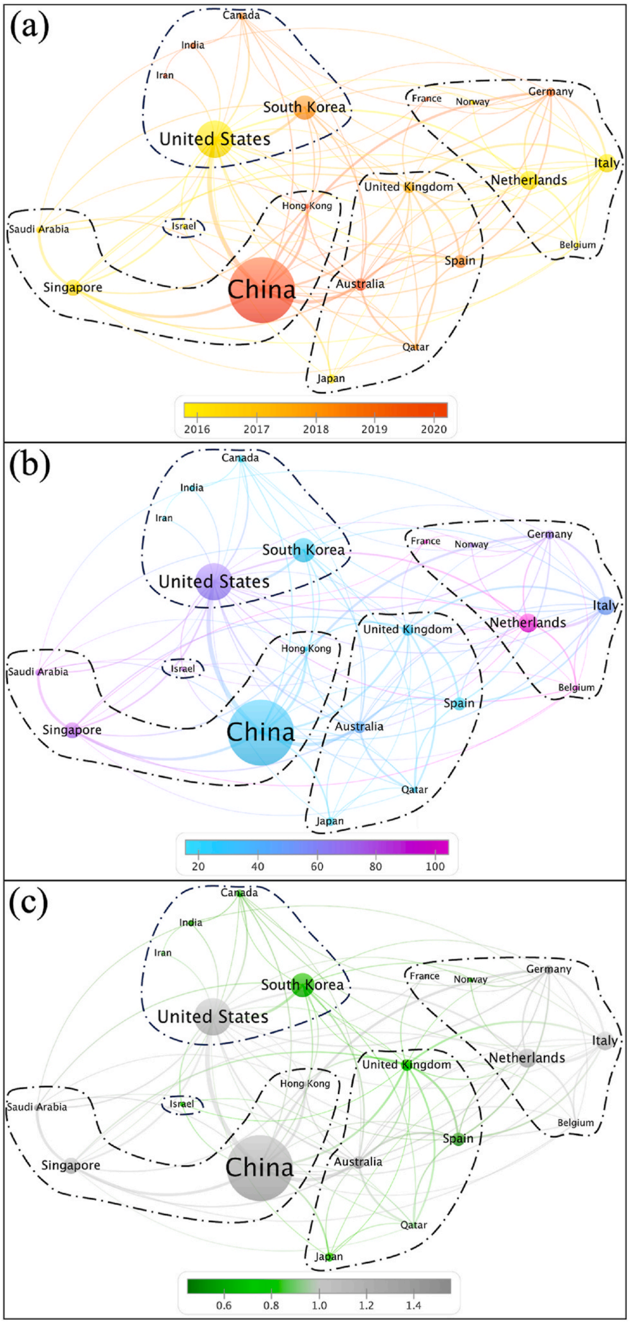

Fig. 7. Co-authorship analysis of countries **(a)** documents average age (average publication year) (DAA_{It}), **(b)** average global citations per document ($AGCD_{It}$), and **(c)** average relative global citations ($ARGC_{It}$) (weights = documents, min. number of documents of a country = 15, clusters with single item are removed).

opportunities to communicate to readers the most robust journals in a scientific subject. This study also investigated information from important journals related to SGE. Table 4 includes various indicators used to analyze the scientific impact of the top 20 journals based on their number of publications on SGE technologies.

Journal of Membrane Science is the leading source with most SGE articles published (135), together with the highest global citations (12393), *h*-index (61), and *g*-index (110) values. These metrics indicate that the papers published in this journal stand out also for their quality. Besides, this journal published the oldest SGE article in the collected dataset 48 years ago. However, it is one of the journals with a low *m*-index value (1.245) because of this old publication.

Maybe it is not fair to evaluate a journal according to *m*-index in scientific disciplines with an old history such as SGE because this criterion may mislead readers. With 133 articles, Desalination has published 2.46 times more than Desalination and Water Treatment, the third most publishing journal. Among the top 20 journals, ACS Nano appears to be the youngest source publishing about SGE (i.e., the first published article in this journal was in 2019). Nano Energy is also one of the newest journals publishing SGE articles (2018). This journal published its first SGE article in 2018 and, up to date, has only published 26 articles. Nano Energy journal has been cited 975 times and has an *h*-index of 19. Furthermore, the *m*-index value is 2.714, which indicates that this journal is at the top among other journals in terms of the normalized impact of its articles. The values in Table 4 may be useful to illustrate the academic impact of journals for researchers working on SGE, but more is needed. Other factors, such as the journal's general scope of publication, target audience, peer review process, and publication policy, can also affect the quality of the journal. Therefore, SGE researchers need to consider more than one indicator and factor when evaluating the journals in which they want to publish their articles.

Analyses were also conducted on the research institutions to which the authors of the published works are affiliated. According to the number of the yearly published articles, the main research institutions are presented in Fig. 8. It should be noted that the Biblioshiny tool counts affiliations according to authors; for example, if two authors of a paper belong to the same affiliation, the tool counts this affiliation as two, not as one.

As it is depicted in Fig. 8, among the top 10 affiliations, the first institute to publish in the field of SGE was the European Centre of Excellence for Sustainable Water Technology (WETSUS) with a frequency of 6 in 2009. However, WETSUS's publications were limited in the following years and other affiliations took the lead. Nanyang Technological University and Università Degli Studi di Palermo (UNIPA), which published their first SGE publications in 2012, and National University of Singapore, which published its first SGE paper in 2013, remained as the dominating institutions in the field of SGE for many years. Università Degli Studi di Palermo (UNIPA), which contributed in the SGE research with 8 articles in 2012, continued to publish with an increasing trend taking the leadership from National University of Singapore in 2018 whose number of publications amounts to 203 articles at the end of 2023. Beihang University, on the other hand, accessed this SGE field very late, in 2017, with a frequency of 5 articles per year; but with its high number of publications made since 2021, it ranked second with 166 articles at the end of 2023. The importance that Dalian University of Technology and the Technical Institute of Physics and Chemistry (Beijing, China) have given to the field of SGE in recent years can be seen by the number of papers they have published. By 2023, these two institutions published 166 and 165 articles, respectively.

Most important SGE articles were identified based on their high global citations (*GC*), and the Top 20 articles, together with their metrics, are summarized in Table 5.

The article's global citations are an indicator of international recognition and how influential a published article turns out to be. The article published by Siria A. et al. (2013) [23] in Nature under the title "Giant osmotic energy conversion measured in a single transmembrane boron nitride nanotube" is the most globally cited SGE article with 877 citations. This paper highlights the fabrication and use of a hierarchical nanofluidic device made of a boron nitride nanotube and the finding of very large osmotic-induced electrical currents generated by salinity gradients. The article also claims that this result is due to the abnormally high surface charge of the inner surface of the nanotube. The following nano-assembly method using nanostructures enabled the study of nanoscale fluid, ion, and molecule transport. When the articles in the dataset are sorted according to their local citations (i.e., most cited article in the collection), the study reported by Post et al. (2007) [138] entitled "Salinity-gradient power: Evaluation of pressure-retarded osmosis and reverse electrodialysis" was found to be in the first place

Table 4
Top 20 journals based on the number of published articles on SGE technologies.

Journal	Number of Articles	First Year of Publication	Global Citations (*GC*)	*h*-Index	*g*-Index	*m*-Index
J. Membr. Science	135	1976	12393	61	110	1.245
Desalination	133	1982	5464	40	68	0.930
Des. Water Treat.	54	2009	1285	20	35	1.250
Env. Sci. Technol.	47	2008	5558	37	47	2.176
Energy	35	1978	1208	19	34	0.404
Nano Energy	33	2018	975	19	31	2.714
Ener. Conv. Manage.	33	2015	607	15	24	1.500
Membranes	31	2013	306	11	16	0.917
App. Energy	28	2013	1299	19	28	1.583
Energies	28	2014	352	11	18	1.000
ACS App. Mater. Int.	27	2013	671	12	25	1.000
Electro. ACTA	24	2013	593	15	24	1.250
Renewable Energy	23	2014	614	13	23	1.182
J. Mater. Chem. A	20	2014	773	14	20	1.273
J. Power Sour.	20	2014	594	14	20	1.273
Chem. Eng. J.	20	2011	817	10	20	0.714
Water Research	18	2013	853	13	18	1.083
ACS Nano	16	2019	734	10	16	1.667
Adv. Functional Mater.	15	2010	1244	12	15	0.800
J. American Chem. Society	14	2014	1589	12	14	1.091

Low — High

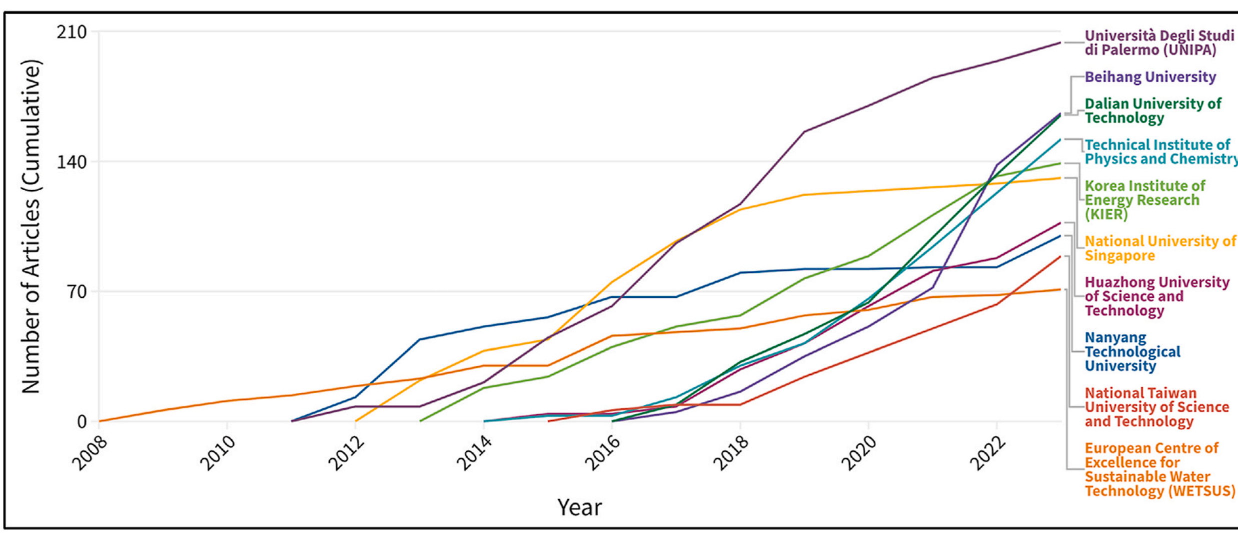

Fig. 8. Top 10 affiliations over time SGE publications.

with 210 cited by value. In this study, the two membrane-based energy conversion techniques, PRO and RED, were compared in terms of power density and energy recovery. According to the model calculations conducted in this study, the potential performances of both PRO and RED are much more advanced. However, it is explained that both methods need to be improved. The article "Power generation with pressure retarded osmosis: An experimental and theoretical investigation", published by Achilli A. et al. (2009) [136] in the Journal of Membrane Science, has been cited 207 times locally (i.e., local citations). In this study, a PRO model was developed to predict water permeate flux and power density under specific experimental conditions. It must be pointed out that a nonlinear correlation was found between the global citations (GC) and the articles' local citations (LC) (see LC/GC ratio in Table 5). No clear trend could be detected between the GC and LC values (i.e., the LC/GC ratio varies between 1.96 % and 46.75 %). The article exhibiting the highest LC/GC ratio (46.75 %) is entitled "The Potential for power production from salinity gradients by Pressure retarded Osmosis" and published by Thorsten and Holt in 2009 [149]. This study used PRO technology for energy generation, and some laboratory experimental data were given to validate the developed model. The article that shows the highest RGC_i value (17.04), which indicates that it is the article that has received the highest number of global citations

Table 5
Top 20 SGE articles based on their global citations [23,24,84,107,134–149].

Article	Global Citations (GC)	Local Citations (LC)	LC/GC Ratio (%)	Relative Global Citations (RGC_i)	Global Citations per Year (GCY_i)
Siria A., 2013, Nature [23]	877	127	14.48	7.15	73.08
Feng J., 2016, Nature [134]	763	126	16.51	17.04	84.78
Lee K. L., 1981, J. Membr. Sci. [135]	635	125	19.69	3.91	14.43
Achilli A., 2009, J. Membr. Sci. [136]	621	207	33.33	2.78	38.81
Amy G., 2017, Desalination [137]	511	10	1.96	10.97	63.88
Post J. W., 2007, J. Membr. Sci. [138]	488	210	43.03	1.44	27.11
Yip N. Y., 2011, Environ. Sci. Technol.-a [139]	474	143	30.17	2.69	33.86
Dlugolecki P., 2008, J. Membr. Sci .[140]	445	106	23.82	1.73	26.18
Gao J., 2014, J. Am. Chem. Soc. [141]	436	77	17.66	5.22	39.64
Post J. W., 2008, Environ. Sci. Technol. [24]	430	169	39.30	1.68	25.29
Klayson C., 2013, Chem. Soc. Rev. [142]	409	43	10.51	3.33	34.08
Guo W., 2010, Adv. Funct. Mater. [143]	403	71	17.62	3.26	26.87
Zhang Z., 2019, Nat. Commun. [144]	376	73	19.41	9.14	62.67
Siria A., 2017, Nat. Rev. Chem. [145]	351	89	25.36	7.54	43.88
Guo W., 2013, Acc. Chem. Res. [146]	346	8	2.31	2.82	28.83
Brogioli D., 2009, Phys. Rev. Lett. [107]	345	90	26.09	1.54	21.56
Veerman J., 2009, J. Membr. Sci-a [147]	342	143	41.81	1.53	21.38
Loeb S., 1976, J. Membr. Sci-a [84]	333	115	34.53	1.25	6.80
Vermaas D. A., 2011, Environ. Sci. Technol. [148]	329	145	44.07	1.87	23.50
Thorsten T., 2009, J. Membr. Sci. [149]	323	151	46.75	1.45	20.19

Low — **High**

among the articles published in the same year, is Feng J. et al. (2016)' article published in Nature under the title "Single-layer MoS_2 nanopores as nano power generators". Besides, this article has the highest global citations annually (84.78). In this SGE study, a device using single-layer molybdenum disulfide (MoS_2) nanopores was proposed, claiming that a sizeable osmotic current could be obtained due to the salt gradient and to the atomic-thick MoS_2 membrane. The study also highlights that the MoS_2 nanopore generator drives a MoS_2 transistor, thus demonstrating a self-powered nanosystem [134].

Trending research topics (i.e., most popular and discussed interesting topics) in the SGE field have been investigated through the provided authors' keywords in the published articles. The evolution of the detected trending topics on SGE over time is shown in Fig. 9. Note that for better interpretability, authors' keywords expressing the same phenomenon have been converted to the main expression (i.e., RO is replaced with reverse osmosis, PRO replaced with pressure retarded

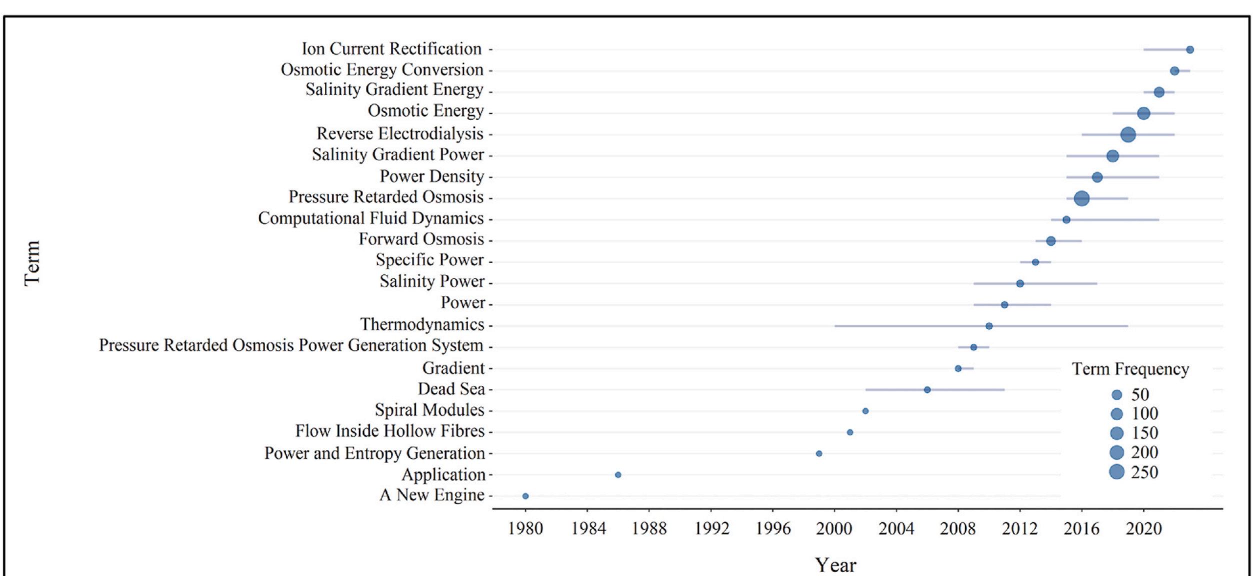

Fig. 9. Trending topics in SGE based on Author's keywords (word min. frequency = 1, number of words per year = 1).

osmosis, FO replaced with forward osmosis, etc.)

As shown in Fig. 9, the basic topic SGE has been the same for most of the years, even though the words change. For instance, the keywords power and entropy generation, power, salinity power, salinity gradient power, SGE, and osmotic energy harvesting indicate that the same goal is pursued. In addition, the types of membranes used in SGE systems are expressed with keywords such as flow inside hollow fibers and spiral modules. Thermodynamic investigations of the SGE process started in 2000 and continued to be studied until 2020. This is a long-lasting trending topic term. The process of modeling and simulating the dynamics, motion, heat transfer, chemical reactions, and other physical phenomena of fluids in SGE systems with numerical methods started in 2014 and continues to this day. The examination of the considered technologies for energy extraction are PRO and RED. Interestingly, it can be read from Fig. 9 that the real applications of SGE were carried out mainly in the Dead Sea [150–155], and this research topic continued between 2002 and 2011. The trending topic of 2023 is ion current rectification (ICR) [156–164], which is an electrodynamic phenomenon in the electrolyte solution that is described as the asymmetric potential-dependent ion flux via a confined environment, resulting in asymmetric electrical current-voltage behavior caused by the impact of an asymmetric double layer structure. The mechanism of ICR can be explained by thermodynamic or kinetic regulation of the electrical double layer structure. The accumulation or dispersion of ions in the electrolyte solution changes because fixed charges on the nanopore's surface change the nanopore's ionic conductivity. Nanopore surface charge can alter the ionic activity in the following ways: i) electric double layer (EDL) formation and ion selectivity (asymmetric distribution of surface charge) and ii) asymmetric geometry and ion accumulation/exhaustion (i.e. conical nanopores). Through EDL formation and ion selectivity (asymmetric distribution of surface charge): The charge on the nanopore surface affects the ionic conductivity through EDL formation. On a negatively charged surface of the nanopore channel, a redistribution of charges takes place at the interface of the solution and the surface of the channel; and the fixed surface charges are balanced by counter ions in the solution. The first layer of the EDL is known as the Stern layer, which consists of counter ions adsorbed on the solid surface. The diffuse layer is the second layer that follows the Stern layer in the solution. In this layer, there are more counterions than ions with the same charge, creating an uneven distribution. This layer plays an important role in balancing the charges at the surface. The combination of the Stern and diffuse layer forms the length of the EDL, which is called the Debye length. The electrical potential on the surface of the charged nanochannel is maximum at the surface, while it decreases as it moves away from the surface reaching the zeta potential at the Debye length. Reducing the nanochannel size to the nanometer scale allows EDL to be effective. Furthermore, the extension of the EDL into the nanochannel increases the diffusion rate of counter ions, leading to ion selectivity. In a conical nanopore, ion accumulation or depletion can occur depending on the direction of the applied voltage. When a positive voltage is applied, cations move to the wide end and anions to the narrow end. At the narrow end, the passage of anions is blocked due to surface charge and ion depletion results in low ionic conductivity. At negative voltage, cations move to the narrow end and ion accumulation occurs at the narrow end because the surface allows the passage of cations, resulting in high ionic conductivity.

The ICR method can be applied in various applications besides the SGE domain, such as in biosensors, ionic transistors, ionic accumulators, ionic separators, ionic modulators, etc. [165–168].

An analysis of the number of words in the titles and abstracts of articles can guide readers in terms of compliance with academic writing rules, readability, effectiveness, and indexing. This type of analysis is also useful for revealing how articles are entitled and summarized in different journals. In Fig. 10, the word count distributions of the titles and abstracts of the published articles in the collection are given with a joint plot.

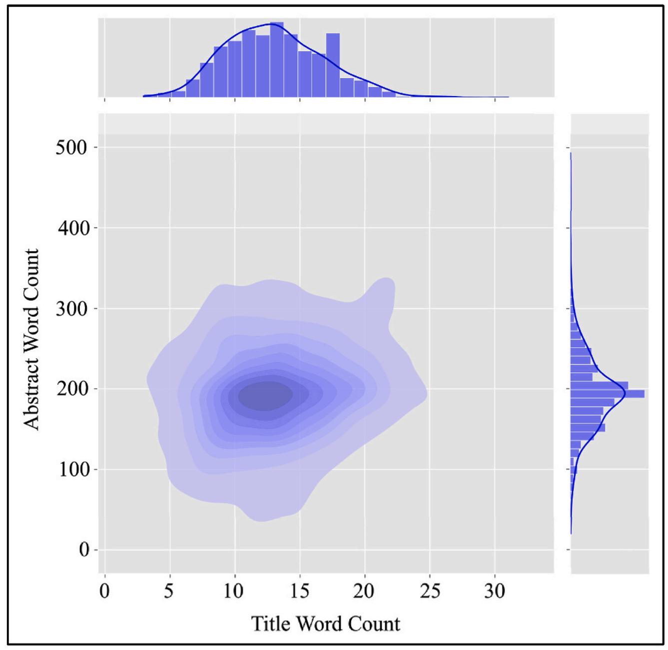

Fig. 10. Joint plot of word counts of titles and abstracts of SGE-published articles.

When Fig. 10 is examined, it is seen that SGE researchers choose the titles of articles with a number of words between 11 and 14, which are mostly 13 words (i.e., mode and median values). The longest title contains 31 words, whereas the shortest title includes only 3 words. The preferred number of words in writing abstracts varies between 180 and 210, the mode and median values 197 and 194, respectively. The article with the longest abstract includes 493 words, whereas the shortest one has 20 words.

Analyzing the abstracts of articles in a scientific field with text mining (TM) can visually and statistically reveal the general feelings, expectations, and realizations of research in the studied field. For example, word cloud analysis helps identify the most important or popular concepts, terms, problems, or solutions in the field by showing the most frequently occurring words in abstracts. Sentiment analysis helps to quantify the general attitude, perspective, expectations, or criticism of research in the field by determining whether the authors' statements in the abstracts express a positive, negative, or neutral tone. Powerful text mining methods are employed in the present study to reveal all these intriguing and exciting features hidden in the abstracts of SGE articles. Fig. 11 shows the word clouds of titles and abstracts of the SGE research field.

Fig. 11(a) reflects the frequency of words in the titles of the published SGE articles. According to this analysis, the 5 commonly used words by SGE researchers in the titles are energy (571), membrane (425), power (417), reverse (357), and electrodialysis (328). Considering these values, it is clear that SGE scientists work a lot on the reverse electrodialysis (RED) technology for SGE. Additionally, the words osmosis (273), pressure (232), and retarded (215), being within the top 15 words, indicate that one of the dominant energy production technologies is the pressure retarded osmosis (PRO). Fig. 11(b) represents the word cloud of the abstracts of the published articles. The top 5 words in this figure are membrane (3590), energy (3531), power (2954), water (1716), and high (1559). As can be seen from this analysis, the frequency of some words is high. Using the same words too much in abstracts may cause the reader to lose interest and disrupt the fluency of the text. For this reason, SGE researchers should be more careful when writing abstracts of their articles. The suggestion to SGE researchers is to avoid repeating the same words as those normally written in SGE articles and to vary the structure and length of the written sentences.

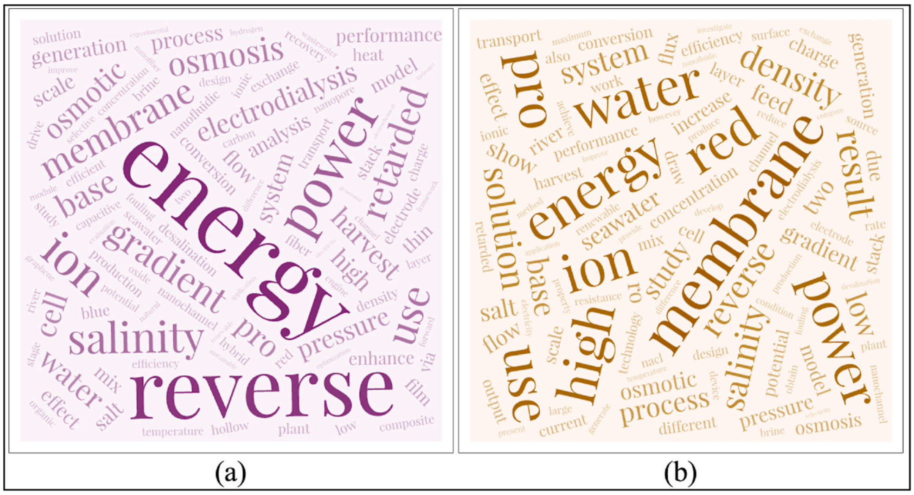

Fig. 11. Word clouds of **(a)** titles and **(b)** abstracts of the SGE articles.

Sentiment and emotion analysis applied to the abstracts of the published SGE articles are illustrated in Fig. 12. This sentiment analysis is divided into 3 classes: positive, neutral, and negative. The sum of an abstract's positive, neutral, and negative scores equals 1. On the other hand, emotion analysis is divided into 5 classes: fear, joy, disgust, sadness, neutral, anger, and surprise. The sum of an abstract's fear, joy, disgust, sadness, neutral, anger, and surprise scores equals 1. Fig. 12 shows the score distributions of sentiment (Fig. 12(a)) and emotion (Fig. 12(b)) with both the density plot (extensive illustrations) and dominant sentiment/emotion (small illustrations). Note that since some articles do not include abstracts, the sentiment analysis was carried out on 1265 documents. Furthermore, since the emotion model cannot process abstracts with more than 512 tokens, emotion analysis was conducted on 1245 documents.

The *y*-axis of Fig. 12 shows the densities (at which values the data points become more frequent) of the analysis results. When Fig. 12(a) is examined, it is understood that SGE researchers are generally optimistic about this technology and the results they obtained in their studies (1111 positive sentiment abstracts). However, the fact that 141 articles had negative sentiment emphasizes that the difficulties experienced in the field of SGE are still a problem researchers must solve. Neutral sentiments were rarely encountered so that they could be ignored (13 articles). Fig. 12(b) indicates whether SGE researchers reflect their personal feelings in their abstracts. The number of abstracts written with neutral emotion (1236) suggests how the authors in this domain do not reflect their personal emotions when writing the abstracts of the articles. While the emotions disgust (8) and anger (1) were measured so little that they could be ignored, emotions such as fear, joy, sadness, neutrality, and surprise were not dominantly encountered.

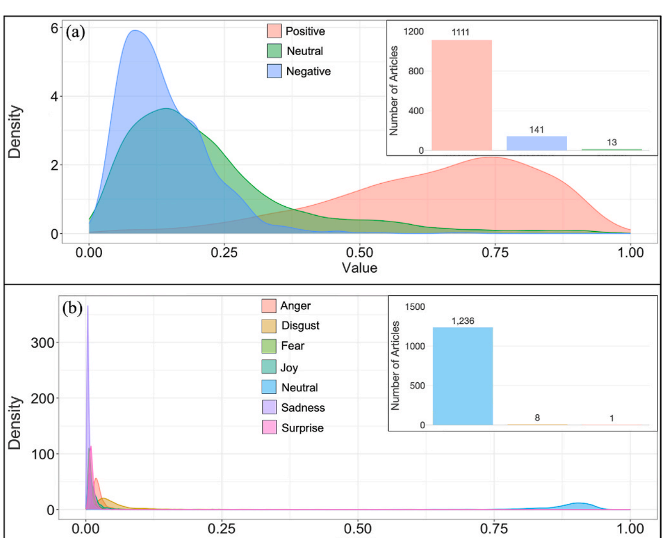

Fig. 12. Sentiment **(a)** and emotion **(b)** analysis of the abstracts of the SGE articles.

Beyond descriptive analyses we draw conclusions based on correlation tests to determine the presence of relationships among different results. Attempts have been made to correlate each of the variables such as number of pages, number of references, number of authors and sentiment results of the SGE articles with the normalized global citation counts. We also analyzed the correlation of authors' collaboration links (i.e., number of co-authors) with global citation counts. The obtained results are illustrated in Fig. 13.

Fig. 13(a) shows the relationship between the relative global citations and page count. There is a very weak, slightly negative relationship, indicated by the almost straight regression line plotted between them and a correlation value of -0.01 (Pearson's correlation coefficient r). This means that the page count does not have a linear correlation with the citation count. The data points are scattered over a large area, which supports the lack of a strong relationship. Fig. 13(b) shows the correlation between the relative global citations and the author count. It shows a weak, positive relationship (Pearson's $r = 0.23$). The regression line has a slight upward slope, but the points are still quite scattered, suggesting considerable variability. However, it can be argued that SGE articles with more authors receive more citations. The reason for this result is that more authors mean a broader professional network. Each author's own circle could potentially expose the article to more people, and this may have led to an increase in the relative global citations value. Fig. 13(c) shows the relationship between the relative global citations and the reference count values of the SGE articles. With a Pearson's r value of 0.20, a weak positive relationship is found. The regression line has a positive slope, but again the data points are widely dispersed. A higher number of references to SGE articles may be associated with slightly more citations. This type of relationship may indicate that the well-referenced article has explored the topic in depth and is well-connected to the existing literature. This can be valuable for other researchers in the field. Researchers may also tend to cite articles that reference their own work. This may generate a "citation cycle". Fig. 13(d) examines the relation relative global citations - sentiments of articles. Since sentiments are categorical, this figure uses a box plot to examine whether the median values obtained in each sentiment show a significant change. As can be clearly seen, the black line connecting the median values moves almost horizontally. It can be said that the

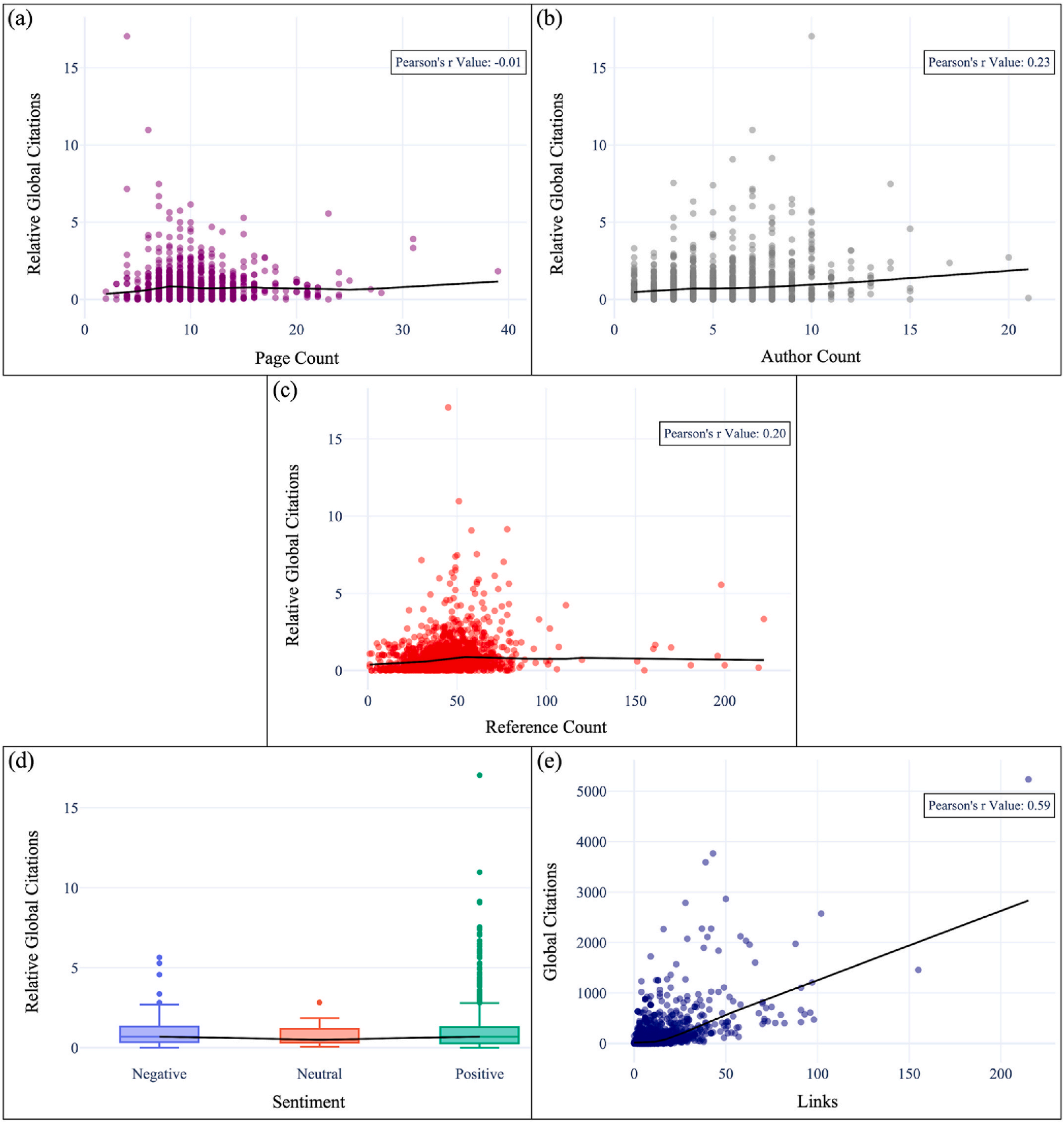

Fig. 13. Correlation analysis of **(a)** relative global citations – page count, **(b)** relative global citations – author count, **(c)** relative global citations – reference count, **(d)** relative global citations – sentiment of articles and **(e)** global citations – links of authors.

sentiment conveyed in the abstract of the articles has a limited impact on the relative global citations value obtained by the articles. Finally, the correlation between an author's global citations and number of co-authors (links) was analyzed (Fig. 13(e)). A very strong positive correlation was found (Pearson's $r = 0.59$) in this case. The regression line has a clear upward slope, and while there is scatter, the points are clustered closer together around the line. This suggests that SGE researchers with more links receive more citations, or vice versa. One reason for this result is that having a broader network can mean that research reaches more people and is cited more often. Co-authors promote the article to researchers in their own circle. Furthermore, a greater number of links often implies greater expertise and recognition in the field. This can lead to research being taken more seriously and receiving more citations.

It should be noted that numerous factors affect the number of citations an article or author receives. These include the article's open access status, its impact, the journal's impact factor, the author's academic reputation, and the field and scope of the work. The approach used above only examined relationships between attributes uniformly.

Beyond the primary objective of this study, it is recommended that future research should conduct more comprehensive analyses that consider all variables affecting the number of citations an article or author receives. Especially recently, causal inference methods integrated with ML have gained great significant importance in studying the effect of multivariate systems on a single variable.

4. Conclusions

Due to humanity's environmental and economic benefits, using renewable energy sources is inevitable. The salinity gradient energy concept, a promising renewable energy harvesting method, relies on the difference in salinity between two water streams for energy generation. To reveal the multifaceted footprint of studies in the field of SGE, this paper combines features of leading data processing methods such as bibliometrics, data mining, and machine learning. The dataset included 1270 articles downloaded from Scopus on January 22, 2024. The results indicate that the SGE has been studied for a research period of 48 (1976–2023) years; 2323 authors have contributed to this field; since 2012, the number of published articles has increased significantly. Jiang L. is the leading author in metrics such as most publications (79), most citations (5233), highest *h*-index (39), and *g*-index (72), but he is also one of the longest publishing in this field (since 2010). According to the co-authorship analysis of authors, 8 important social networks (working groups) were identified. China and the USA have the highest number of articles published, with 393 and 218 articles, respectively, and have the highest level of collaboration among themselves (36 documents). The Journal of Membrane Science, with 135 articles, 12393 global citations, 61 *h*-index, and 110 *g*-index, is the most dominant source (journal). Among the leading affiliations, the first institute that published in the field of SGE was the European Centre of Excellence for Sustainable Water Technology (WETSUS) but the leading institution by 2023 is Università Degli Studi di Palermo (UNIPA) with 203 articles. The top articles are as follows: Siria A. et al. (2013) in Nature with the title "Giant osmotic energy conversion measured in a single transmembrane boron nitride nanotube" is the most cited article globally (877), Post et al. (2007) with the title "Salinity-gradient power: evaluation of pressure-retarded osmosis and reverse electrodialysis" is the most cited article locally (210). The ion current rectification has become the trending topic in 2023. Energy (571), membrane (425), power (417), reverse (357), and electrodialysis (328) are the most common words in titles. The sentiment results showed that SGE researchers were optimistic about this technology (1111 articles), and the authors did not reflect their personal emotions in the abstracts, with 1236 neutral emotion scores. According to the energy harvesting technology analysis, RED (487 papers) and PRO (375 papers) stand out as the most widely used methods. With 66 papers, AccMix ranks third. PRO has been the more common energy harvesting technique for many years. RED, however, has continued to gain attention and become the primary energy harvesting technology focused on over the past five years.

China's growing interest and leading position in SGE research offer significant opportunities for those interested in collaborating with Chinese institutions and researchers. This could lead to transfer of knowledge, joint projects, and access to different resources. The Journal of Membrane Science's status as a leading journal indicates that it is an important resource for accessing the most current and influential work in this field. The fact that RED and PRO are the dominant technologies increases the potential for returns to specialization in these areas and improvements in membrane performance, system design, etc. However, researchers should not forget the fact that RED energy harvesting technology has become more popular among researchers in recent years. Emerging trends, such as ion current rectification, can provide guidance for those wishing to explore new areas of research and pioneering studies. Contact with the leading researchers and institutions identified in the present study can be useful for mentoring, collaboration, and professional development. The general optimism of researchers shows that there are still some problems to be solved and technologies to be developed further in the field of SGE. Furthermore, researchers should also actively seek out more co-authors and try to collaborate with researchers from different institutions, disciplines, and even countries, as this can reach a much wider audience and boost their metrics. All the analysis carried out throughout this manuscript and the results obtained can shed light on the SGE decisions and researchers' studies.

5. Key gaps, limitations and future directions

Although SGE is a promising renewable energy source, there are still some significant gaps in its practical applications. The performance (i.e., power density and durability of the SGE system) and cost of existing membranes remain the biggest barriers to commercialization. It is critical to understand the long-term performance and resistance to fouling of membranes in high salinity gradients (i.e. brine) and real water sources (seawater, wastewater). Nanofluidic membranes offer significant potential to address these multifaceted challenges thanks to their customizable structures and advanced material options. Furthermore, more system-level modeling and optimization studies are needed to unlock the full potential of different SGE technologies, especially PRO and RED, and hybrid systems (i.e. RED-heat engine for combined salinity and temperature gradients). Integration with energy storage and the environmental impact of SGE systems also require further studies. If the trade-off between efficiency and power density can be overcome, SGE can be integrated as a sustainable energy source.

This study aimed to comprehensively examine the dynamics of research in the field of salinity gradient energy using bibliometric methods, data mining and ML techniques. However, our study has some limitations and these offer important opportunities for future research. For instance, only the Scopus database was used for data collection. While Scopus was chosen for its broad coverage and high data quality, it excludes other sources such as Web of Science, Google Scholar, and other domain-specific databases. This can lead to potential biases in terms of journal coverage, language, and publication type. Future studies could attempt to overcome this limitation by conducting sensitivity analyses comparing results from different databases or by using dataset combination methods (i.e., data harmonization, duplicate record removal, etc.). Furthermore, the inclusion of other literature (reports, theses, dissertations, patents) and publications in languages other than English could provide a more complete picture of the SGE field. Future studies could integrate qualitative analysis methods (i.e., expert interviews, case studies) or quantitative modeling approaches (i.e., life cycle assessment, techno-economic analysis) to delve deeper into the technical, economic, and environmental aspects of SGE technologies. Finally, given the rapid advances in the field, it would be useful to regularly update such bibliometric and data mining analyses to identify new trends and research gaps.

CRediT authorship contribution statement

Mohamed Khayet: Conceptualization, Data Curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing - Original Draft, Writing - review & editing. **Ersin Aytaç:** Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - Original Draft. **Mohamed Essalhi:** Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - Original Draft. **Andrea Cipollina:** Formal Analysis, Investigation, Methodology, Visualization, Writing - review & editing. **Loreto García-Fernández:** Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. **Jorge Contreras-Martínez:** Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing - review & editing. **Carmen García-Payo:** Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Writing - review & editing. **Alejandro Ruiz-García:** Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **Alberto Figoli:** Formal Analysis, Methodology, Visualization, Writing - review & editing.

Data availability

Data for this article, including csv files are available at Google Drive at https://drive.google.com/file/d/14DwANgd3QvrMZEQVFqQwEnuoTcusEaz0/view?usp=drive_link and https://drive.google.com/file/d/14CYUaAHZJ4TyWwSvOv1eZfxghyA5-8HS/view?usp=drive_link and the data analysis scripts (sentiment and emotion) of this article are available in the interactive notebook Google Colab at https://colab.research.google.com/drive/1BH33aw04TaNreZmXnz1cT_hPPaMwNLbJ

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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Data availability

As indicated in the Data Availability section of the article, links to all Data are available at Google Drive and in the interactive notebook Google Colab.

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