

Mapping research trends in plant-based green corrosion inhibitors: A bibliometric analysis (2020–2025)

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ABSTRACT

The increasing concerns relating to environmental and health problem from conventional corrosion inhibitors have focused on plant-based green alternatives. This study uses bibliometric analysis on plant-based corrosion inhibitors between 2020 to 2025 using the data from the Scopus database. The analysis shows the increasing of publication, with a peak observed in 2024, reflecting the expanding global interest in sustainable approaches to corrosion protections. China and India are the leading contributors to the field due to strong industrial demand and national sustainability initiatives, while Ramezanzadeh, B., and Guo, L., are the most prolific authors that make a considerable impact on the research landscape. The subject area dominated by Chemistry and Materials Science and also including engineering and environmental sciences. Keyword co-occurrence analysis has revealed that the subject of research mainly concerns inhibition performance, with special attention to plant extracts, electrochemical evaluation techniques, and

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acidic environments such as hydrochloric acid medium. The growing integration of computational modelling and theoretical approaches implies a move towards mechanism-based and predictive studies. These findings demonstrate that research on plant-based corrosion inhibitors is growing toward more sustainable, application-oriented, and interdisciplinary approaches. Thus, the bibliometric analysis provides valuable guidance for researchers and industry stakeholders in identifying emerging trends, optimizing inhibitor selection, and advancing the development of environmentally friendly corrosion protection technologies.

1. INTRODUCTION

In carbon steel, corrosion is one of the most severe problems, often causing damage to the surface. Corrosion of carbon steel is inevitable due to exposure to alkaline and acidic environments in applications such as oil and gas pipelines, boilers, platforms, and structural applications [1]. More than 50% of the steel used in industry suffers from problems related to surface weakness, performance degradation, equipment failure, reduced flexural and surface bonding capacity, dimensional variation, and other effects. In 2016, the National Association of Corrosion Engineers (NACE) reported that the cost of corrosion cost was expected to reach USD 2.5 trillion, or 3.4% of the world's Gross Domestic Product (GDP) [2]. The vast economic significance underscores the serious importance of cost-effective and sustainable corrosion management solutions.

Specifically, several techniques can be employed to prevent corrosion, including alloying additions, surface coatings, reduction of metal impurity content, cathodic protection, metal plating, and others [3-5]. Nowadays, corrosion inhibitors are among the most widely used approaches for improving corrosion resistance. In essence, corrosion inhibitors provide a simple and cost-effective way to control corrosion in both acidic and alkaline environments. They reduce corrosion by creating barriers on the metal surface through chemical reactions [6].

Generally, corrosion inhibitors are typically categorized into anodic, cathodic, and mixed-type inhibitors based on their mechanisms. The selection of inhibitors depends on their ability to retard or hinder the cathodic, anodic, or both reactions on the surface [7]. Concurrently, the implementation of corrosion inhibitors shifts the corrosion potential of the inhibited metal toward the cathodic or anodic direction, eventually forming a protective layer on the metal due to changes in the activation energy of the oxidation reaction.

Current corrosion inhibitors are problematic because they are mostly made from hazardous materials that pose risks to humans and the environment. Prolonged exposure to inorganic corrosion inhibitors is hazardous to human health, adversely affects animals and plants, and contributes to environmental degradation [8]. In addition to these concerns, recent developments in corrosion-prevention research have

led to the use of more natural sources as inhibitors for industrial applications. Accordingly, applying corrosion inhibitors is straightforward and can be performed "in situ," allowing ongoing processes to remain uninterrupted.

Despite the increasing number of review studies on plant-based corrosion inhibitors, most existing works rely on qualitative summaries and focus primarily on reporting experimental findings without systematically analyzing global research patterns. Consequently, there is limited understanding of the evolution of this research field in terms of collaboration networks, emerging themes, and research gaps. Bibliometric analysis offers a quantitative and objective approach that enables the mapping of scientific knowledge structures through publication trends, co-authorship networks, and keyword relationships. Therefore, this method provides deeper insights compared to traditional reviews and is particularly valuable in identifying future research directions. In this context, the present study aims to conduct a comprehensive bibliometric analysis of plant-based green corrosion inhibitors from 2020 to 2025.

2. LITERATURE REVIEW

Plants have been widely used as corrosion inhibitors for metals in acidic environments due to their eco-friendliness and their promising effectiveness. This review discusses the recent research on different plant extracts in terms of their corrosion inhibition performance, underlying mechanisms, and potential industrial applications.

Artemisia herba-alba extract (AHA) was shown by Berrissoul Loukili et al. (2020) to actively inhibit corrosion in HCl solutions, as evidenced by weight-loss measurements, surface and electrochemical analyses, including Scanning Electron Microscopy (SEM–EDX) coupled with Energy Dispersive X-ray spectroscopy (EDX), and potentiodynamic polarisation. The results of these approaches showed that the extract has significant inhibitory activity and is a mixed-type corrosion inhibitor [9].

Deghhani, A., and Ramezanzaded, B. (2023) revealed that rosemary extract exhibits mixed-type inhibition, achieving an inhibition efficiency of up to 92% for steel in 1 Molar HCl. The inhibition performance was evaluated using electrochemical methods, including potentiodynamic polarisation, EIS, and weight-loss tests. Additionally, surface morphology was examined using Field Emission Scanning Electron Microscopy (FE-SEM) and Atomic Force Microscopy (AFM) [10].

Other researchers have reported the corrosion-inhibition effect of chamomile flower extract (CFe) on mild steel in HCl solutions. Several methods were used, including FE-SEM and AFM morphological examinations, electrochemical tests, and spectroscopic analysis. Their results indicated that CFe could form a protective layer on metal surfaces, effectively preventing corrosion [11].

Additionally, Fekkar. et al. (2020) investigated the characteristics of *Chamaerops humilis* L. fruit extracts for mild steel in an HCl solution. The researchers utilized potentiodynamic polarisation, weight-loss analysis, and EIS to assess the effectiveness of the extracts. The result reported the potential of plant inhibitors to reduce corrosion in acidic environments [12].

Regarding Daoudi, W. et al. (2024), *Rosmarinus officinalis* L. (ROL) essential oil has the potential to act as a green corrosion inhibitor for mild steel in a 1 Molar HCl solution. Gravimetric and electrochemical techniques, including EIS and potentiodynamic polarisation, determined the maximum inhibitor efficiency

of 90% at a concentration of 1.5 g/L. The results exhibit that the essential oil is an environmentally friendly corrosion inhibitor for mild steel in acidic environments [13].

Pisum sativum L (pea) leaf extract (PSLLE) as a green corrosion inhibitor for Q235 steel in sulfuric acid (H_2SO_4) solution was studied by Chen J. et al. (2023). Tafel polarisation analysis and surface topography methods confirmed that PSLLE forms a stable film that reduces corrosion. PSLLE achieved a maximum inhibition efficiency of 95.9% at 600 mg/L and 298 K. This indicates that PSLLE is highly effective and has strong potential as an environmentally friendly corrosion inhibitor [14].

Xiuli et al. (2020) also investigated the corrosion inhibition of *Lilium brownii* leaf extract on X70 steel in HCl solutions [15]. Their research used experimental analysis and demonstrated that the extract exhibits chemical and physical adsorption characteristics, indicating that it is a mixed-type inhibitor. Furthermore, Thakur et al. (2022) also investigated the corrosion inhibition of *Cnicus Benedictus* extract on mild steel in HCl solution. They conducted experimental and theoretical analyses and observed that the extract exhibited higher inhibitor efficiency and suggested an adsorption mechanism, supported by a Density Functional Theory (DFT) calculation [16].

Moreover, a comparison of the studied materials shows that some plant extracts exhibit high corrosion inhibition efficiency in acidic environments. Of these, PSLLE was the most efficient, reaching up to 95.9% for Q235 steel in H_2SO_4 solution at 600 mg/L. Extracts in HCl showed good and consistent results. For example, rosemary extract produced 92% efficiency for steel in 1 M HCl, and ROL essential oil achieved 90% efficiency for mild steel in 1.5 g/L in the same environment. In comparison, other plant extracts, such as AHA, CFe, *C. humilis L.* fruit extracts, *L. brownii* leaves, and *C. Benedictus* extracts, have also been reported to be effective in reducing corrosion on metal surfaces. Notably, these findings show that plant extracts containing heteroatoms, aromatic rings, and functional groups such as hydroxyl and carbonyl groups can effectively adsorb onto metal surfaces and reduce corrosion effects [17], [18].

Overall, the reviewed studies show similar trends for plant-based corrosion inhibitors. Most investigations of inhibitor performance were conducted in acidic environments, such as hydrochloric acid (HCl). Based on the reported inhibition performance, mixed-type inhibitors were generally effective, with some plant extracts reportedly delaying both anodic and cathodic reactions. Electrochemical techniques such as potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and weight-loss measurements have been the primary techniques of corrosion testing. These findings were supported by surface-morphology tools such as FE-SEM, AFM, and EDX. Extraction from *Pisum sativum* leaves, rosemary, and *Rosmarinus officinalis* essential oil demonstrated strong potential, particularly for plants containing heteroatoms and oxygenated functional groups for sustainable corrosion protection. This trend indicates that the current approach in science to advancing safer, more effective, and better mechanistically understood corrosion-inhibiting systems, although consistent testing conditions are required for comparable results.

3. RESEARCH QUESTION

3.1 Temporal and disciplinary trends

RQ1: What are the current trends? Based on the publication year, what are the current research trends in using plants as corrosion inhibitors for mild steel?

RQ2: What is the document category based on the research subject?

3.2 Authorship and global collaboration

RQ3: Who is the most prolific author?

RQ4: What is the partnership between countries in co-authorship?

RQ5: What about creating a network map using co-citation analysis based on authorship?

3.3 Geographical distribution

RQ6: Which country published this research the most?

3.4 Thematic focus and keywords

RQ7: What are the popular keywords associated with the research?

4. METHODOLOGY

Bibliometric analysis is a systematic approach for gathering, organizing, and analyzing bibliographic information from scientific publications to identify research trends, authors, and thematic developments within a specific research field [19-21]. Accordingly, advanced methods, such as document co-citation analysis, are used in this study, along with standard information, including publishing journals, publication years, and relevant author classifications.

A thorough bibliography and accurate results are ensured through an iterative process involving the selection of relevant keywords, literature searches, and analysis of the results to create an effective literature review [22]. Hence, to ensure the reliability and quality of the dataset, this study focused on high-quality journal articles to yield insights into the theoretical stances that shape the research discipline. Furthermore, only papers published in academic journals were examined exclude conferences, books, and lecture notes to guarantee that only publications of the highest quality were included to maintain a consistent standard of quality within the analysis [23].

Specifically, Elsevier's Scopus was selected for its extensive coverage of high-quality scientific publications across multiple disciplines. Correspondingly, the database facilitated the collection of relevant publications on plant-based corrosion inhibitors published between 2020 and May 2025, which were subsequently used for further bibliometric analysis. To ensure data accuracy, all duplicate records were identified and removed via automated filtering in the database, followed by manual verification. Meanwhile, irrelevant articles were further excluded based on title and abstract screening to ensure alignment with the research scope.

Despite its comprehensive coverage, reliance on a single database may limit the inclusion of relevant studies indexed in other databases such as Web of Science (WoS) or Google Scholar. Therefore, this limitation should be considered when interpreting the findings of the present study.

4.1 Data search strategy

The study's screening sequence determined the search terms for article retrieval. The study started by assembling 5,454 articles from online and querying the Scopus database. Then, the query string was changed to focus on corrosion inhibitors using the search phrases "plant OR green" AND "corrosion inhibit*". therefrom these results, 2,062 articles identified through the search string in Table 1 were used to perform a bibliometric analysis. Table 2 show the selection criteria applied to the Scopus database as of May 2025. Meanwhile, Fig. 1. shows the research framework for the data collection process.

Table 1. The search strings

Scopus	TITLE-ABS-KEY (plant OR green AND "corrosion inhibit*") AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025))
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Table 2. The selection criterion is searching

Criterion	Inclusion	Exclusion
Timeline	2020-2025	<2020
Language	English	Non-English
Document Type	Article	Non-Article
Source type	Journal (Article)	Proceeding, Book, Review

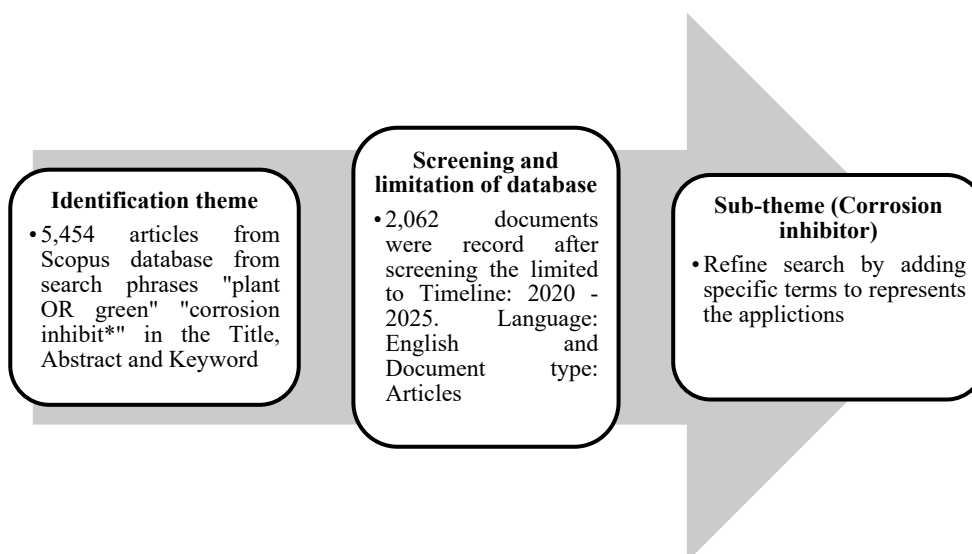


Fig. 1. Research framework on the data collection process

4.2 Data analysis

Nees Jan van Eck and Ludo Waltman developed VOSviewer, a bibliometric software, at Leiden University in the Netherlands [19], [20]. VOSviewer is commonly used to visualize and analyze literature for generating network visualizations, clustering similar items, and creating density maps. Using this software, researchers can investigate co-authorship networks, co-citations, and keyword co-occurrence and understand the research landscape [24], [25]. Following this, the interactive interface, along with regular updates, enables effective and dynamic exploration of extensive datasets. In essence, VOSviewer is a significant tool for researchers seeking insights into technical research areas, attributed to its ability to calculate metrics, personalize visualizations, and adapt to different bibliometric data sources [26].

One of VOSviewer's most significant features is its ability to transform a complex bibliometric dataset into visually intelligible maps and charts [27]. The software is excellent for clustering similar items, developing density maps on network visualization, and analyzing keyword co-occurrence. Moreover, its user-friendly design enabled learners and experts to navigate study landscapes effectively [28]. VOSviewer's continuous development ensures it remains at the forefront of bibliometric analysis by providing insightful information and scalable visualizations due to its ability to recognize co-authorship and citation networks, demonstrating that VOSviewer is a flexible and essential tool for researchers seeking understanding and significant insights in their fields..

Furthermore, datasets containing PlainText-formatted information on publication year, article title, author name, journal name, citations, and keywords were collected from the Scopus database between 2020 and May 2025. VOSviewer software version 1.6.19 was utilized to analyze these datasets. This software simplifies map exploration and creation using VOS networking and mapping techniques. As an alternative to the Multidimensional Scaling (MDS) method, VOSviewer places objects in low-dimensional spaces to ensure the distance between any two items appropriately represents their similarity and relatedness [20]. In this respect, VOSViewer is equivalent to the MDS approach [21]. Unlike MDS, which is mainly concerned

with the calculation of similarity metrics such as cosine and Jaccard indices, VOS utilizes a more appropriate technique to normalize occurrence and includes association strength (AS_{ij}) given in Eqs. 1 and 2 as [29]:

$$AS_{ij} = \frac{1}{4} C_{ij} \quad (1)$$

$$W_{ij} \quad (2)$$

which, under the supposition that the co-occurrence of *i* and *j* is statistically independent, is proportional to the ratio between the observed number of co-occurrences of *i* and *j* and the expected number of co-occurrences of *i* and *j*. Thus, after lowering the weighted sum of the squared distances between each pair of items, VOSviewer arranges the items in the form of a map with the assistance of this index.

5. RESULTS AND FINDINGS

5.1 What are the research trends in plant-based green corrosion inhibitors in mild steel according to 2020-2025?

Fig. 2. illustrates a line graph titled "Documents by year," representing the number of documents or publications for the last five years, from 2020 to 2025. The data are retrieved from Elsevier B.V., which owns and operates the Scopus database, demonstrate a generally upward trend in research output over the observed period. The number of publications increased steadily from 280 in 2020 to 454 in 2024, indicating a growing global interest in environmentally sustainable corrosion mitigation strategies.

The number of documents increased gradually from 2020 to 2022. Research into plant-based corrosion inhibitors has attracted interest for many years, and this trend seems to be accelerating as people's understanding of the environmental and health risks posed by conventional synthetic inhibitors grows. However, the most significant increase occurs between 2021 and 2023, indicating a dramatic increase in publications during that period. This highlights increased research activity and increases academic engagement in sustainable material development. The recent increase in documents may be related to the greater incorporation of green chemistry and global trends towards eco-friendly engineering. The peak in 2024 can be attributed to several contributing factors.

As sustainability frameworks and environmental regulations have been implemented in recent years, researchers and industry have begun evaluating possible natural alternatives, such as plant-based inhibitors. Second, corrosion problems affect oil and gas, marine engineering, and infrastructure maintenance sectors. Thus, there is a growing interest in low-cost, biodegradable substitutes. Furthermore, increased research funding and national innovation policies in countries possessing strong materials research capacity have also driven the publication output in this field. However, the decline in 2025 should be interpreted cautiously, considering that the data are limited to partial records up to May 2025 and do not represent a complete annual dataset. In summary, the datasets indicate that there is currently a nascent and growing interest in plant-based corrosion inhibitors, indicating a shift towards sustainable and environmentally conscious corrosion control technologies.

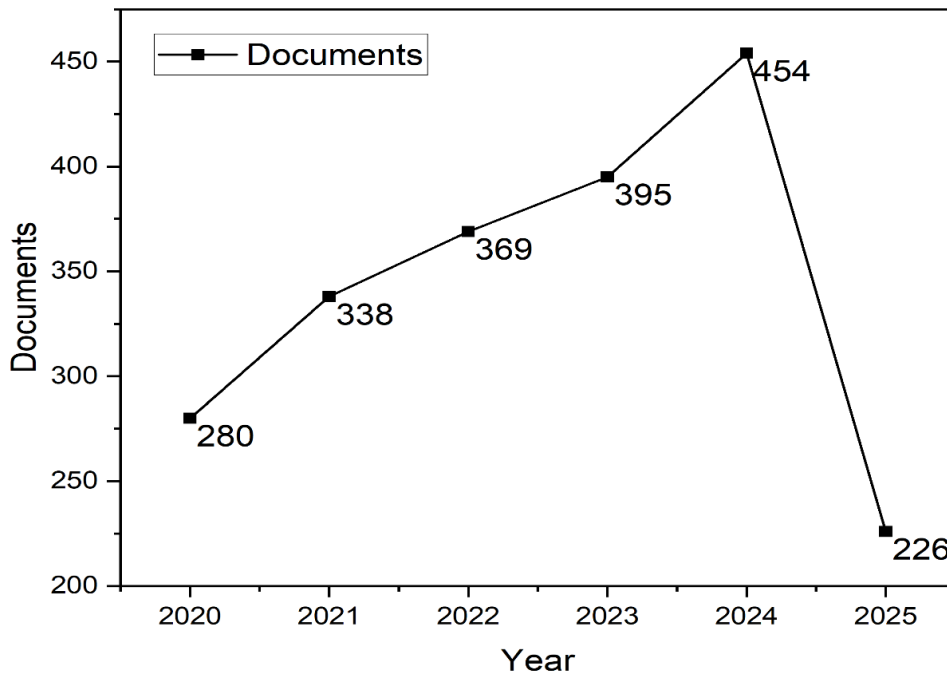


Fig. 2. Graph research trends in plants as corrosion inhibitors in mild steel according to the year 2020-2025

Table 3 shows that publications on plants as corrosion inhibitors increased in 2024, to 454, accounting for 22.02% of all publications and representing a 14.94% increase from the previous year. Thus, this upward trend suggests growing research into eco-friendly, sustainable corrosion-prevention methods. There were 280 publications (13.58%) in 2020, followed by 338 publications (16.39%) in 2021, representing a 20.71% increase, and 369 publications (17.89%) in 2022, reflecting a further 9.17% increase from the previous year. However, the number of publications in 2025 (226) appears significantly lower, though it may be an incomplete count given that the year is still ongoing. In general, the analysis indicates an increasing focus on plant-based corrosion inhibitor research from 2020 to 2025, as an alternative to conventional corrosion-control solutions.

Table 3. Number of documents and percentages of research trends in plants as corrosion inhibitors in mild steel according to the years 2020-2025

Year	Document	Percentages	Percentages of increments
2025	226	10.96	-
2024	454	22.02	14.94
2023	395	19.16	7.05
2022	369	17.89	9.17
2021	338	16.39	20.71
2020	280	13.58	-

5.2 What are the types of documents by subject of research?

Fig. 3 shows the distribution of publications by subject area, illuminating the interdisciplinary nature of the study of plant-based green corrosion inhibitors. There are sections of the chart corresponding to different subjects. The largest slice (24.7% of the pie) belongs to the Chemistry subject area, indicating that most of the database's documents are linked to chemistry. The second largest chunk (23.3% of the pie) is Materials Science. This highlights the key contributions of chemical interactions and material surface characteristics to corrosion inhibition mechanisms. In addition, studies in chemistry focus on adsorption behaviour, molecular structure, and reaction mechanisms of plant-derived compounds, while studies in materials science focus more on surface modification, protective film formation, and the durability of inhibitor coatings.

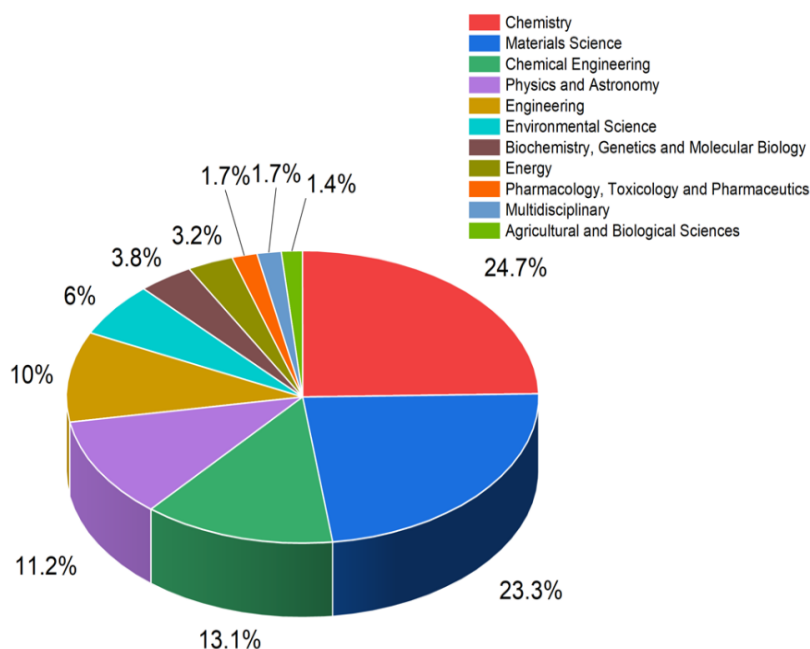


Fig. 3. Documents distribution by subject of research

Meanwhile, the Chemical Engineering (12.5%) and Physics and Astronomy (11.2%) also play major roles in process optimization, thermodynamics, and electrochemical modelling in corrosion investigations. Engineering research (10.0%) focuses on corrosion prevention in industrial systems in pipelines, marine systems, and mechanical components. Environmental Sciences (6.0%) plays an increasingly noticeable role, reflecting emerging interest in global environmental concerns and corrosion prevention. This trend highlights the gradual shift towards the introduction of green chemistry and eco-friendly, biodegradable components. Biochemistry, Genetics and Molecular Biology (up to 3.8%), and Energy (up to 3.2%) are the top areas in this database that demonstrate biological compounds and energy-based systems in corrosion research. There are some smaller contributions from Pharmacology, Toxicology, and Pharmaceutics

(1.7%), Multidisciplinary (1.7%), and Agricultural and Biological Sciences (1.4%), further highlighting an ongoing trend in research in this domain.

The distribution of subject areas confirms that research on plant-based corrosion inhibitors is inherently multidisciplinary, related to fundamental chemistry, materials science, and engineering applications. This interdisciplinary integration is essential to advancing sustainable and effective corrosion protection technologies.

Table 4 presents the number of publications and percentages across various subject areas. This analysis uses a prominent bibliographic database that comprises citations and abstracts from publications that have undergone peer review. Notably, Chemistry has the most publications, with 1040, or 24.7% of the total across all subject areas. Material Science is the second-largest subject area, with 983 publications (23.3%). These two subject areas comprise nearly half (48%) of the analyzed publications.

Chemical Engineering is the third most popular subject area, with 553 publications (13.1%), followed by Physics and Astronomy and Engineering, with 471 publications (11.2%) and 421 publications (10.0%), respectively. Environmental Science has 254 publications (6.0%), while the combined subject areas of Biochemistry, Genetics, and Molecular Biology have 159 publications (3.8%). Energy is also a popular field with 133 publications (3.2%). Pharmacology, Toxicology, and Pharmaceutics have 73 publications (1.7%), and the Multidisciplinary category has 70 publications (1.7%).

This analysis shows how research publications are distributed across different subject areas and highlights areas of interest and potential strengths or areas of focus in the analyzed dataset. In the same way, the subject areas are likely to overlap or be interdisciplinary, and the data should be interpreted within the specific time period and scope of the analysis.

Table 4. Summary of publications and percentages of the subject area

Subject Area	Number of Publication	Percentages %
Chemistry	1040	24.7
Materials Science	983	23.3
Chemical Engineering	553	13.1
Physics and Astronomy	471	11.2
Engineering	421	10.0
Environmental Science	254	6.0
Biochemistry, Genetics, and Molecular Biology	159	3.8
Energy	133	3.2
Pharmacology, Toxicology and Pharmaceutics	73	1.7
Multidisciplinary	70	1.7

5.3 Who writes the most significant number of articles?

5.3.1 Top 10 Scholars

Fig. 4 presents the distribution of publications among the top 10 most productive authors in the field of plant-based green corrosion inhibitors. Among these, Ramezanzadeh, B., emerges as the most prolific contributor with around 44 published documents, followed closely by Guo, L., and Berdimurodov, E., with approximately 42 and 32 publications, respectively. Other notable contributors include Lgaz, H., Dagdag, O., Li, X., Bahlakeh, G., Zarrouk, A., Berisha, A., and Deng, S., each contributing between 24 to 31 documents within the study period. The chart shows the relative publication output of these authors within the chosen research domain. As such, this visual representation enables comparison of their scholarly productivity and potential impact in their respective fields.

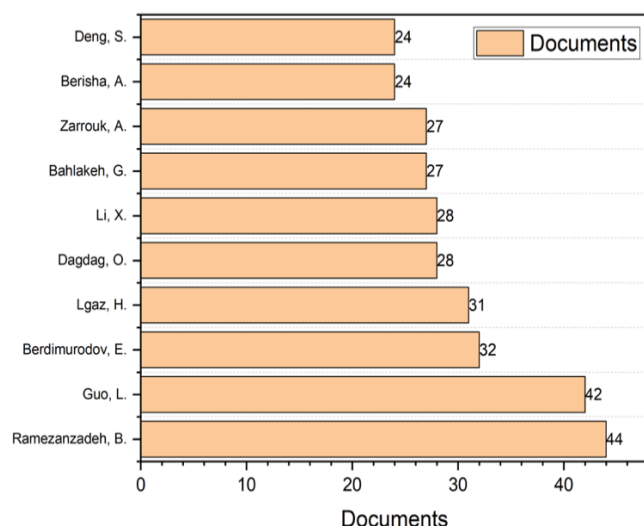


Fig. 4. List of authors concerning scholarly publications in Scopus

These researchers are dominant due to sustained research engagement and their specialization in corrosion science in the development and evaluation of eco-friendly inhibitors. Apart from their number of publications, citation metrics, and h-index values further indicate their significant academic influence in the field. For example, Ramezanzadeh, B., has a high h-index and citation count, indicating that his work is widely recognized and frequently referenced, especially in advanced materials and coating technologies.

Table 5 lists the 10 top author contributions based on the number of publications and their percentages in a specific research field or domain. Six countries are leading in this field, with China (3 authors), Iran (2 authors), South Korea (2 authors), Uzbekistan (1 author), Morocco (1 author), and Serbia (1 author). The top author ranked by the number of publications is Ramezanzadeh, B., from Iran, with 44 publications (2.13%), an h-index of 96, and 29,203 total citations. The second top author is Guo, L. from China, with 42 publications (2.04%), 65 h-index, and 13,776 total citations, followed by Berdimurodov, E. (30 h-index with 2,503 citations) and Lgaz, H. (61 h-index with 12,378 citations) from Uzbekistan and South Korea,

tied with 32 and 31 publications each (1.55% and 1.50%). Additionally, authors such as Dagdag, O. (South Korea), Li, X. (China), Bahlakeh, G. (Iran), Zarrouk, A. (Morocco), Berisha, A. (Serbia), and Deng, S. (China) also feature in the top 10 list, contributing between 1.16% to 1.36% of the total publications analyzed. In essence, this bibliometric analysis sheds light on the productivity and impact of individual authors, potential collaborations, and research trends within the specific field of study.

Table 5. Analysis of the author based on the number of publications and percentages

Author Name	Scopus Author Identifier	h-index	Total Citations	Total Documents	Total Publications 2020-2025	Percentages	Country
Ramezanzadeh, B.	26421358600	96	29203	511	44	2.13	Iran
Guo, L.	25934264300	65	13776	325	42	2.04	China
Berdimurodov, E.	57218857113	30	2503	237	32	1.55	Uzbekistan
Lgaz, H.	56707358100	61	12378	290	31	1.50	South Korea
Dagdag, O.	56538627800	44	5891	231	28	1.36	South Korea
Li, X.	55718152600	47	7524	191	28	1.36	China
Bahlakeh, G.	36801103000	64	11963	175	27	1.31	Iran
Zarrouk, A.	36125763200	87	20897	707	27	1.31	Morocco
Berisha, A.	6602750115	49	6877	236	24	1.16	Serbia
Deng, S.	8532179100	46	6866	201	24	1.16	China

A geographical pattern was observed among the top contributors, including China, Iran, and South Korea. This distribution is consistent with the publishing trends of countries exhibiting relatively high research productivity in corrosion studies. The high concentration of top authors in those areas could be attributed to research facilities, excellent collaboration between academic and industrial organizations, and investment in sustainable materials technologies.

The presence of multiple authors in the same regions suggests active research clusters and cooperative networks that support this research. These collaborations often integrate experimental, computational, and theoretical approaches, enhancing the depth and quality of research outputs. This highlights that the authorship analysis is focused on a combination of productive researchers and regionally concentrated research groups for the development of plant-based corrosion inhibitors. Besides, this concentration of expertise implies that future research on plant-based corrosion inhibitors may be influenced by only a small group of established researchers and collaborative networks.

5.4 What are co-authorship countries' collaboration?

This network visualization was constructed using VOSviewer software to depict co-authorship collaborations among countries in the context of bibliometric analyses of research publications, as shown in Fig. 5. The nodes represent individual countries, and the lines connecting indicate the collaborations. Meanwhile, the thicker lines and larger nodes suggest more frequent or larger collaborations. The countries are grouped by color to display regional or geographical cooperation. The green cluster shows the largest countries among major Asian countries, including China, India, and Saudi Arabia, pointing to strong intra-

regional cooperation, not only in addressing industrial challenges but also in common research priorities. These countries are also taking an active interest in corrosion research, particularly in the infrastructure and manufacturing sectors, which are characterized by significant activity in sustainable materials. Interesting clusters include those of the Middle East, North Africa, Europe, and Southeast Asia.

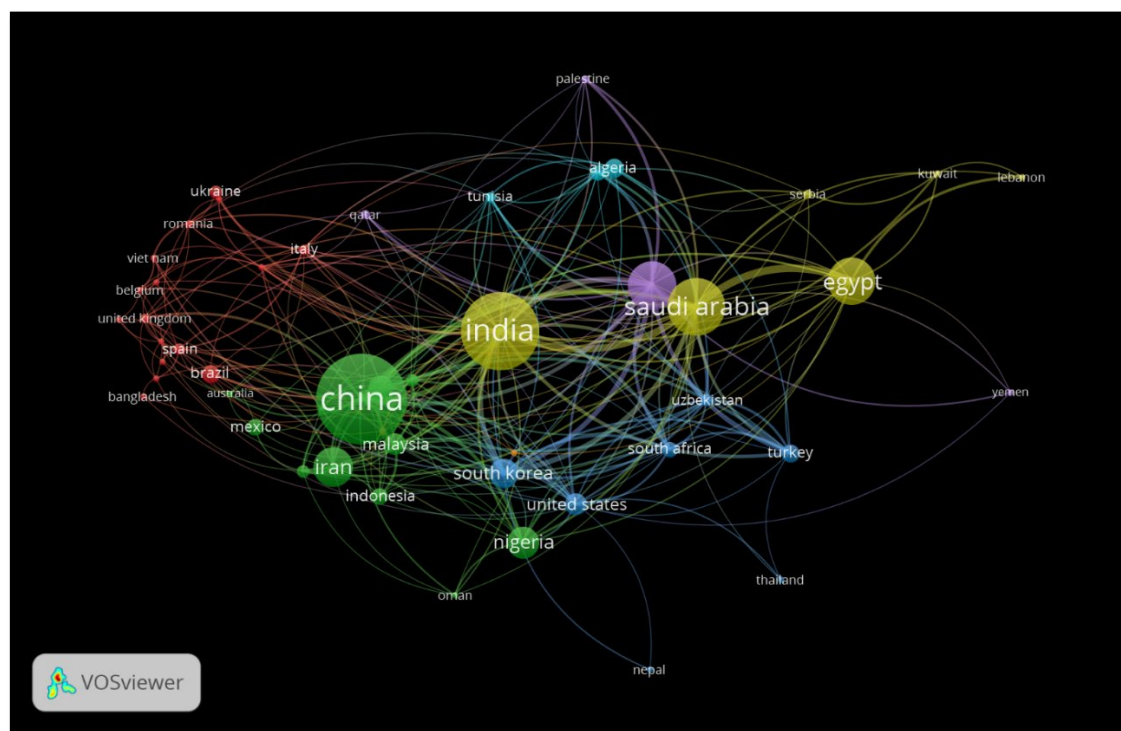


Fig. 5. Co-author's collaboration among countries

Meanwhile, the United States is at the network's hub, serving as a key collaborator across multiple regions. This central positioning indicates that the United States contributes significantly to international research partnerships, knowledge exchange, and interdisciplinary collaboration. Its involvement across different clusters reflects strong global connectivity and research influence. The largest node in Southeast Asia is Malaysia, where publications and collaboration links are much stronger than in Indonesia, Thailand, and Vietnam. This highlights that Malaysia is actively participating in regional and international research networks and has potentially benefited from institutional collaborations in corrosion science and materials engineering.

The co-authorship network highlights a globally interconnected research landscape through both regional collaboration clusters and international partnerships. These patterns indicate that knowledge exchange and collaborative research play a crucial role in advancing the development of plant-based corrosion inhibitors in industrial and environmental challenges. This collaborative structure suggests that future advancements in plant-based corrosion inhibition research will increasingly rely on international partnerships that integrate diverse expertise and technological capabilities.

5.5 Network mapping based on co-citation by authorship?

Fig. 6. displays the analysis of co-occurrences among cited authors in scholarly publications. The visualisation is a network graph in which each node represents an author, and the node size corresponds to the author's citation frequency or impact. The colors indicate different clusters or groups of closely related authors. The analysis shows multiple clusters that reflect different research specializations within the field.

The most prominent figure is Guo, L., who occupies a central position, and a large node size indicates a high volume of publications and a pivotal role within a tightly interconnected research cluster. Moreover, his connections with researchers such as Tan, Bochuan, Qiang, Yujie, and Marzouki, Riadh reflect his leadership in collaborative projects, integrating theoretical and experimental methodologies. Additionally, Guo's position at the central suggests his significant contribution to collaborative and widely cited research that plays a significant role in shaping the field's direction, particularly in studies involving adsorption behavior, electrochemical testing, and inhibitor formulation.

In contrast, Ramezanzadeh, B. had appeared as a dominant figure within a separate purple cluster, characterized by fewer but well-defined co-authorships. However, despite his spatial separation from the central core, his large node size indicates he is a prolific author. This leads to a distinct research direction focused on advanced materials, such as nanocomposite coatings, hybrid polymers, or surface modification techniques for corrosion protection. At the same time, his relative isolation suggests a specialised niche or regional network, but the impact remains considerable, likely due to his contributions to the development of durable, multifunctional, corrosion-resistant materials

Another significant cluster is centred on Lgaz Hassane and Berdimuradov, Elyor, whose close collaboration points to a strong, cohesive research team. This group frequently studies plant-derived inhibitors, adsorption isotherms, thermodynamic modelling, and electrochemical evaluation, as evidenced by their frequent co-publications. Their contributions have advanced mechanistic understanding of corrosion inhibition, especially in acidic media such as hydrochloric acid (HCl) and sodium chloride (NaCl), often using weight-loss and electrochemical methods. This group strongly emphasises sustainable chemistry and low-toxicity materials, aligning with global environmental and regulatory concerns.

Furthermore, Li, Xianghong situated in more distant but well-defined clusters, appears to contribute through advanced theoretical investigations, including DFT, molecular dynamics, and quantum chemical descriptors. Their work supports the predictive modelling of inhibitor behaviour and enhances the mechanistic comprehension of inhibitor-metal interactions at the molecular level. At the same time, these authors are connecting the basics of computational chemistry with corrosion applications and thus give an even deeper theoretical basis for corrosion studies.

In general, the co-citation network reflects a coherent and advancing field of research with relatively more interlinked collaborative groups and specialized research clusters. This balance of collaborative and specialized research reflects the development of plant-based corrosion inhibitors as the discipline evolves from experimental and theoretical research to applied studies, where the field advances holistically and in an interdependent manner.

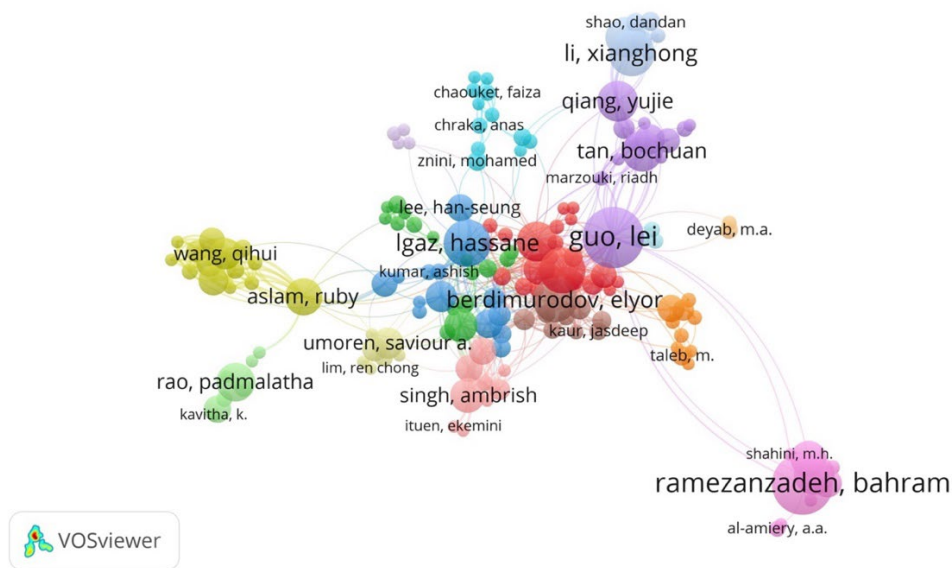


Fig. 6. Network mapping based on co-citation by authorship

5.6 Which country published this research the most?

Fig. 7. shows the distribution of publications by country, providing insight into the global research landscape of plant-based green corrosion inhibitors. China leads the field with approximately 507 publications, followed by India with around 391 publications, indicating that both countries are the primary contributors to this research domain.

The dominance of China can be attributed to several interrelated factors. Rapid industrialization and the widespread application of metal in transportation, energy, manufacturing, and product industries have increased the corrosion-related challenge and increased the enthusiasm for research in corrosion prevention and treatment. The estimated cost of corrosion in China is around 2127.8 billion RMB (~310 billion USD), which can be considered as approximately 3.34% of GDP and reinforces the urgency of establishing the solution to corrosion [30]. Government support such as research funding, tax incentives, and the development of innovation centres has also been key to boosting research productivity. China has a very strong position in the research and development of plant-based inhibitors, rooted in urgent industrial demand, strong government policy, and a huge scientific base. China's so-called "Made in China 2025" strategy is a green manufacturing initiative that encourages industries to switch from conventional inhibitors to sustainable alternatives, such as plant-based corrosion inhibitors [31]. Moreover, the Chinese government offers substantial support for research, tax incentives, green finance projects, reducing barriers to research and investment in sustainable materials. At the same time, China has an innovation ecosystem that is well-coordinated, including manufacturing innovation centres and state-level laboratories that bring universities, industry, and government agencies together. Together, these initiatives accelerate research, development, and widespread application of advanced corrosion protection technologies [32], [33].

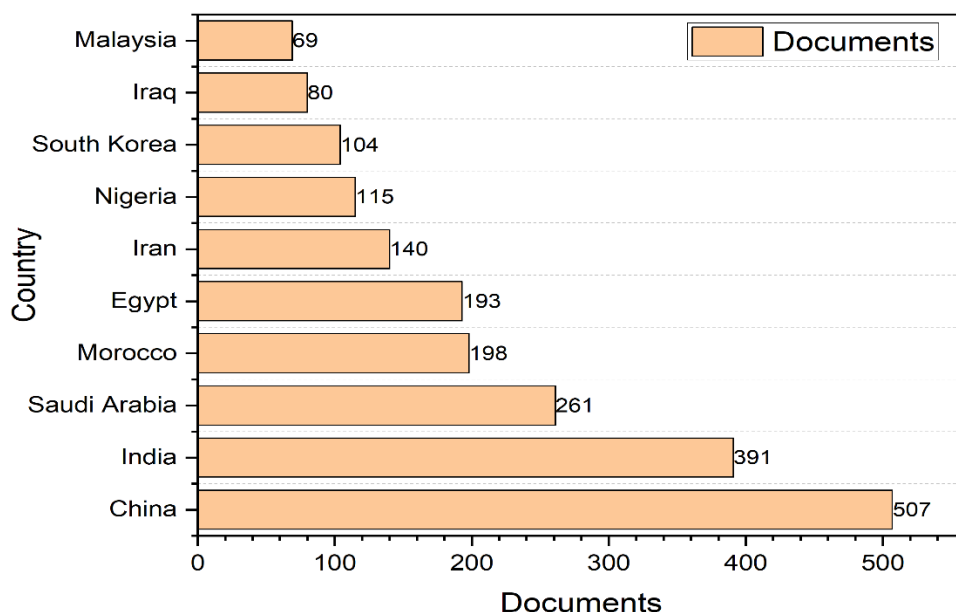


Fig. 7. List of countries of publications related to Plant as Corrosion Inhibitors

Similarly, India demonstrates substantial research output, which can be attributed to its expanding industrial sectors and increasing emphasis on sustainable technologies. Corrosion in key industries, especially the petrochemical sector has a major effect, and therefore, the increased research has focused on corrosion prevention strategies, including plant-based inhibitors. Earlier literature mentions the high economic losses contributed by corrosion in India [34], stressing the importance of developing effective and sustainable approaches in addressing corrosion in India.

On the other hand, several Middle Eastern and North African (MENA) countries also demonstrate notable contributions to this field of study. Among them are Saudi Arabia (~ 261 publications), Morocco (~198 publications), Egypt (~193 publications) followed by Iran (~ 140). These regions are characterized by harsh environmental conditions and strong dependence on oil and gas industries, where corrosion poses significant operational challenges. Consequently, research in these countries is often driven by the need for cost-effective and locally available corrosion mitigation solutions. Other countries also contribute to the research landscape, albeit at a more moderate level. With modest but relevant numbers of publications include Nigeria (around 115), South Korea (around 104), Iraq (around 80), and Malaysia (around 69) from Southeast Asia. In Southeast Asia, Malaysia stands out as an emerging contributor, reflecting growing research capacity and increasing involvement in sustainable materials research.

Table 6 shows the top 10 countries or territories with the most publications in research areas or fields. The publications and percentage of publications by each country/territory are shown in the table. China has the most publications, with 507, accounting for 16.41% of the total results. India comes second with 391

publications, accounting for 12.65% of the total results, while Saudi Arabia comes third with 261 publications, accounting for 8.47%.

Additionally, Morocco has 198 publications, which comprise 6.41% of the total publications. Egypt has 193 publications, representing 6.25% of the total results. Iran has 140 publications, representing 4.53% of the total results. Nigeria has 115 publications, which represent 3.72% of the total results. South Korea has 104 publications, representing 3.37% of the total. Iraq has 80 publications, 2.59% of the overall results, and Malaysia follows with 69 publications (2.23%).

According to the data, China and India are the most widely covered by research in this domain, accounting for nearly 29.06% of the total publications published. A number of other Middle Eastern countries such as Saudi Arabia, Morocco, Egypt, and Iran also come in the top ten, all indicating that there is strong research activity in those areas. In keeping with this, the comprehension of these results should consider factors such as population size, research funding, and areas of specialization within each country.

The geographical distribution of publications indicates that research activity is strongly influenced by industrial demand, economic impact of corrosion, and national research policies. The concentration of publications in specific regions indicates that a consensus exists between research priorities and practical corrosion challenges, and in this way, plant-based corrosion inhibitors demonstrate their sustainable relevance in the application of various industrial applications.

Table 6. Summary of the number of publications and the percentages of the countries that published the research

Country	Number of Publication	Percentages %
China	507	16.41
India	391	12.65
Saudi Arabia	261	8.47
Morocco	198	6.41
Egypt	193	6.25
Iran	140	4.53
Nigeria	115	3.72
South Korea	104	3.37
Iraq	80	2.59
Malaysia	69	2.23

5.7 What are the popular keywords related to the study?

Fig. 8. presents the keyword co-occurrence network generated using VOSviewer, illustrating the primary research themes in plant-based green corrosion inhibitors. In this network, each node represents a keyword, with the size of the node indicating its frequency of occurrence. The connections between nodes represent co-occurrence relationships, while different colours denote clusters of closely related research topics.

At the network's core lies the keyword "inhibition," representing the central research theme around which various subtopics revolve. As such, closely associated terms such as "eco-friendly corrosion inhibit," "m hcl," "plant extract," and "electrochemical investigation" suggest a dominant emphasis on natural or plant-based corrosion inhibitors tested predominantly in acidic environments, especially HCl.

environmental conditions. In particular, the intricate web of interlinking keywords signifies a highly interdisciplinary approach, combining green chemistry, materials science, theoretical computation, and electrochemical validation.

The resulting keyword co-occurrence network provides evidence that studies of plant-based corrosion inhibitors are focused on inhibition performance and are expanding to diverse materials, environments, and methodologies. Thus, this demonstrates a maturing research field for both sustainability considerations and practical industrial applications.

6. CONCLUSION

This study presents a comprehensive bibliometric overview of research on plant-based green corrosion inhibitors from 2020 to 2025 and indicates increasing global interest in sustainable corrosion mitigation strategies. The findings validate that the field is highly interdisciplinary, especially in Chemistry and Materials Science, which have contributed to advances in electrochemical evaluation and computational modelling.

The analysis reveals that current research is primarily focused on inhibitor performance, with increasing emphasis on eco-friendly plant extracts in corrosive environments and on integrated experimental–theoretical approaches. Geographical and collaboration patterns also show that research development is highly influenced by industrial demand, the economic impact of corrosion, and national sustainability initiatives.

In addition to these research findings, several important future research directions can be identified. Further work on the industrial application of plant-based inhibitors should also be conducted to bridge the gap between laboratory research and real-world implementation. Moreover, comparative studies evaluating the efficiency and stability of different plant extracts under various environmental conditions to find the most effective candidates are warranted. The scalability and long-term performance of these green inhibitors are also critical challenges that must be addressed to ensure practical adoption.

This study is limited by its reliance on a single database (Scopus) and a defined time frame, which may not capture all relevant publications or earlier foundational work. Nevertheless, the findings provide valuable insights into the field's evolution and current direction.

Importantly, plant-based corrosion inhibitors are aligned with green chemistry and sustainable engineering and may contribute contributing to global sustainability goals (SDGs) by the United Nations Sustainable Development Goals (SDGs). These materials align with SDG 9 (Industry, Innovation and Infrastructure) by facilitating durable industrial systems, SDG 12 (Responsible Consumption and Production) by expanding the use of renewable natural resources, and SDG 13 (Climate Action) by reducing reliance on toxic chemical inhibitors. Therefore, by mapping the evolution of research trends and identifying key contributors and themes, this work provides a foundation for future studies aimed at developing cost-effective, environmentally friendly, and industrially viable corrosion inhibitors derived from natural resources.

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8. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, financial conflict of interest and commercial and declare the absence of any conflicts of interest with the funders.

9. AUTHORS' CONTRIBUTIONS

Hazriel Faizal Pahroraji: Conceptualization, supervision, writing-review, and editing; **Siti Khadijah Alias:** Conceptualization, methodology, formal analysis; **Haryana Mohd Hairi:** Writing-review and editing; **Bulan Abdullah:** Review and validation; **Mohd Al-Fatihhi Mohd Szali Januddi:** Review and validation. **Masalina Md Ali:** Review and editing.

10. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the authors used AI-assisted technologies solely to enhance readability and refine language, not to generate content or theories. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication

11. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

12. ETHICS STATEMENT

This study did not involve human participants or animal subjects. Ethical approval was therefore not required for this research.

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