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ORIGINAL ARTICLE

25 years of progress on plants as corrosion inhibitors through a bibliometric analysis using the Scopus database (1995–2020)

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Abstract The increasing awareness of people on green materials and chemistry has stimulated researchers around the globe to turn towards natural resources. As a growing topic with limitless potential, plants as corrosion inhibitors (PCI) have received substantial attention due to their eco-friendly, biodegradable, inexpensive, and abundantly available. Therefore, with the understanding of the importance of this topic, this study is conducted in the format of a descriptive systematic literature review (SLR) to assess the global research trends on PCI according to the number of published articles, co-authorships in correspond to countries/academic institutions and co-occurrences of author keywords. In the span of 25 years, from 1995 to 2020, 2237 articles from journal and conference proceedings were collected. Results have displayed that since 2003, the number of articles produced per year has increased significantly, wherein in 2020 alone, more than 250 articles have been published. The steady increment of publication has now resulted in a large accumulation of articles up until 2020. About 45% of the overall publications originate from India, Nigeria and

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China compared to other countries. In conclusion, the progress of PCI research presented in this study should provide a general overview of the correlation between researchers worldwide for better international collaboration and broadening knowledge.

1. Introduction

Corrosion is a major cause of economic issues and safety concerns in many countries. The problem is commonly affiliated to metal due to its unstable characteristic, wherein its pure form will undergo corrosion reaction to become more stable. Although stability is regarded by many as a favourable occurrence, it is the opposite in this case. When a metal is corroded, its mechanical qualities such as hardness and durability will significantly deteriorate (Kamaruzzaman et al., 2021). Hence, if the infrastructure is made of steel or alloys, suitable corrosion prevention methods need to be implemented to reduce the risk of catastrophic incidents such as the collapse of a building. To date, corrosion has been identified as one of the foremost perpetrators of high maintenance costs in multiple industries, particularly on the infrastructures near the offshore area. In fact, an evaluation performed by the National Association of Corrosion Engineers (NACE) in 2016 suggests that the worldwide expense induced by corrosion reaches a staggering amount of USD 2.5 trillion per year (Tang, 2019). The total cost of corrosion can be summarized from both direct and indirect costs. Examples of the direct cost include the repairs and replacement of corroded parts, while the indirect cost is mainly associated with incidents like the leakage of oils due to the thinning of pipelines caused by corrosion.

One of the highly effective ways to reduce corrosion is by implementing corrosion inhibitors. Nowadays, most of the available and researched corrosion inhibitors are of organic and inorganic types. The difference between these two classes can be identified according to their protective mechanisms. An organic corrosion inhibitor functioned through the adsorption process, whereas the inorganic class is more specific and protects either the anodic or cathodic sites (Umoren et al., 2015; Tiu and Advincula, 2015). Recently, the movement of the "green" concept in chemistry has propelled many researchers to shift their focus to natural products as a potential alternative to resolve the issue of corrosion. Following this trend, an increasing amount of studies on organic corrosion inhibitors are now rapidly performed (Tamalmani and Husin, 2020). Several other reasons for the increase of attention towards the organic type are their tendency to work efficiently in various acids concentration, inability to poison or negatively affect the refinery catalyst, inexpensive, very low or no toxicity, and environmentally acceptable. As one of the well-received discussion in the organic category, plants as corrosion inhibitors (PCI) has been selected as the main topic of this study.

Plants are generally abundant, non-toxic and easily accessible. Globally, it is estimated that more than 500 thousand varieties of plants are distributed across different landscapes. Owing to this enormous potential, previous researchers have evaluated various parts of a plant such as its root, fruit, stem, leaf and extracted or vegetable oils as an inhibitor for different metals, including mild or carbon steel, aluminum, stainless steel and copper (Srivastava et al., 2012). The assessment is not limited to the substrates since the medium of immersion can also differ from simulating certain areas or industrial processes. So far, the most popular testing solutions included but were not limited to sodium chloride (NaCl), hydrochloric acid (HCl), sulfuric acid (H_2SO_4) and nitric acid (HNO_3). Although there has been a drastic increase in interest in PCI for the last 25 years, very few studies have been published to investigate the trend based on the global scientific publication perspective. Hashemi et al. (Hashemi et al., 2018) presented research trends on the topic of microbiologically influenced corrosion (MIC) for a period of 71 years from 1945 to 2016, where corrosion inhibitors were included as a minor topic since the whole review was more on the topic of monitoring, modeling and mechanisms of MIC towards corrosion. Conversely, another loosely related bibliometric study was performed by Hassan et al. (Hassan et al., 2020), in which their research was a general overview of the publication metrics of the "Arabian Journal of Chemistry". The minor connection with our topic is that the journal has published a moderate amount of publications focusing on corrosion inhibitions. Nevertheless, it is only considered one of the many discussed topics along with studies of wastewater, photocatalytic degradation and water sample. In addition, the study by Hassan et al. used both Scopus and Web of Science (WoS) databases, while the review conducted by Hashemi et al. is limited to the Scopus database.

Even though Scopus and WoS databases are recognized to overlap on a large scale in journal indexing, certain journals have been identified to be indexed differently by both databases. As of now, Scopus is acknowledged to have the most extensive database compared to WoS in terms of the abstract and citation of peer-reviewed publications over multiple ranges of scientific fields (Aghaei Chadegani et al., 2013). As for Google Scholar, another popular database with a huge collection of documents, it has two major disadvantages. First, the database cannot specifically provide the user with the number of conference articles. Second, its search engine highly relies on the search option selected by the users, causing the search results to fluctuate on a great scale easily. Hence, selecting the Scopus as the data source of this study should ensure a comprehensive coverage on topics that may not have been included and discussed in WoS alone. In this paper, the objectives include: i) to examine the temporal distribution pattern of PCI journal articles and conference papers; ii) to present the leading contribution by authors, countries and its respective academic institutions or affiliations; iii) to emphasize the frequently occurred keywords and issues on PCI; iv) to establish the list of leading of countries according to the testing substrates and medium; v) to give an insight for potential collaborations and future trends. The discussion is presented in a descriptive SLR format to provide insight into each objective without adding new scientific theories to the current progress. The analysis compiled in this article should provide a substantial proposition to help researchers and practitioners better understand the topics of PCI for their respective purposes.

2. Methods

A bibliometric study is a systematic method to analyze and gain insight into the global research trend of a particular topic or field using the available database online. This method of reviewing is critically different compared to the standard review paper. It is distinguished by its unique approach to the collective interest of previous publications to ascertain the researchers' direction, limitations, challenges, and accomplishments in a specific research field.

2.1. Data source and search strategy

The collection of articles to cover the 25 years of progress on PCI was conducted on July 21, 2021 using the Scopus database. The central theme of this article was centralized on the topics of corrosion inhibitors, particularly the application

of plant extracts. The process of text mining was started by inserting the terms "corrosion inhibit*" and followed by a string of terms to represent the different parts of a plant such as the leaf, flower, fruit, stem, seed and peel in the title abstract. Through proper execution of text mining using appropriate terms, data from textual documents comprising both linguistic and statistical can be clustered and transformed into visuals for ease of understanding. Based on the initial results, 2237 documents were collected, with the oldest recorded publication dating back to 1949, and the most recent ones are in this year of 2021. The query string used for this search was as follows: TITLE-ABS (("corrosion inhibit*") AND (plant OR leaf OR flower OR fruit OR bark OR stem OR root OR peel OR extract)). After modifying the search strings to limit the findings for only journal articles and conference proceedings from 1995 to 2020, the results obtained reduce to 1924 documents. In short, these results were selected according to year, source, author, affiliation, country/territory, subject area, and document type. It is important to note that the latest search string has already excluded the standard review article, which contained terms such as progress, review, overview, updates, bibliometric and potentiometric.

Next, the extraction process to get the information of single-country publication (SCP) for a specific country was conducted by limiting the search result using the code of AFFILCOUNTRY. The ranking assessment to construct an organized tabulation of data was carried out using the bibliometric indicators available in the Scopus website, such as the total publications, CiteScore, Field-Weighted citation impact (FWCI), total citations and h-index. Additionally, to get an overview of the researcher's interest on the tested substrates and corrosive solutions, we have created two sub-themes (Fig. 1) that were further divided into mild or carbon steel, aluminum, stainless steel and copper for the substrates, and NaCl, HCl, H_2SO_4 and HNO_3 for the solutions. The search string for each substrate and medium was run separately. The approach for the individual components of sub-themes was performed using the previous search strings (1924 results), with additional terms were included as the representation. For instance, two terms must be included in the search string for aluminum, i.e., "aluminium" OR "aluminum", due to British and American spelling differences. The results for the sub-themes were discussed according to the number of output publications per year of the top 5 countries. The general procedures of data collection and restriction are presented in Fig. 1. The list of search strings constructed for both main and sub-themes are given in Table S1 of the supplementary material.

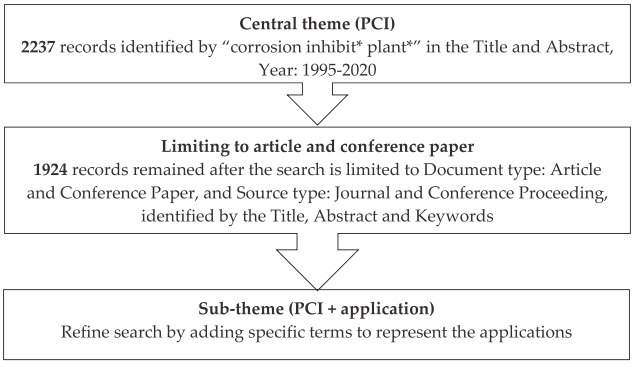


Fig. 1 Research framework on the data collection process for primary and sub-themes.

2.2. Bibliometric maps

The bibliometric maps were created from 1924 records obtained from the Scopus database using the VOSviewer software (version 1.6.17). The software is selected as the key tool of the study because of its free to use policy and can support a wide range of databases, including Scopus, Web of Science, Dimensions, Lens and PubMed. The design of the maps used items as the representation of the topic of interest, which can be either countries or author keywords. The strength of the relationship between one item and another is measured by the software and displayed as a numerical number that can be easily interpreted. For example, when the connection between two items is stronger, the reading of the link will exhibit a higher numerical value.

In terms of the co-authorship evaluation, the link strength connecting two items represents the shared amount of publication, i.e., journal articles and conference proceedings between two countries. The publication was selected according to the affiliation of co-authors. So, when an article has authors of different countries and affiliations, this will be identified as a joined publication for both countries. In addition, the total link strength acts as an indicator of the total co-authorship strength of a given country with the others. Likewise, the link strength between two author keywords for the co-occurrence bibliometric maps represents the number of articles where the keywords have occurred together. The construction of data representation for both tables and figures was made using a full counting system. Further explanation of the available functions of the software can be obtained using the instruction manual (2021).

2.2.1. Assessment of co-authorship

The study of co-authorship covered an extensive range of datasets. including all 90 countries affiliated to 4660 authors. The countries were clustered based on their respective continents: Asia, Europe, America, Africa, and Oceania and the maps were presented in network visualization mode using a full counting system.

2.2.2. Assessment of co-occurrence

Assessment on the co-occurrence based on author keywords includes 3126 keywords from the extracted records. Before creating co-occurrence maps, the keywords selected by the VOSviewer were filtered to reduce the redundancy and ensure that each keyword would have a distinct meaning. For example, keywords such as acid medium, acid solution, acid media and acid medium were counted as one and re-labelled as the acid solution. The process results in 3054 keywords that was used for the maps. The minimum occurrences of author keywords were set at default which is 5 with 107 keywords were generated. The constructed maps were presented in the overlay visualization mode using a full counting method. In this mode, the item's colour and link strength indicate the average publication year of documents containing the selected keywords.

2.3. PCI testing solutions and substrates

The comparison between the main theme (keywords co-occurrences) and sub-themes (total number of publications) was made to understand the broad selection of researchers on the type of testing substrates and solutions. For instance, one of the most popular substrates in this topic is mild steel. Hence, the search string was edited to count all publications that stressed "mild steel" keywords. Based on the collected records, the leading countries according to the number of publications corresponding to the selected substrate and testing solutions were analyzed.

3. Results and discussion

3.1. Publication productivity and trends of research interest

Across 25 years from 1995 to 2020, up to 2237 articles have been published with the primary interest in plants as an effective corrosion inhibitor (Fig. 2). Prior to the year 2003, it was observed that the interest on the PCI topic fluctuated a bit, where a slow increase in the publications output was displayed from 1995 to 1997 before dropped in the year 1998. Then, in the year 1999, the publication productivity started to increase again until the year 2000. But, the rate of increment was unable to find a firm footing and continue to descend before it picked up the pace in the year 2003. During the year 2003 and forward, a rapid increase in the number of publications is recorded, suggesting a turning point for stronger research interest in PCI. The growth rate continues to increase steadily and accumulated a large quantity of cumulative total publications. In comparison to 1995, after 10 years, the year 2005 recorded an increase of 500% of the annual growth rate (AGR). This achievement was later doubled in 2010. Furthermore, it was discovered that the number of articles produced increased by 50 in the subsequent two and three years from 2011 until the end of 2018. After 2018, in only a short span of two years, publication productivity escalated to 100. Thus, it is estimated that this number will continue to rise in correspond to the increase of people's awareness of the importance of eco-friendly materials to reduce pollution. Nevertheless, a considerable number of these publications are not free to access for more people to read. In fact, based on the statistic from the Scopus database, out of 1924 articles, only 25.5% (491 articles) were published on the open-access platform. Hence, we would like to suggest that more articles be included as an open-access type for better awareness and citation.

PCI research topics are growing trends, and many researchers worldwide are working actively to contribute to this field. The diversity of this topic is evident according to the distribution of total publications on the following subject areas: Chemistry (931 articles), Materials Science (810 articles), Chemical Engineering (489 articles) and Engineering (443 articles). The rapid awareness of PCI research areas can also be attributed to its extensive deployment of the usage of herbs as the main ingredients. Herbs as a medicinal plant are positively accepted globally as a beneficial substance to humans and animals. So, when researchers introduced popular herbs such as *Rothmannia longiflora* (Akalezi et al., 2015); *Andrographis paniculata* (Maria et al., 2019); *Leucaena leucocephala* (Kamaruzzaman et al., 2020), cinnamon (Bouraoui et al., 2019), ginger (Liu et al., 2019) and valerian extracts (El-Katori et al., 2019) in their studies, the social acceptance can be boost significantly for the developing technology. In terms of the publication language, although most articles were published in English (1830; 95.1%), some articles were also published in Chinese (60; 3.1%), Portuguese (10; 0.5%) and Russian (5; 0.3%).

3.2. Preferred journals

Based on the compiled data of the top 10 most productive journals in PCI research areas, two different publishers, Emerald and Elsevier, each owned two journals in the list (Table 1). These journals were "Corrosion Science" and "Journal of Bio and Tribo Corrosion" for Elsevier, and "Anti Corrosion

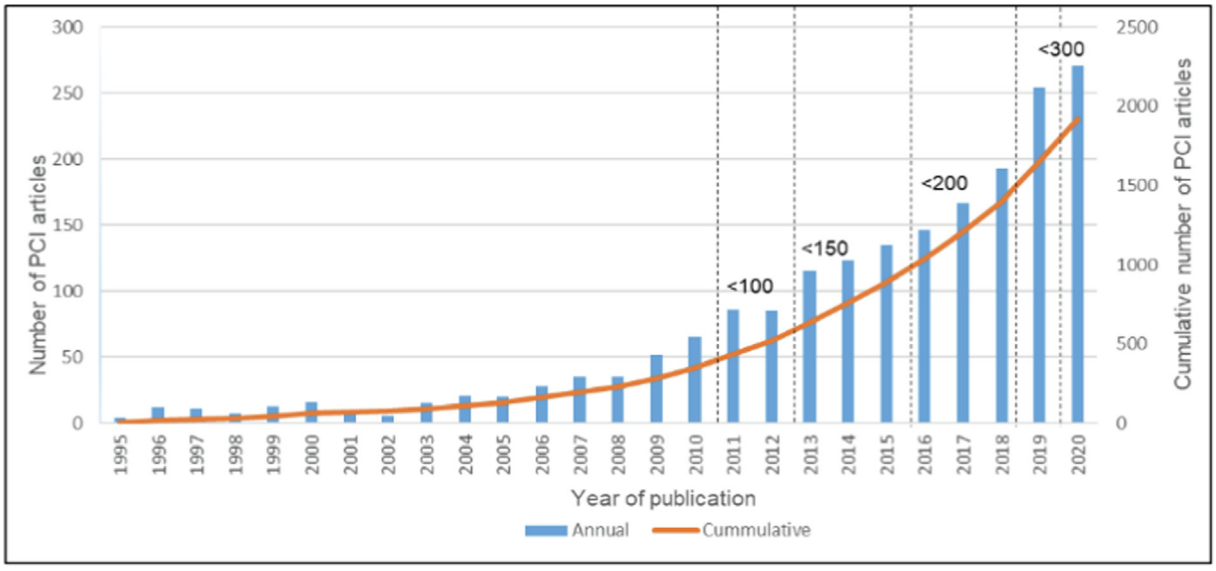


Fig. 2 The numbers of research articles and conference papers on PCI indexed in Scopus from 1995 to 2020.

Table 1 The top 10 most productive journals on PCI research with their most cited article from 1995 to 2020.

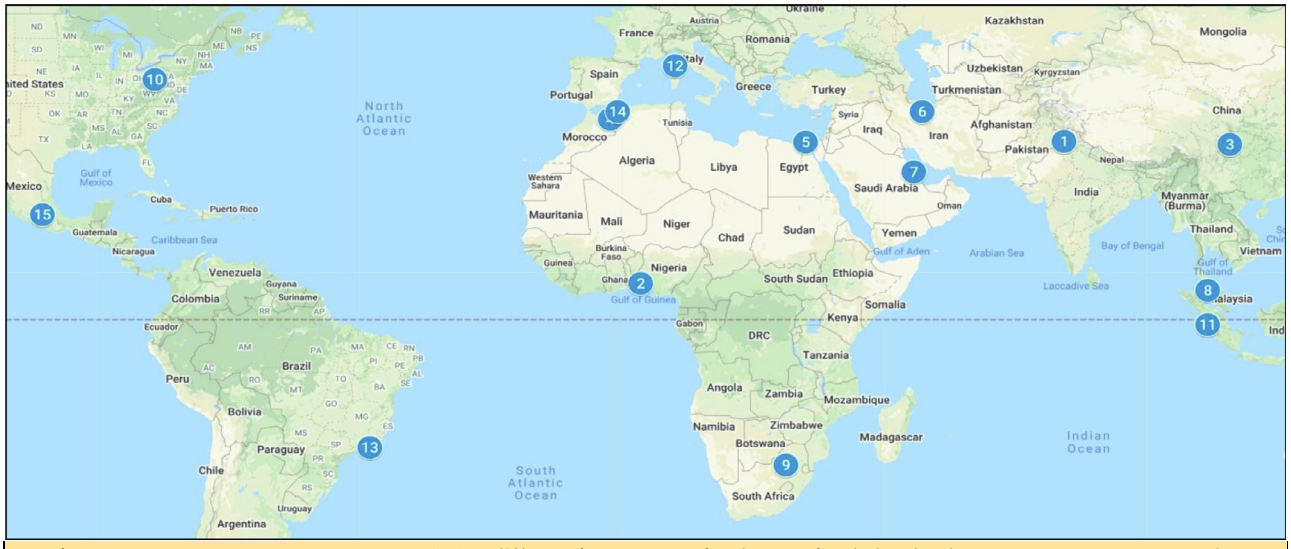
Rank	Journal	TP (%)	CiteScore (year)	The most cited article (reference)	Times cited	FWCI.	Publisher
1	International Journal of Electrochemical Science	156 (8.2)	2.7 (2020)	Temperature effects on the corrosion inhibition of mild steel in acidic solutions by aqueous extract of fenugreek leaves (Noor, 2007)	219	2.06	University of Belgrade
2	Journal of Materials and Environmental Science	58 (3.1)	1.4 (2016)	Green corrosion inhibitor: Inhibitive action of tannin extract of *Chamaerops humilis* plant for the corrosion of mild steel in 0.5 M H_2SO_4 (Benali et al., 2013)	79	4.43	University of Mohammed Premier Oujda
3	Corrosion Science	43 (2.3)	10.0 (2020)	Corrosion inhibition by *Justicia gendarussa* plant extract in hydrochloric acid solution (Satapathy et al., 2009)	544	11.71	Elsevier
4	Journal of Bio and Tribo Corrosion	41 (2.2)	3.6 (2020)	Corrosion inhibition of carbon steel in 1 M hydrochloric acid solution by aqueous extract of *Thevetia peruviana* (Fouda et al., 2016)	40	2.83	Springer
5	Journal of Molecular Liquids	39 (2.1)	8.4 (2020)	*Glycyrrhiza glabra* leaves extract as a green corrosion inhibitor for mild steel in 1 M hydrochloric acid solution: Experimental, molecular dynamics, Monte Carlo and quantum mechanics study (Alibakhshi et al., 2018)	172	19.27	Elsevier
6	Portugaliae Electrochimica Acta	37 (2.0)	2.9 (2020)	Corrosion inhibitive effect and adsorption behaviour of *Hibiscus sabdariffa* extract on mild steel in acidic media (Oguzie, 2008)	93	1.58	Portuguese Electrochemical Society
7	Asian Journal of Chemistry	31 (1.7)	0.7 (2020)	Corrosion inhibitor of mild steel by polar extract of *Theobroma cacao* peels in hydrochloric acid solution (Yetri and Jamarun, 2015)	20	0.54	Chemic Publishing Co.
8	Anti Corrosion Methods and Materials	28 (1.5)	1.9 (2020)	Eco-friendly corrosion inhibitors: The inhibitive action of *Delonix regia* extract for the corrosion of aluminium in acidic media (Abiola et al., 2007)	123	5.06	Emerald
9	Der Pharma Chemica	27 (1.5)	0.9 (2015)	Inhibition of steel corrosion in hydrochloric acid solution by chamomile extract (Hmamou et al., 2012)	66	3.78	Scholars Research Library
10	Pigment and Resin Technology	27 (1.5)	1.5 (2020)	Eco-friendly corrosion inhibitors: Inhibitive action of ethanol extracts of *Garcinia kola* for the corrosion of mild steel in H_2SO_4 solutions (Okafor et al., 2007)	102	3.21	Emerald

TP: total publication; FWCI: Field-Weighted citation impact.

Methods and Materials" and "Pigment and Resin Technology" for Emerald. The rest of the journals are not based on the same publishers and are scattered across the globe. Interestingly, the two highest-ranked journals were both owned by universities. The most productive journal was the "International Journal of Electrochemical Science" with 156 articles covering 8.2% of the total publication, followed by "Journal of Materials and Environmental Science" (58; 3.1%), "Corrosion Science" (43; 2.3%), "Journal of Bio and Tribo Corrosion" (41; 2.2%) and "Journal of Molecular Liquid" (39; 2.1%). Although "Corrosion Science" is ranked third on the list, their most cited articles published in 2009 received a staggering 544 citations compared to the first one on the list with only 219 citations.

Following the analysis of the CiteScore, despite most of the journals being calculated according to the year 2020, two journals on the list, "Journal of Materials and Environmental Science" and "De Pharma Chemica" were identified to be last indexed in the years 2016 and 2015, respectively. Based on the CiteScore 2020 report, only two journals managed to have a CiteScore of 5 and beyond. The journal with the highest CiteScore was "Corrosion Science" (10.0), while the journal with the lowest CiteScore was "Asian Journal of Chemistry" (0.7). Additionally, it is interesting to point out that although the journal of "Pigment and Resin Technology" was placed on the tenth position, their most cited article has a higher citation than the second, fourth, sixth, seventh and ninth-ranked journals. Many researchers consider CiteScore as a great way to measure the amount of 'audience' received annually by a journal. As such, it is understandable that the value of CiteScore can significantly affect the authors when deciding the journal to publish their works.

Here, apart from CiteScore, we also want to suggest another parameter to be considered: the Field-Weighted Citation Impact (FWCI). FWCI is a parameter calculated according to the ratio of the total citations received by an article in respect to the expected total citations on the average scale for a particular subject area. Hence, when the FWCI value is equal to 1, the article published in the journal received an expected or normal coverage on a global scale. If the value is more than 1, it is a clue that the article is cited more than expected. For instance, the FWCI of the most cited article



Rank	Country	TPc	S.C.P. (%)	The most productive academic institution	TPi
1	India	425	84.2	Lovely Professional University	37
2	Nigeria	226	65.5	Covenant University	55
3	China	208	77.4	Southwest Petroleum University China	29
4	Morocco	136	43.4	Université Mohammed Premier Oujda	71
5	Egypt	129	68.2	Mansoura University	48
6	Iran	117	94.0	Institute for Color Science and Technology	65
7	Saudi Arabia	109	43.1	King Fahd University of Petroleum and Minerals	31
8	Malaysia	85	67.1	Universiti Sains Malaysia	37
9	South Africa	83	14.5	Tshwane University of Technology	37
10	United States	73	64.4	University of Pittsburgh	5
11	Indonesia	61	98.4	Universitas Andalas	9
12	France	57	7.0	Universita di Corsica Pascal Paoli	17
13	Brazil	49	93.9	Universidade Federal do Rio de Janeiro	23
14	Algeria	45	64.4	Université Abou Bekr Belkaid Tlemcen	9
15	Mexico	36	72.2	Universidad Autónoma del Estado de Morelos	15

TPc: total publications of a given country; TPi: total publications of a given academic institutuions; SCP: single-country publications.

Fig. 3 The top 15 leading countries and academic institutions in PCI research field.

from "Corrosion Science" is 11.71, which indicates that it is cited 1071% more than expected on the global average. Nonetheless, in our humble opinion, although CiteScore and FWCI can be good criteria to be measured by the authors when selecting a journal, the authors also have to consider if the journal can present the works to the correct viewers by analyzing their list of published articles before submission.

3.3. Leading countries and institutions

Fig. 3 displays the list of the top 15 countries with their corresponding most productive academic institutions, which have contributed significantly to PCI research activities worldwide. The top 3 countries on the list, i.e., India, Nigeria and China, cover about 45% of the total publications, signifying that these countries are the major contributors to the advancement of the PCI research area. India was determined to be the leading country with their total publication reached 425 articles, covering about 22% of the global production. With almost one-half of India's overall publications, both Nigeria and China were ranked second and third, respectively. Despite being ranked first, it was ascertained that their most productive academic institution, the Lovely Professional University, has a lower total publication (TPi) than most institutions listed on the top 10. Otherwise, the Université Mohammed Premier Oujda from Morocco has the highest productivity, with the TPi achievement being 71 articles.

Among the listed 15 countries, the countries with more than 2/3 single country publications (SCP) were only India (84.2%), China (77.4%), Iran (94.0%), Indonesia (98.4%), Brazil (93.9%) and Mexico (72.2%). The high values of SCP suggest a strong intra-country-collaboration, which means that most of the country's publications have authors affiliated with only one country. In other words, these publications do not have much involvement from authors of other countries. The country with the least SCP was France at 7.0%, where 52 out of 57 publications were affiliated with authors of 19 different countries. The low number of SCP is not a bad indicator since it demonstrated an extensive international collaboration which can promote a better sharing of knowledge and expertise. South Africa, for example, despite being considered by many to have low economic growth, strife in this research area with 85.5% (70 articles) of its publications were connected to 12 countries, ranking it at the 9th place on the list.

Moreover, out of the 15 listed institutions, the best three universities were ranked in the top 200 according to the World University Ranking 2020 – Universiti Sains Malaysia (ranking 147th), University of Pittsburgh (ranking 163th) and King Fahd University of Petroleum and Minerals (ranking 186th). This demonstrates that the research interest of PCI is slowly gaining the attention of the top universities in the world.

Fig. 4 illustrates the distribution of countries based on their respective continents. For example, the items with the red color represent the countries from Asia, green for Europe, blue for America, yellow for Africa and purple for Oceania. The distance and thickness of the lines between a country indicate the strength of their relatedness, which can correspond to the degree of collaborative works in the PCI research area. The highest number of countries based on their continents that contribute to PCI research interest starts from Asia (28) and Europe (28), followed by Africa (13), America (10) and Oceania (1). Based on the analysis performed on co-authorship, India was identified to have the highest affiliation linked to 24 countries with 95 times of co-authorship. The list was followed by Morocco (22 links, 98 co-authorships), Saudi Arabia (22 links, 91 co-authorships), France (19 links, 70 co-authorships) and China (19 links, 67 co-authorships). Besides,

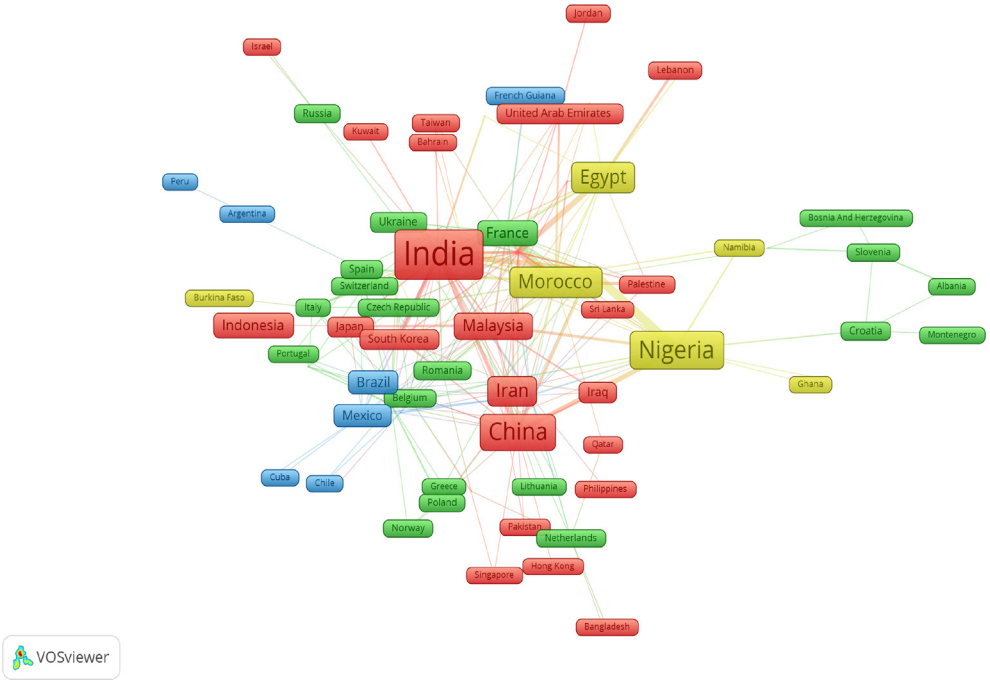


Fig. 4 A bibliometric map fabricated according to the co-authorship in network visualization mode. The following URL can be used to open Fig. 4 in online VOSviewer: https://bit.ly/33pW8mh.

Table 2 List of the most prolific authors in PCI research area.

	Author	Scopus author ID	Year of 1st publication*	TP	h-index	TC	Current affiliation	Country
1	Ramezanzadeh, Bahram	26421358600	2009 [a]	340	59	11751	Department of Surface Coating and Corrosion, Institute for Color Science and Technology	Iran
2	Hammouti, Balkheir	700460437	1995 [a]	673	71	20053	Faculty of Science, University of Mohammed I	Morocco
3	Ebenso, Eno E.	55090810500	1995 [a]	465	68	15945	Institute of Nanotechnology and Water Sustainability, University of South Africa	South Africa
4	Bahlakeh, Ghasem	36801103000	2011 [b]	136	38	3877	Department of Chemical Engineering, Faculty of Engineering, Golestan University	Iran
5	Singh, Ambrish	57202898174	2010 [a]	140	34	4154	School of Material Science and Engineering, Southwest Petroleum University	China
6	Loto, Cleophas Akintoye	7003588626	1987 [a]	207	27	2390	Department of Mechanical Engineering, Covenant University (until 2020)	Nigeria
7	Oguzie, Emeka Emmanuel	6602237269	2004 [a]	124	39	5512	School of Environmental Sciences, Federal University of Technology	Nigeria
8	Fouda, Abdel Aziz Sayed	56231506400	1980 [a]	283	33	4941	Chemistry Department, Faculty of Science, Mansoura University	Egypt
9	Loto, Roland Tolulope	57194737023	2011 [a]	185	19	1189	Department of Mechanical Engineering, College of Engineering, Covenant University	Nigeria
10	Zarrouk, Abdelkader	36125763200	2010 [a]	426	58	7959	Department of Chemistry, Faculty of Sciences, Mohammed V University	Morocco

*Role in co-authorship, superscripts.
[a] First author.
[b] Co-author.

it was recognized that more than 2/3 (62 countries) of the countries listed had collaborative publication less than 10. Also, some countries, including Thailand, Bangladesh, Bahrain and Cuba were not affiliated with any other countries on publications related to PCI.

The high strength of international collaboration of a country can be attributed to several factors, including the broad networking of researchers with authors of different countries, visiting scholars, foreign postgraduate students, and fundings received from outside resources. Hence, the dynamic of international collaboration needs to be considered an important aspect to increase flexibility and promote stable research projects that may produce excellent outputs with better benefits to humankind.

3.4. Leading authors

Table 2 tabulates the list of 10 most famous authors in the field of PCI, affiliated to six different countries which are Nigeria (3 authors), Iran (2 authors), Morocco (2 authors), China (1 author), Egypt (1 author) and South Africa (1 author). Based on their year of first publication, it can be discerned that there are two possible pioneers of the PCI research interest: A.A.S. Fouda (year of first publication: 1980) and C.A. Loto (year of first publication: 1987). In general, the first publication of these authors ranged from 1980 to 2011, where 9 out of 10 authors had a role as the first author. It is also important to note that while the list is based on the Scopus database results, there are no rules applied to determine the sequence of authors. Thus, it is based on the readers to decide if they want to rule it according to the author's total citation, h-index or else. On a side note, the h-index is a value generated by the database to estimate an author's productivity and the citation impact of their published article on the topics of interest.

B. Hammouti from Morocco is undoubtedly placed on top of the list with excellent records of 673 publications since 1995, 71 h-index and 20,053 total citations. The second and third best authors who were E.E. Ebenso and B. Ramezanzadeh from South Africa and Iran, also have stunning records of total citations above 10,000. In relative to other authors, both of the youngest researchers, i.e., G. Bahlakeh and R.T. Loto, began their first publication in 2011 and managed to be selected as one of the most prolific authors in a short span of 10 years. Moreover, it is also interesting to mention that both R.T. Loto and C.A. Loto from Nigeria were affiliated to the same department, Department of Mechanical Engineering, Covenant University, until the year 2020, prior to the retirement of C.A. Loto.

3.5. Author keywords

The VOSviewer tabulated a total of 3054 author keywords according to the collected database. After analyzing the results, re-labeling was done on keywords with similar or congeneric meanings to prevent redundancy. Up to 107 keywords met the threshold when the minimum of occurrences was set to 5 for the construction of bibliometric maps.

3.5.1. Terminology and concept

Based on our analysis of Fig. 5, an unexpected result was shown for the most frequently encountered keywords, where the term 'mild steel' was determined to have the highest occurrences of 408 with 83 links to other keywords. The sequence was followed by 'corrosion' (401 occurrences, 86 links), electrochemical impedance spectroscopy, EIS (299 occurrences, 77 links) and 'corrosion inhibitor' (293 occurrences, 80 links). The high selection of the term 'mild steel' as an author keyword is possibly due to its suitability as a representation for the testing substrates of many articles. It is commonly under-

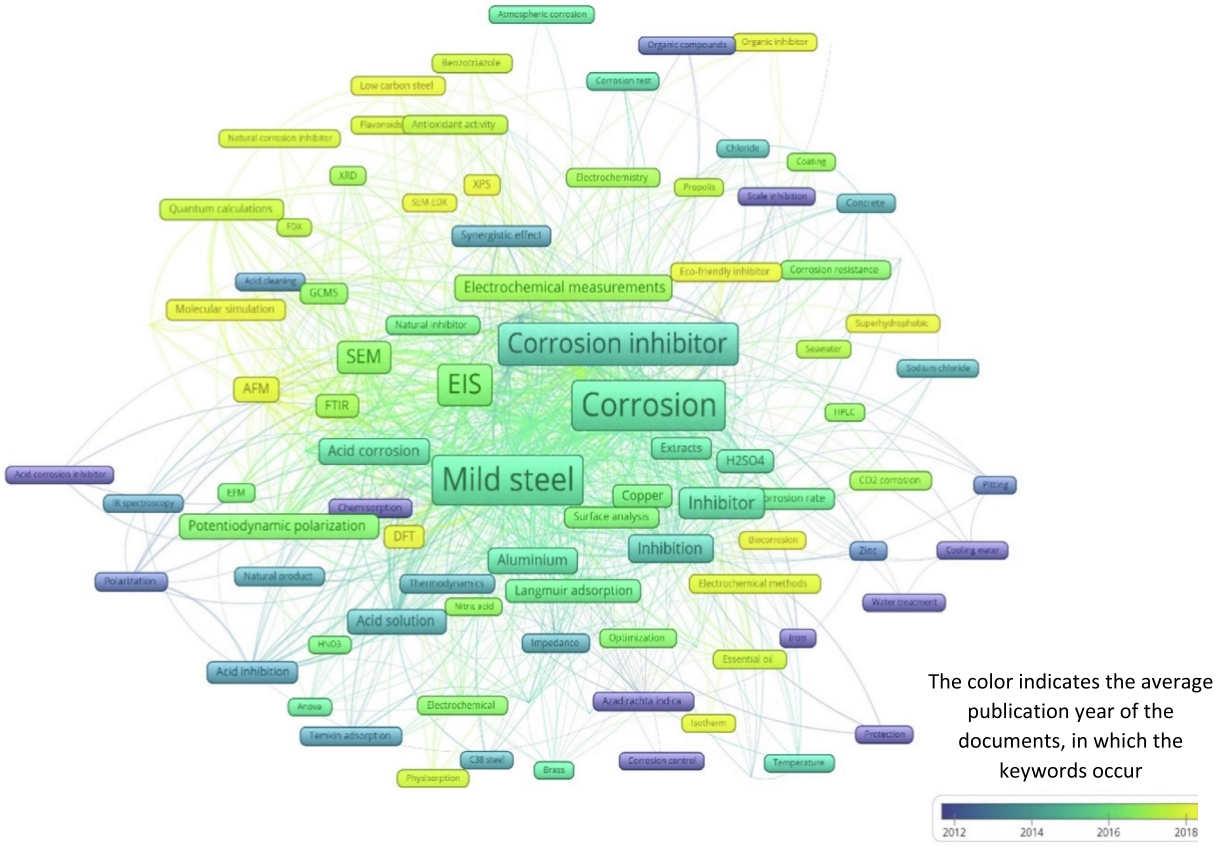


Fig. 5 A bibliometric map fabricated according to the author keywords co-occurrence in overlay visualization mode. The following URL can be used to open Fig. 5 in VOSviewer: https://bit.ly/3iHn1X0.

stood that mild steel is the most popular type in various industries but possesses a significantly low chemical resistance (Mehmeti and Berisha, 2017). As such, it is generally considered the primary goal of many researchers, where each aims to fabricate an efficient corrosion inhibitor to slow down the corrosion reaction on this steel.

Besides, we also discovered several other keywords attributed to the instruments and techniques used for the analysis purpose. Among the list, apart from 'EIS', the term 'weight loss (157 occurrences) was the next highest, followed by scanning electron microscope or 'SEM' (149), 'polarization measurement' (106), atomic force microscopy or 'AFM' (64) and Fourier transform infrared spectroscopy or 'FTIR' (54). In terms of the testing solution, 'HCl' is the most popular with 96 occurrences linked to other 49 keywords, followed by 'H_2SO_4' (50 occurrences, 41 links), 'NaCl' or 'chloride' (7 occurrences, 9 links) and 'HNO_3' (5 occurrences, 11 links). On top of the 'mild steel' or 'carbon steel' terms, other terms to represent the testing substrates were also available, including 'aluminum' (83 occurrences), 'copper' (47), 'stainless steel' (19), 'zinc' (11) and 'brass' (6).

3.5.2. Topic of interest

As an evolving technology with the essential purpose to promote eco-friendly materials, PCI performance continues to receive considerable attention. Keywords such as 'green inhibition' were repeated 179 times among the recorded database, which signifies a collective interest of researchers in this field. The use of plant extract in this field is widely accepted as a type of green inhibitor due to several characteristics such as being renewable, cheap, biodegradable, and safe to both humans and the environment. The development of green inhibitors is commonly fabricated through two methods, either by identifying new chemistries to create a new and safe product or by reformulating the available inhibitors to have a better effect. As presented in Fig. 2, the increasing number of publications per year on this topic is a great indicator to justify the importance of using plant extracts to solve corrosion. Furthermore, the versatility of plants is not limited to the variation of phtochemicals but also to their quantity which can differ based on different parts of plants, age, vegetative cycle, geographical and climatic conditions (Salleh et al., 2021). Due to these aspects; the researchers' community has given much attention to test plants of different conditions on substrates exposed to various corrosive solutions.

Many authors also discussed the mechanisms of PCI, and this is associated with the use of the 'adsorption' term, which appeared 179 times and linked to 65 other keywords. Adsorption reflects the initial process of inhibition by plant extracts. The process, in short, occurs when the molecules of inhibitors adsorb onto the metal surface to form layers of protective barrier that prevent redox reaction from being initiated. The types of adsorption mechanisms are varied into two types, i.e., physisorption (7 occurrences, 13 links) and chemisorption (8 occurrences, 19 links). But, plants generally performed better

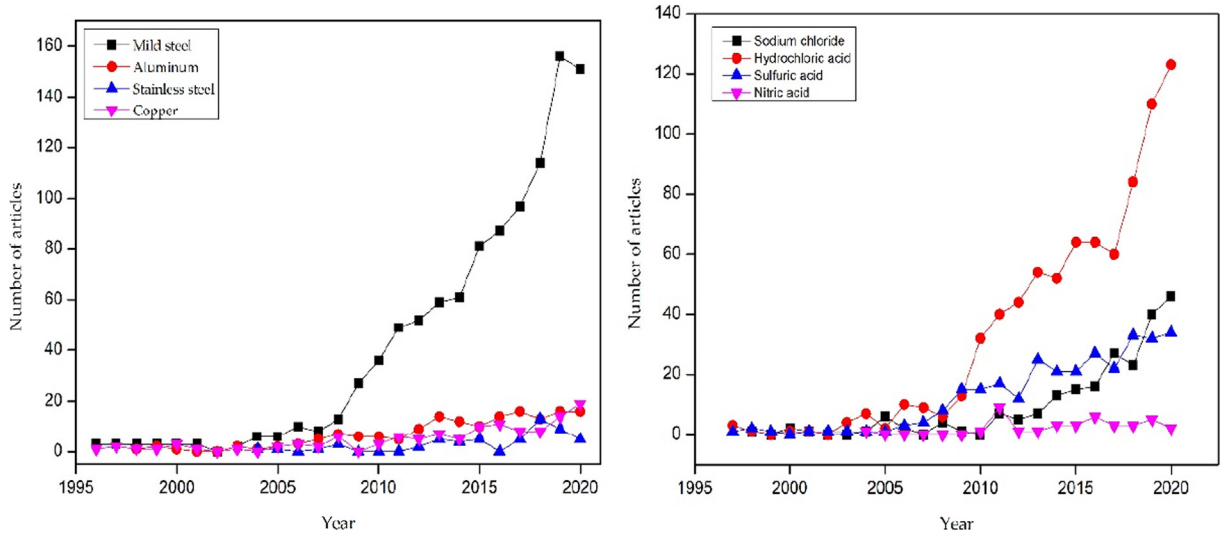


Fig. 6 Research trends of the selected testing (a) substrates and (b) medium in PCI.

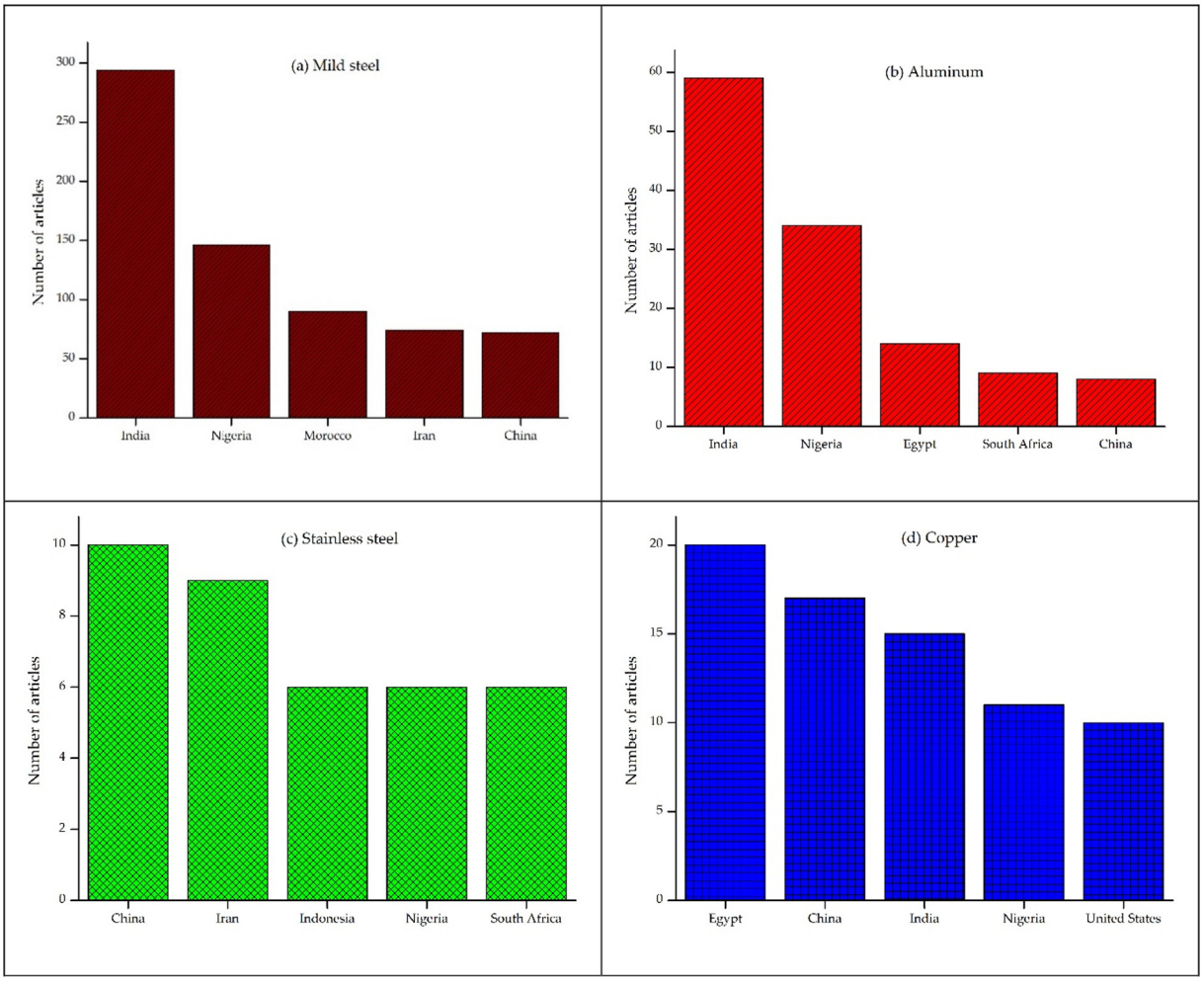


Fig. 7 Five countries with the most publication on the selected research trends of testing substrates.

adsorption functions by combining both of them as a mixed mechanism, where it acts on both anodic and cathodic sites.

In addition, evaluation methods such as EIS, polarization measurement and weight loss are time-consuming and can be expensive. Thus, through the usage of current technology, computer analysis can perform a theoretical calculation to predict specific inhibitors' efficiency effectively with a lower cost. Apart from its ability to forecast the inhibitor's overall effi-

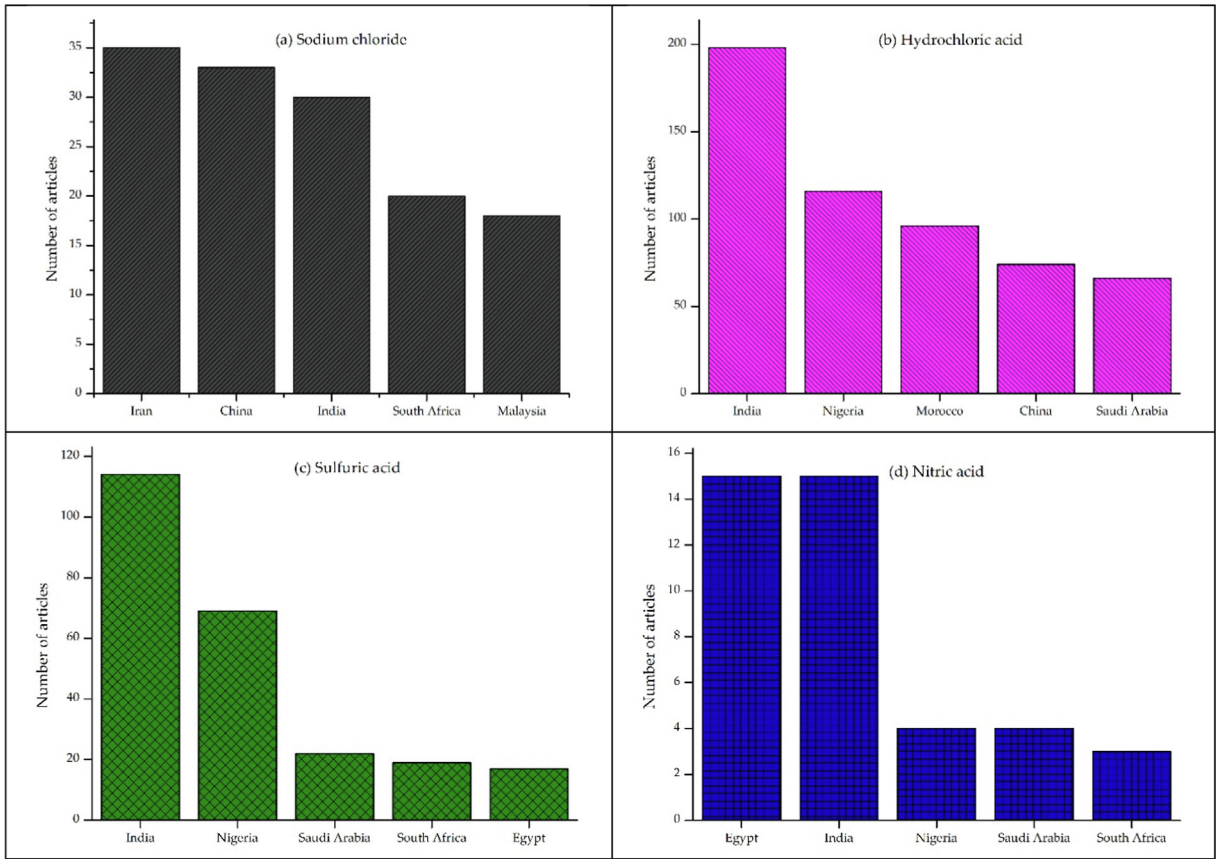


Fig. 8 Five countries with the most published articles on the selected research trends of testing solutions.

ciency, this technique can also tone down the research cost that transpires due to the try and error screening test of raw specimens. The applicability of this method is evident based on the term 'molecular simulation', which was found to occur 21 times and links to 23 keywords. On top of that, two author keywords indicate the type of molecular simulation, including the density functional theory or 'DFT' (44 occurrences) and 'Monte Carlo' (9). Another recent interesting discussion was on the issue of synergistic effects (25 occurrences, 26 links). It is a study of synergistic behavior, commonly between two types of inhibitors, where the aim is to enhance the inhibitor efficiency compared to its respective individual capabilities. To date, several synergistic studies between different PCIs include butanolic extract of *Elaeoselinum thapsioides* and *Reutera lutea* (Benahmed et al., 2020), leaves and stem extracts of *Sida acuta* (Eduok et al., 2012), and potassium iodide and *Achillea santolina* extract (Fouda et al., 2019).

3.6. Distribution of PCI publications based on testing substrates and solutions

Following the number of articles, frequency of author keywords co-occurrences, and constructed bibliometric maps, a significant correlation was found between the outputs and the central and sub-themes. Fig. 6 displayed that mild steel and HCl were the most popular testing substrate and solution among the research community of PCI, with major values of 1033 and 784 articles, respectively. Based on this data, relative to the total search result of 1924 articles, the percentage of researchers selecting mild steel and HCl as their primary interest was 53.69% and 40.75%, respectively. For the substrates, the list was followed by aluminum (161 articles), copper (119 articles) and stainless steel (54 articles). In comparison, for the testing solutions, the list was followed by H_2SO_4 (298 articles), NaCl (217 articles) and HNO_3 (38 articles).

The application of mild steel in the PCI research fields started to become popular in 2005 and has since exponentially increased to be the most selected substrate. This suggests that more researchers realize the importance of mild steel as the main material for various infrastructures such as steel buildings, bridges, and pipelines (Suganya et al., 2018; Angst, 2018). Although there was a slight increase in the number of publications for other substrates from the same year, their trends were incomparable to mild steel even until 2020. This observation was unexpected as substrates such as aluminum and stainless steel are relatively popular nowadays as construction materials. Hence, the low attention given on both steels can only be attributed to the perception of many researchers, which consider them to be almost invulnerable towards corrosion. As for the testing solutions, HCl began to receive notable attention from 2006. Its trend was observed to increase in general, with only a slight drop in 2014 and 2017. Contrary to the substrates, other testing solutions besides HCl also experienced increased trends, with the only exception being HNO_3. The popularity of HCl is within our expectations since it is known as the most used acid for the chemical cleaning process in multiple industries.

Moreover, we found that most publications that focused on mild steel and aluminum were published by authors affiliated to the country of India, with Nigeria being the second for both substrates (Fig. 7). In addition, countries such as Nigeria and China were discovered to be among the top 5 for publications of all substrates. In terms of the testing solutions (Fig. 8), India was recorded to have the highest number of articles that selected HCl and H_2SO_4 in their studies. On top of that, among the listed countries, only India was present in the top 5 for each testing solution. Other countries such as Iran, Morocco, and Malaysia were listed in different solutions and only once.

3.7. Limitation of study

By limiting the search of "corrosion inhibit*" and restricting it for terms including plants, leaf and flower within titles and abstracts, the results presented by the Scopus might not cover all the PCI-related articles. This can occur because some researchers might not include the selected terms but instead use a different expression to represent their research interests. Besides, some author keywords in the co-occurrence analysis might also have been left out by VOSviewer during the screening of the database due to the missing information from the journals. Thus, it is recommended that future works include databases from other sources such as the Web of Sciences, which will make the bibliometric study more comprehensive and interesting.

4. Conclusion

This study was conducted to provide a general overview of the growth of PCI research trends from the year 1995 to 2020 using the Scopus database, covering up to 1924 articles published through standard journals and conference proceedings. Prior to the first stage of data collection, several refining processes, such as excluding unrelated articles and review articles, were executed. Next, a series of figures fabricated using the VOSviewer software were constructed to visualize the textual documents. Then, tables tabulating the list of most productive journals and authors were presented following the arrangement created by the Scopus website. Publication growth was observed to be slow during the first 10 years and has only picked up the pace from 2005. According to the trend observed, it is anticipated that the research interest of PCI will continue to escalate for a few more years. We have also found that countries/academic institutions from India, Nigeria and China were the ones that have contributed the most in the number of total articles in the PCI research area. These massive entities can serve as opportunities for countries with fewer publications to make international collaborations and broaden their knowledge. Last but not least, we have presented several topics to illustrate the tendency of researchers in selecting the type of substrates and testing solution as the focus of their study. We discovered that mild steel and sodium chlorides were the most popular testing substrate and solution. We aimed for this study to be a valuable source of information for researchers interested in exploring the beneficial properties of plant extracts as corrosion inhibitors with the qualities of non-toxic, available abundantly, inexpensive and safe for both humans and the environment.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.arabjc.2021.103655.

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