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Review

Bibliometric Map on Corrosion in Concentrating Solar Power Plants

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Abstract: Concentrating solar power (CSP), also known as solar thermal electricity (STE), is increasing its deployment worldwide. One of the potential ways to decrease costs in CSP plants is the improvement of corrosion resistance between the heat transfer fluid (HTF) and storage materials, and the materials used for pipes, tanks, containers, and receivers. This paper assesses the literature on this topic (290 publications) through a bibliometric analysis, identifying the trends of the research, the topics of most interest to researchers, and literature gaps. Most documents are from Spain, Germany, and the United States of America. Results show that the most recent approaches for corrosion migration are selective coatings and the use of nanoparticles to reduce corrosiveness. The use of nitrates is changing to other salts such as chloride mixtures and potassium compounds. In addition, the techniques used to evaluate corrosion results are dominated by scanning electron microscopy (SEM), X-ray diffraction (XRD), and electrochemical testing, but new dynamic techniques are starting to be used, representing the biggest gap that needs to be filled for the testing of components such as solar receivers.

Keywords: corrosion; concentrating solar power (CSP); solar thermal electricity (STE); bibliometric analysis; trends

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1. Introduction

In 2010, the International Energy Agency [1] stated that by 2050, concentrating solar power (CSP, also known as STE—solar thermal electricity) could provide 11.3% of global electricity. Moreover, CSP should become a competitive source of bulk power in peak and intermediate loads. In 2016, the CSP/STE market had 7.638 GMWe installed worldwide [2], of which 4.8 GWe were operational and the rest were under construction. In 2020, the amount of installed capacity worldwide of CSP rose to 6.2 GWe [3].

There are four main technologies for CSP/STE: parabolic trough, tower, linear Fresnel, and parabolic dish [2,4]. Parabolic trough and linear Fresnel systems track the sun along one axis, and therefore use line focus; tower and dish systems track the sun along two axes, using point focus. For each technology, the heat transfer fluid (HTF), the thermal energy storage (TES) systems, and the power cycle is chosen from different available options.

Although commercially being addressed with success, corrosion is identified as one of the potential ways to decrease costs in CSP plants if alternative methods to prevent it are identified [4]. Both commercially used HTF and storage materials, as well as new studied storage materials, are potentially corrosive [5]. Materials used for pipes, tanks, receivers, etc., are mostly carbon steel, stainless steel and/or Ni-based alloys; materials used as HTF or storage are water, synthetic oils, organic solvents, molten metals, and molten salts [5,6]. A significant number of studies show that molten salt corrosion in metal alloys has a fundamental relationship with the anion type, process temperature, HTF impurity content, cover gas atmosphere, flow state and metal alloy composition. In addition, the risk of materials failure is further increased by thermal cycling and the possibility of mechanical stress in solar plant [7]. The long-term stability of key components is essential to guarantee the reliability of CSP and the confidence necessary for its financing.

A significant number of papers have appeared in the literature recently on the topic of corrosion analysis and mitigation in CSP/STE plants, but the literature on this topic is dispersed and still not well organized, and therefore, it could be difficult to understand the state of the art and the respective gaps on the topic. With this objective in mind, this paper aims to provide a better picture of corrosion on CSP that could help researchers and institutions working on the topic. In this case, bibliometric analysis is a technique that could help to address this issue allowing scientific progress to be evaluated using both a quantitative and qualitative approach. Indeed, bibliometric techniques can be used to evaluate the scientific output in terms of the number of publications and to identify the main authors and institutions studying a certain topic. Furthermore, links between bibliometric items (items can be in terms of co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links) can also be evaluated and visualized in maps using dedicated software. Additionally, by analyzing the keywords used to tag the scope of papers, it is possible to identify research trends and gaps. Recently, bibliometric techniques have been used in the literature to allow a better understating of the state of the art on topics related to energy, such as thermal energy storage [8,9], electrical storage [10,11], solar power [12], and low carbon energy technologies [13].

Therefore, the aim of this paper is to evaluate the literature dealing with corrosion in CSP/STE plants to be able to understand the trends of such research, the topics that have aroused interest among researchers, and finally, to identify literature gaps.

2. Methodology

The literature search was carried out in the Scopus database on 19 January 2022. The Scopus database was used because it compiles more documents on technologies than any other available [14]. The query used was a simple one, but after looking at all the documents found, it appeared likely that all of them were related to the study. The query was "(CSP OR STE) AND corrosion". A total of 290 documents were found and were assessed based on the type of publication, distribution per year, per country, per author, per institution, per subject area, and per journal. Moreover, the relationship between authors and keywords was analyzed using the bibliometric analysis software VOSviewer [15].

3. Results and Discussion

The type of publication in which most documents related to corrosion in CSP/STE were published is shown in Figure 1. In particular, most documents are published as articles/papers (177 documents) and conference papers (90 documents). The high number of conference papers shows that corrosion in CSP/STE is still an important subject for researchers in conference publications. Only 16 reviews and four book chapters were found, showing that this is quite a new topic.

The journals in which most documents are published are shown in Figure 2. In particular, "*Solar Energy Materials and Solar Cells*" was found to be the first choice for researchers to publish studies related to corrosion. From the results it is also noticeable that conference proceedings (*AIP conference proceedings* and *Energy Procedia*) have published various studies that can be consulted in an open access format.

The trend in the number of publications is presented in Figure 3. The first documents appeared in 1968, and between zero and three publications appeared every year until 2005 (in which there were four publications), but the real increase in documents started in 2009 (with eight publications) until there were 33 published in 2019 and 39 published in 2020. This increase coincides with the increases in commercial plants in operation and the capacity of thermal energy storage installed (Figure 4) [3], which shows that this issue is a common development focus among technology developers and researchers.

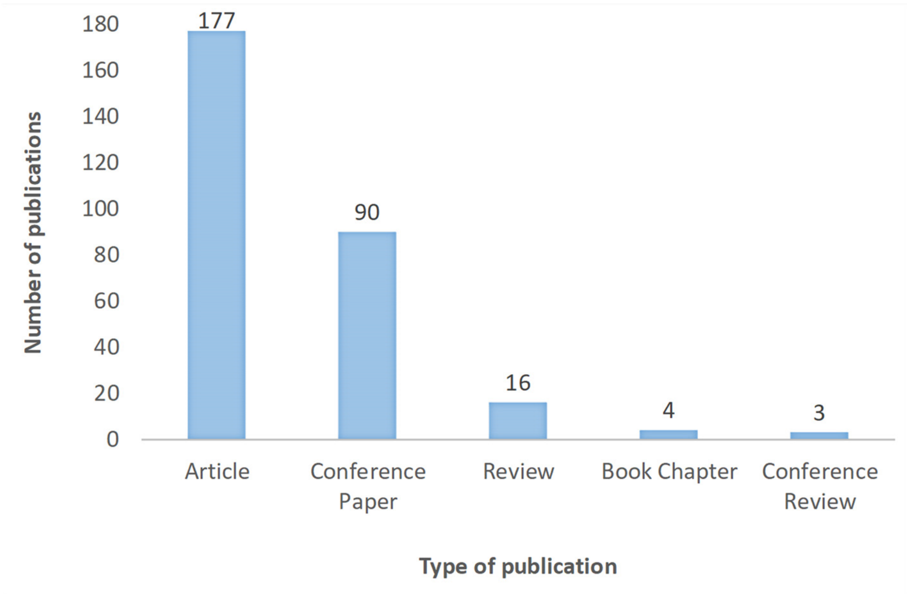


Figure 1. Type of publication.

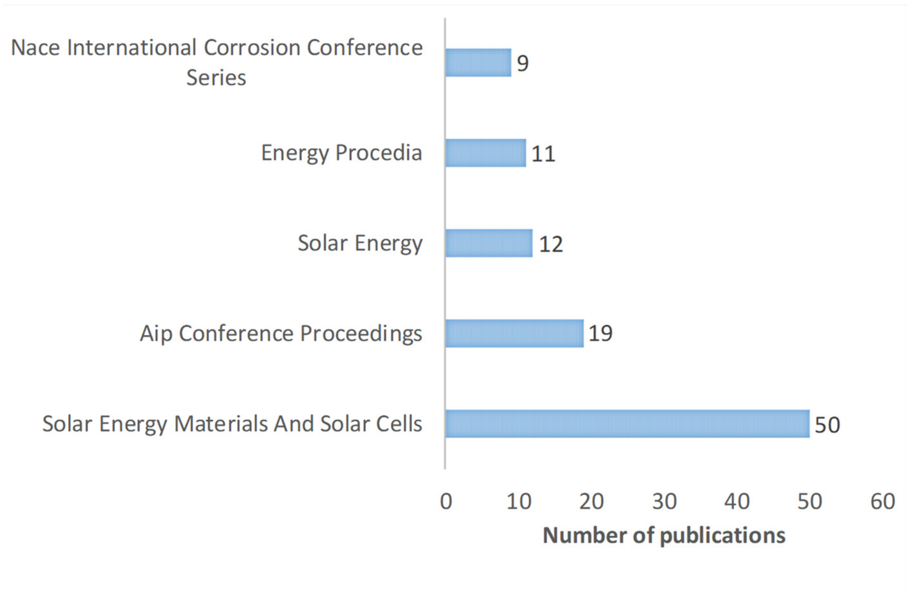


Figure 2. Main journals with publications about corrosion in CSP/STE.

Countries that are researching this topic are shown in the heat map in Figure 5. The top countries are highlighted in Figure 6. In this case, Europe was considered a single territory covering the member states in the EU27. Up to 2021, the countries of the European Union were leading all the territories with the most documents (122), followed by the USA (63 publications), China (with 39), and Chile (17). Within the European Union, Spain and Germany had the highest number of documents published (57 and 47, respectively).

It is interesting to note that the total number of publications per country is in line with the operational capacity installed in each territory, as shown in Table 1 [16].

When studying the publication trends of the five top countries/territories, one can see that the number of documents published per year in the USA has stagnated at 7–8; China, the UK, and Chile are increasing slowly from 1–2 documents per year to 3–4; whereas the European Union increased drastically from 8–10 documents per year to 25 documents in 2019, which represents the highest research output. The network of countries obtained using VOSviewer is shown in Figure 7. The relationship between countries shows three clusters (Figure 7a); the first one includes the European Union, Morocco, and Chile, and this is linked directly with the second cluster that includes Australia, the UK and China; this second cluster is then linked to the third one that includes the USA, Japan and India. It is interesting to see that the countries that were the earliest to start publishing on this topic are the UK and Japan, and the newest ones are Chile, Australia, Morocco, and India (Figure 7b).

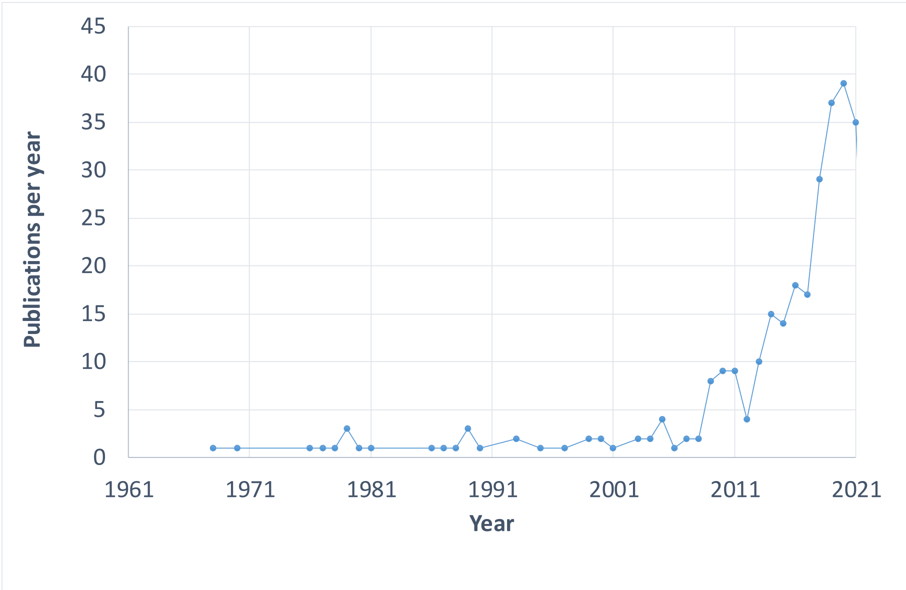


Figure 3. Trends in number of publications.

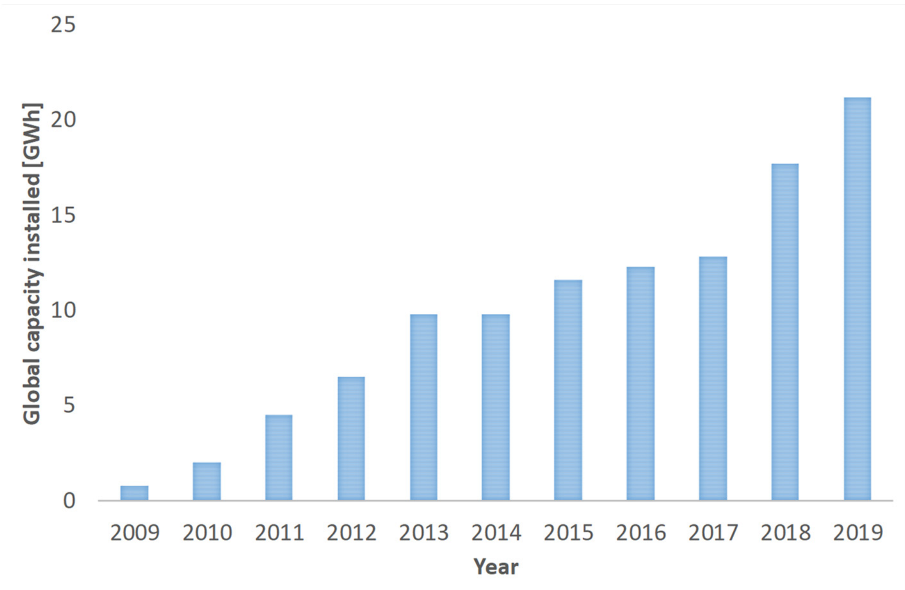


Figure 4. CSP thermal energy storage global capacity [GWh] installed per year. Adapted from [3].

However, it is interesting also to see the relationships within the European Union. In this case, the documents attributed to the countries of the EU by Scopus were downloaded and the relationship between countries can be found in Figure 8. Here there are two main clusters (Figure 8a). The first one shows the strong relationship between Spain, Chile, and Italy. Spain is in the center of this network, and has relationships with the second cluster, that includes Portugal, the UK, Germany, and France. It is worth mentioning that the second cluster is the one with older publications related to corrosion in CSP/STE (Figure 8b).

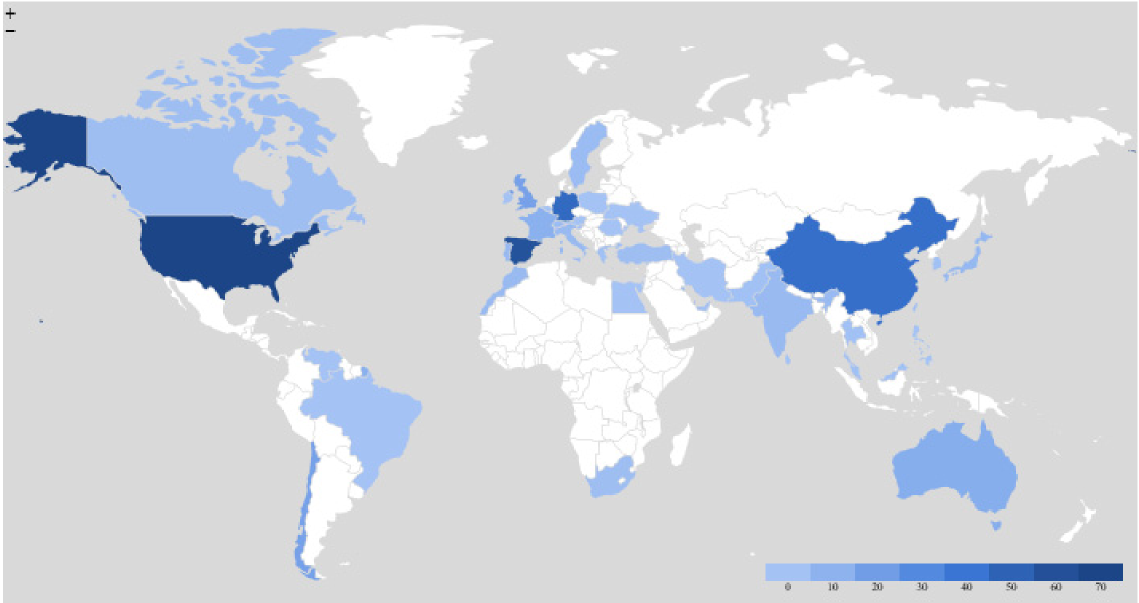


Figure 5. Heat map of countries.

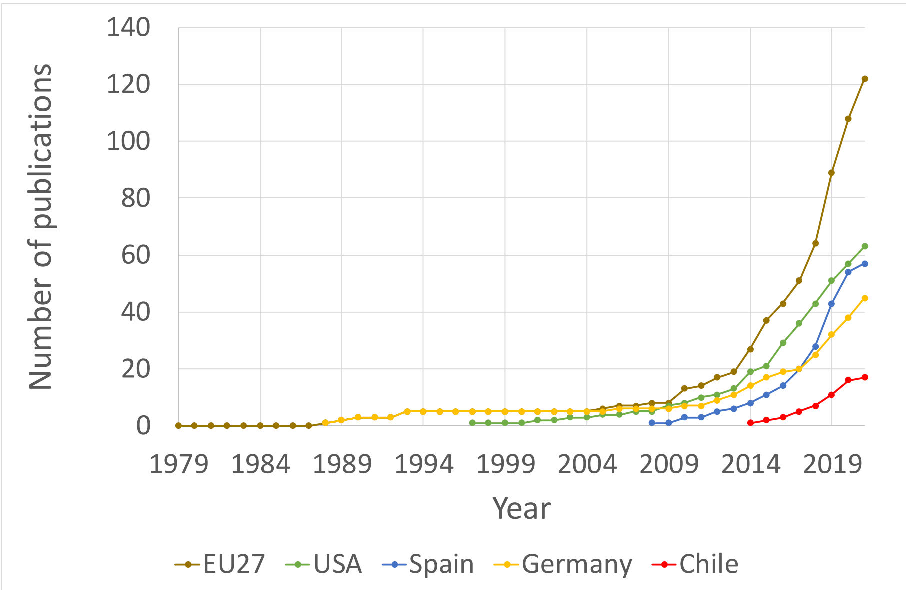


Figure 6. Top countries publishing on the topic including EU27.

Table 1. Operational capacity of CSP installed in different countries/territories [16].

Country/Territory	Operational Capacity Installed [MW]
Europe	2318
USA	1731
China	881
Morocco	533
India	242
Chile	110
Australia	2.6

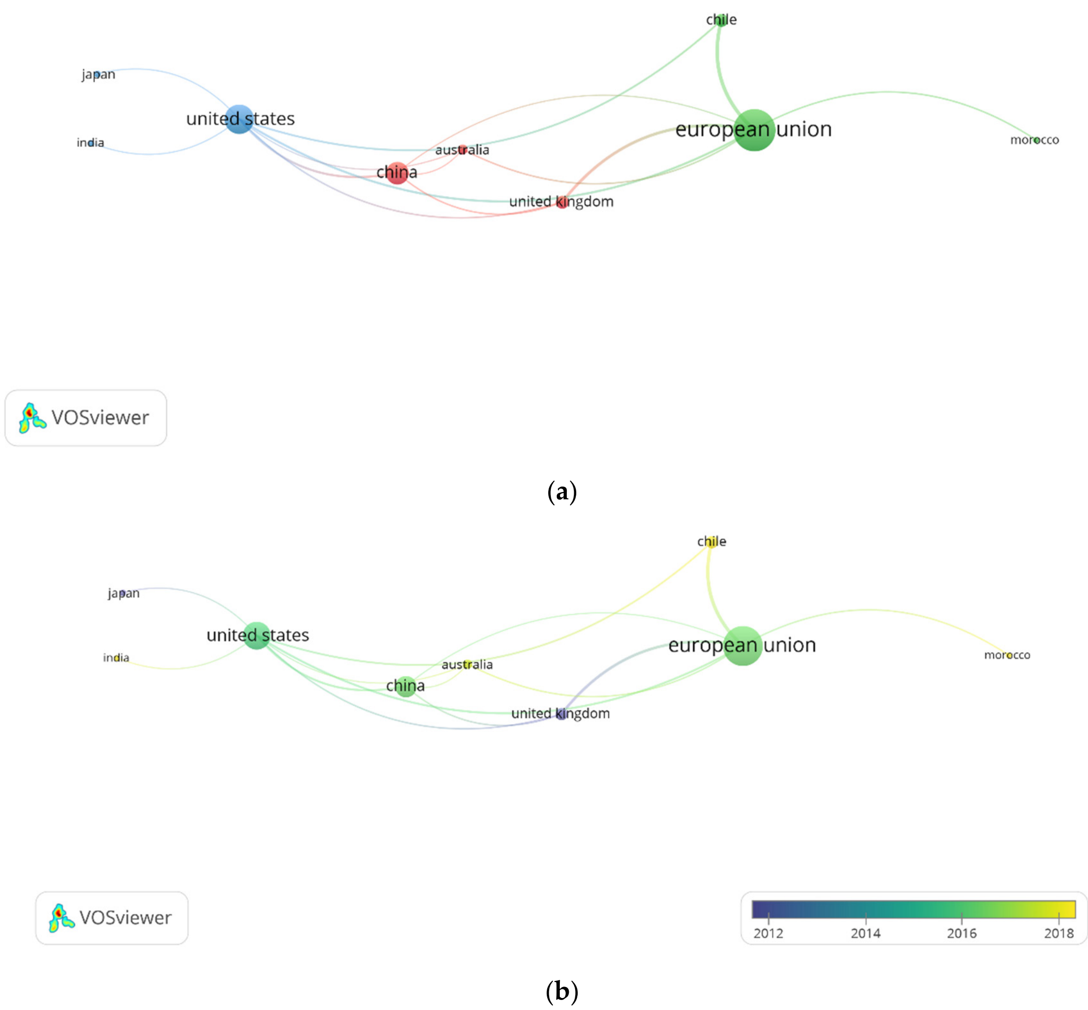
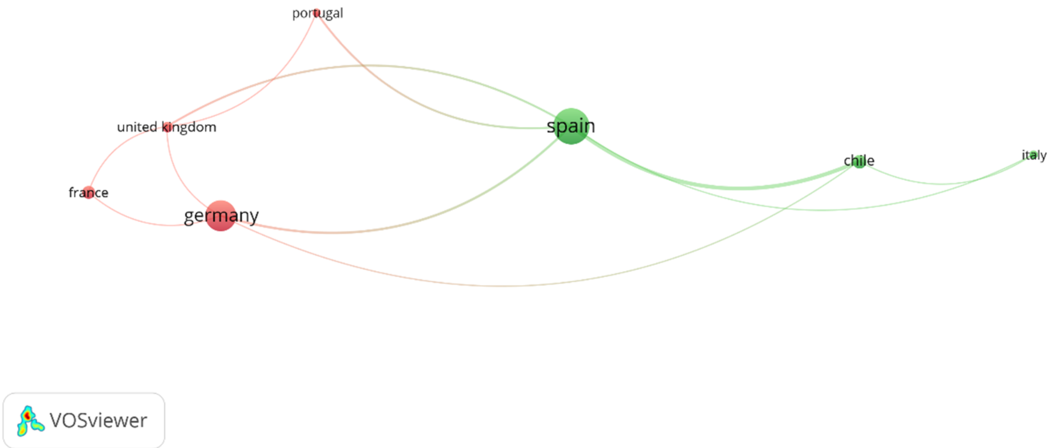


Figure 7. Relationship between countries/territories. (**a**) Relationship between country clusters, and (**b**) Highlights of the date of publication.

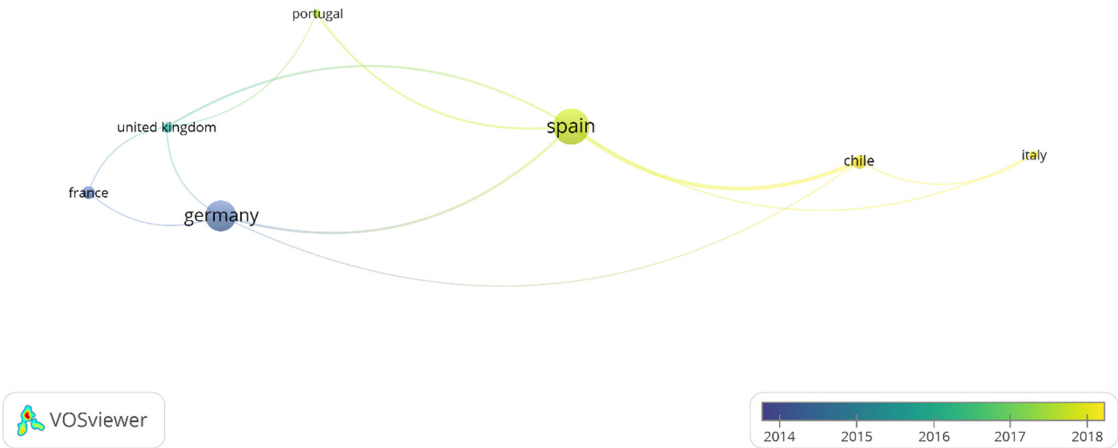
As expected, the institutions with the highest number of documents (at least six documents published on the topic) belong to the countries/territories listed above (Table 2). The European Union is mainly represented by institutions from Germany and Spain. Outside Europe, institutions from Chile (University of Antofagasta), the USA (NREL and University of South Carolina), China (University of Science and Technology Beijing and Inner Mongolia University of Science and Technology), and Australia (Queensland University of Technology) are present in this ranking.

DLR (Germany) is the institution with most documents in the literature. The most cited paper was published in 2012, a study on the compatibility between inertized asbestos-containing waste and molten salts using nuclear magnetic resonance, ex situ X-ray diffraction and scanning electron microscopy [17]. Another relevant document was published in 2018 regarding the corrosion behavior of commercial alloys (stainless steel SS 310, Incoloy 800 H, Hastelloy C-276) with molten salts ($MgCl_2$/NaCl/KCl) [18]. The other two institutions with the highest output are University of Antofagasta (Chile) and Universidad Complutense de Madrid (Spain). Excluding reviews, the most cited document from the Chilean university was a study on the corrosion resistance of pretreated alumina-forming alloys to produce surface passivation that was tested against molten chlorides [5], whereas from Universidad Complutense de Madrid the most relevant study was published in 2012, on the corrosion of two different types of steel (low-Cr alloy steel (T22) and carbon steel (A1)) with a molten nitrate salt mixture [19].

The most published authors (at least 11 documents published) are listed in Table 3. As expected again, the authors with most publications on this topic belong to the institutions listed above, but it is interesting to see that most of them are from Spain and Germany. The author with the most publications is A. G. Fernández, from Universidad del Pais Vasco (Spain).



(**a**)



(**b**)

Figure 8. Relationships between EU countries. (**a**) Relationships between country clusters, and (**b**) Highlights of the date of publication.

Table 2. Institutions with the highest number of documents published.

Institution	Country	Number of Publications
DLR	Germany	22
Universidad de Antofagasta	Chile	17
Universidad Complutense de Madrid	Spain	17
NREL	USA	13
Universitat de Lleida	Spain	13
CIC energigune	Spain	13
Universidad del Pais Vasco	Spain	9
DECHEMA Forschungsinstitut	Germany	8
TECNALIA	Spain	7
Queensland University of Technology	Australia	6
Chinese Academy of Sciences	China	6
Harbin Institute of Technology	China	6
CIEMAT-Plataforma Solar de Almeria	Spain	6

Table 3. Authors with the highest number of publications.

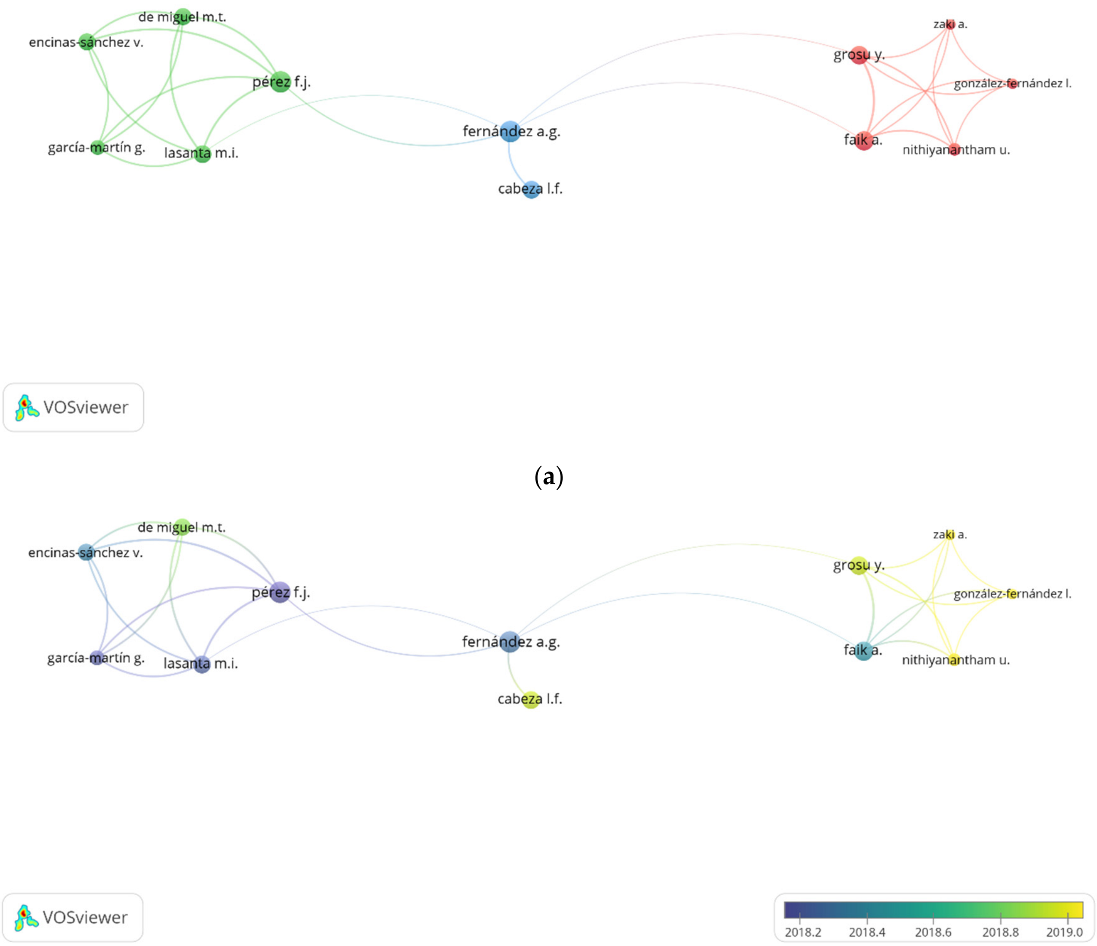
Author	Institution	Country	Number of Publications in This Query	Total Number of Publications	h-Index
A.G. Fernández	Univ del Pais Vasco	Spain	23	59	22
T. Bauer	DLR	Germany	16	69	22
F.J. Pérez	Univ Complutense de Madrid	Spain	15	178	30
A. Bonk	DLR	Spain	14	44	15
A. Faik	Mohammed VI Polytechnic Univ	Morocco	14	102	23
Y. Grosu	Basque Research and Technology Alliance	Spain	13	60	16
L.F. Cabeza	Universitat de Lleida	Spain	12	546	76
W. Ding	DLR	Germany	12	15	9
M.I. Lasanta	Univ Complutense de Madrid	Germany	12	21	10
M.T. de Miguel	Univ Complutense de Madrid	Spain	11	19	8
V. Encinás-Sanchez	Univ Complutense de Madrid	Spain	11	22	8

The most recent publication from this author that is relevant in terms of number of citations was published in 2019 and was a study regarding the corrosion properties of nanoparticles included in molten salts on stainless steel [20]. This author has strong co-authorship with L.F. Cabeza [4,21–25] and F.J. Pérez [19,26–28]. T. Bauer from DRL accounts for 16 documents published on corrosion and has strong collaborations with A. Bonk [29–38] and W. Ding [29–35,39,40]. One of the most recent studies that obtained a significant number of citations concerned two mitigation strategies for corrosion of structural material including the use of corrosion inhibitor and alloys with a protective alumina layer on surfaces [41]. F.J. Pérez also has a higher output of publications on corrosion due to strong collaborations with M.I. Lasanta, M.T. de Miguel, and V. Encinás-Sanchez [42–51]. One of the most recent studies published was a study on the corrosion resistance of austenitic steel HR3C to a carbonate molten salt [52]. Another significant author on the topic is A. Faik from Mohammed VI Polytechnic University with a strong collaboration with Y. Grosu (Basque Research and Technology Alliance) [53–60]. One of the most relevant studies was published in 2018, on the effect of humidity, impurities and initial state on the corrosion behavior of carbon and stainless steels in molten HitecXL salt [61].

The mapping of the authors performed using VOSviewer (Figure 9) shows distinctive clusters grouping authors within the same institution. Figure 9b shows that the authors from University Complutense de Madrid together with A.G. Fernández (originally also from this institution) are those who started to publish on this topic earlier, whereas the authors that are now at or were associated in the past with CIC energiGUNE are those who started to publish on the topic later [53–60,62].

Figure 10 shows the mapping by VOSviewer of the literature found using the query of the Scopus database.

The keywords are grouped into three main clusters. The first cluster, in green, contains the main keywords of the topic ("csp", "corrosion", and "solar energy") and keywords related to "corrosion resistance" of the steel structure of the storage. The second cluster, in red, is related to the mitigation of corrosion caused by molten salts and nitrate salts which are the commercial storage materials used today [19,63–67]. The blue cluster is related to thermal energy storage materials. In the green cluster, different keywords related to different types of steel ("martensitic steel" and "ferritic steel") [68–72], and "alloy" [18,73–80] can be noted. However, "stainless steel" belongs to the second cluster because it is the most common material used for storage structures and relates to the evaluation of corrosion effects by molten salts [18,19,64,67,75,81–88]. Another keyword related to the first cluster is "potassium compounds". The cluster also contains "coatings" (and "aluminium coatings") that represent one of the most common techniques to reduce the corrosion effect of salts [89–94]. The keyword "accelerating ageing" is interesting, representing one of the methodologies used to reduce the time of experiments related to corrosion [95]. The cluster also contains the keyword "costs" because achieving reduction of corrosion costs in CSP plants represents a key aspect. The red cluster, as mentioned, relates to "corrosion mitigation" by acting on the composition of molten salts and nitrate salts at "high temperatures"; here, we note keywords such as "corrosion inhibitor" and "alumina" that is often used as a protective layer against molten salts and as a nanofluid [23,42,96,97]. Indeed, the cluster also contains the keyword "nanoparticles" which includes studies on corrosion-related molten salts doped with nanoparticles for thermal performance enhancement [54,96–99] and corrosiveness reduction [99,100]. The cluster also includes the keyword "chlorides"; this is due either to the potential impurities of "molten salts" or to the fact that today chlorine salts are seen as potential storage salts for future CSP plants working at higher temperatures than the commercial ones and their corrosivity is also known [19,74,75]. Figure 10 also shows the main analytical techniques used to perform studies on corrosion in CSP plants, which can be useful for researchers to see what is currently used to evaluate their tests. Figure 10a shows that "SEM" (scanning electron microscopy), "XRD" (X-ray diffraction), and "electrochemical testing" are widely used [18,23,53,65,101]. However, the biggest gap found in this study was the use of "dynamic corrosion" testing techniques [26,87,97,102], that would be needed to test components such as solar receivers. The third cluster includes storage materials and here we note keywords such as "thermal energy storage", "thermal stability", "thermophysical properties", "operating temperature", and "degradation". It interesting that "PCM" is also found in the literature map; this is due to the intense research carried out into the substitution of the sensible storage systems used today with others that are more economic or which have higher efficiency [18,101,103,104].



(**a**)

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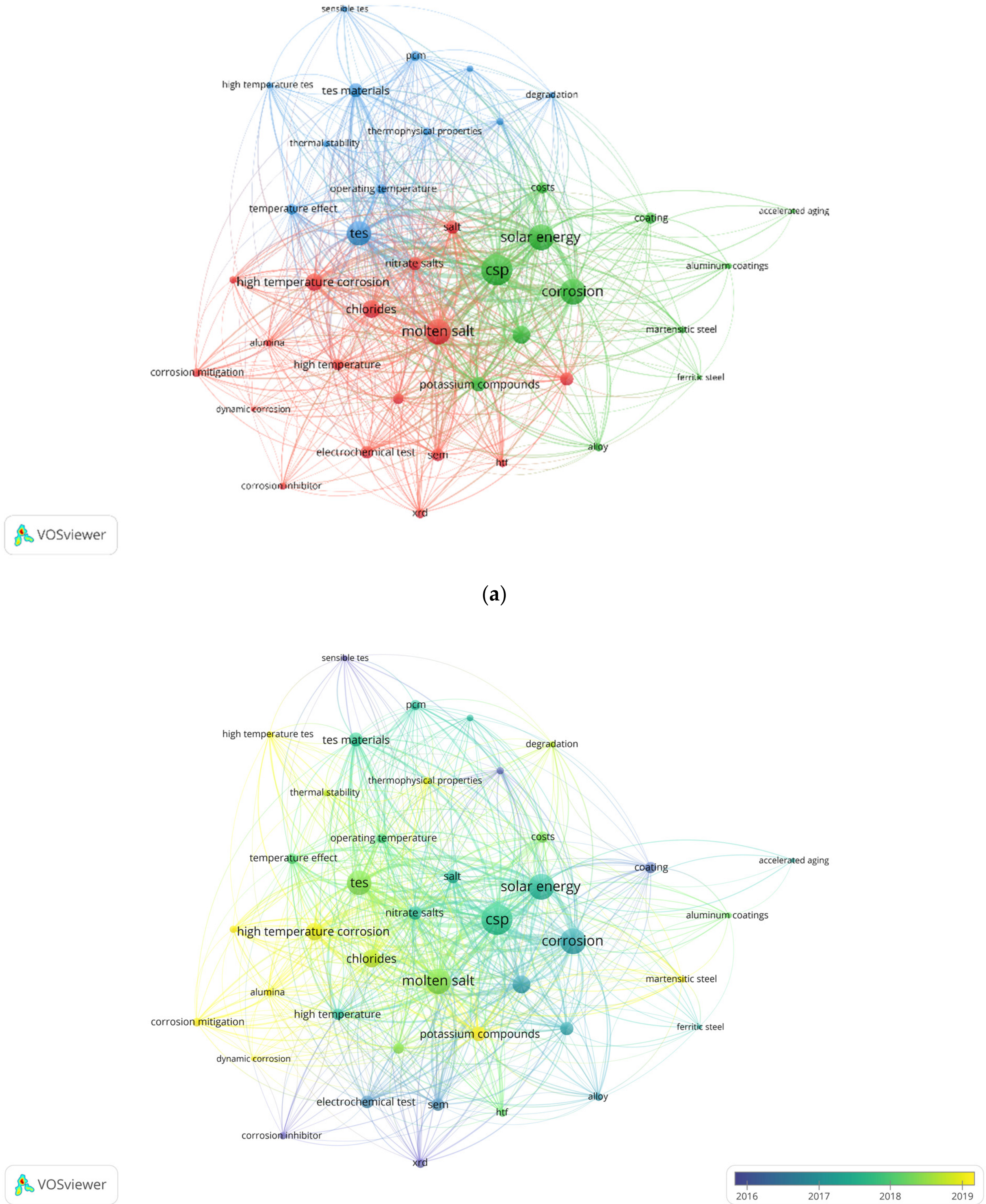
Figure 9. Relationship between authors. (**a**) Relationship between country clusters, and (**b**) Highlights of the date of publication.



(**a**)

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Figure 10. Co-occurrence of keywords. (**a**) Relationship between keywords clusters, and (**b**) Highlights of the date of publication.

The figure shows an overlay visualization that enables better understanding of the latest trends in research dedicated to corrosion in CSP plants. For example, with regard to storage materials, studies carried out on martensitic steel compared to alloys were published recently [99,105]. In terms of storage media, potassium compounds (including potash and potassium nitrate) and chlorides have been considered in recent studies related to corrosion. The results also show that with regard to corrosion techniques, the use of nanoparticles or alumina is the most recent topic studied among researchers, being a promising solution for corrosion mitigation. Furthermore, in terms of corrosion measurement techniques, we see a trend towards use of the dynamic methods: "SEM" (scanning electron microscopy), "XRD" (X-ray diffraction), and electrochemical testing in recent studies [106].

4. Conclusions

Corrosion is a critical issue in concentrating solar power technology, also known as CSP or STE. The durability of materials is very important to guarantee the feasibility of CSP and numerous studies have explored the corrosion behavior of construction materials with different storage media or heat transfer fluids.

In this study, a scientific research field bibliometric analysis was performed, studying more than 200 publications in relevant journals and conference proceedings. The results indicated that most publications come from the European Union and the United States of America, with clear links between these two geographical areas. Other key players are the UK, Japan, China, Australia, Morocco, and Chile; in order of the oldest publications found. In Europe, most research has been carried out in Spain and Germany. The keyword analysis showed that most of the studies are related to evaluating the corrosion rates and resistance of storage container materials, with molten salt being the most mature storage material solution in CSP plants. From the literature, the analysis shows that "SEM" (scanning electron microscopy), XRD (X-ray diffraction) and electrochemical testing are the most widely used techniques for the analysis of the results of tests, but new, innovative dynamic methods need to be developed to test corrosion in other key components in CSP plants, including solar receivers. New approaches to increase the durability of materials are also gaining relevance in recent times, following the latest technology roadmap: the use of selective coatings to lower the cost of construction materials or the use of nanoparticles to reduce corrosiveness. The trend to change from the use of nitrates to other higher stability salts, such as chloride mixtures and potassium compounds, was also detected with an increase in the number of recent publications on this topic.

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