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Review Article

A Review of CiteSpace Visualisation and Analysis of High-Temperature Corrosion Inhibitors for Oil and Gas Fields

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Abstract

With the increasing global energy demand, the exploitation depth of oil and gas fields is gradually increasing. At the same time, importing many high-acid crude oil makes it increasingly heavy and inferior, and its acid value is constantly improving. This change has led to the increasingly severe corrosion problem of oil and gas field equipment, which has become an essential factor affecting the national economy and society's sustainable development. As an economical and practical anticorrosion measure, corrosion inhibitors play a crucial role in the anticorrosion of oil and gas field equipment. Through the research method of biorientation, retrieve the Web of Science database in 2008-2024 about oil and gas field high-temperature corrosion inhibitor research literature information, using CiteSpace measurement analysis software visual analysis in the literature keywords, publications, high citation frequency, cooperation and word clustering information change trend, analyze the research situation of oil and gas field in recent years, summarizes the research hotspot of oil field high-temperature corrosion inhibitor, prominent authors and institutions, reference relationship and development trend. The number of documents on high-temperature corrosion inhibitors in oil and gas fields is smaller, and the authors, institutions, and countries are not closely related. There is less research cooperation on high-temperature corrosion inhibitors in oil and gas fields, and more independent studies exist. China University of Petroleum has the first number of publications, and China is the country with the first number of publications. The study of mass spectrometry for corrosion inhibitors in oil and gas fields is prominent, while the literature on high-temperature corrosion inhibitors is rare.

Keywords

Oil and Gas Field, Corrosion Inhibitor, CiteSpace, Visual Analysis

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1. Introduction

As a powerful scientific literature analysis and visualization tool, CiteSpace plays an important role in academic research and bibliometric analysis. Its application not only helps researchers grasp the development trend and hot spots in the research field, but also improves the efficiency and quality of research, and contributes to the in-depth development of scientific research.

In this paper, I used CiteSpace software to search the literature on high-temperature corrosion inhibitors in oil and gas fields, and performed data cluster analysis. The use of corrosion inhibitors can form a protective film on the metal surface, effectively isolating the direct contact between the corrosive medium and the metal, thereby slowing down or stopping the corrosion process, ensuring the safe operation of the equipment, and significantly extending the service life of the equipment. The cost of corrosion inhibitors is relatively low, but the anti-corrosion effect is very significant. By slowing down the rate of equipment corrosion and reducing the cost of equipment replacement and maintenance caused by corrosion, oil and gas field enterprises can save a lot of money and improve economic efficiency.

With the continuous growth of global energy demand, the development and utilization of oil and gas fields has become an important cornerstone to ensure national energy security and sustainable economic development. However, in the exploitation and processing of oil and gas fields, high temperature, high pressure, and complex medium environments cause severe corrosion problems in the equipment, affecting the operation efficiency and life and dramatically increasing production costs and safety risks. Especially in recent years, with the continuous increase of oilfield exploitation depth and the import of many high-acid crude oil, China's crude oil has become increasingly heavy and inferior. Its acid value has been continuously improved, further aggravating the corrosion problem of crude oil processing equipment and becoming an essential factor affecting the sustainable development of the national economy and society.

Pipeline corrosion during oil and gas exploitation is an inevitable problem, but the corrosion rate can be slowed, and the service life of the pipeline can be reduced. The morphology of corrosion products in the corrosion process is an essential factor affecting the corrosion resistance of pipelines. The doping of alloy elements can alloy the pipeline to change the corrosion morphology, improve the density of the corrosion product layer, and improve the corrosion resistance of pipelines. In addition, similar to the corrosion product layer of coating material, it is also an effective method to improve pipeline corrosion resistance; plasma coating technology of dense coating can block direct contact with the pipe wall and, at the same time imp, the movement of the coating thickness can extend the penetration path of corrosion medium, slow the effect of corrosion rate, two aspects jointly improve pipeline corrosion resistance [1].

There are different types of corrosion in oil and gas fields, such as CO_2, H_2S corrosion, and bacterial corrosion; with the development of most oil fields in China into high-water cut periods, corrosion is increasing. Corrosion inhibitors are an effective means of corrosion control in oil and gas fields. However, the effect of corrosion inhibitor use in different fields varies [2]. Recently, acidification fracturing technology, as an essential measure to increase oil and gas production, has been widely used in the oil and gas field industry. However, acid also causes serious corrosion problems in piping and metal equipment. Adding a corrosion inhibitor is an efficient metal corrosion measure in the medium to low temperature (T=120 ℃) acid environment. With the continuous progress of oil and gas field exploration technology, the depth of oil and gas Wells continues to increase, and the downhole temperature not only reaches or even exceeds 180 ℃. Conventional acidification corrosion inhibitors have low corrosion suppression efficiency and poor dissolution compatibility at high temperatures, which cannot meet the requirements of high-temperature acid corrosion prevention. The acidification corrosion of high-temperature deep wells has not been solved well. Therefore, it is urgent to study the high-temperature and ultra-high-temperature acid corrosion inhibitors, which are of great significance for the safe development of high-temperature oil and gas fields [3].

2. Data Sources and Methods of Research and Analysis

2.1. Data Sources

The data of this article were based on the Web of Science core collection database. The search time was set for the publication date of January 1, 2008, to July 31, 2024: "Oil and gas fields" (Topic) or "High temperature corrosion inhibitors" (Topic), and a total of 886 related documents were retrieved. Export the record content in the plain text file format of "full records and referenced references".

2.2. Methods of Research and Analysis

After importing the dataset into CiteSpace software, we used its built-in "Remove Duplicates" function to accurately deduplicate and select 880 independent records from the Web of Science (WOS) database. The number of Unique Entities included in these documents is detailed in Table 1, and the statistics are done through CiteSpace's entity recognition and counting function. In order to visually show the trend of these independent entities over time, we used Excel software to calculate the number of published papers according to the year and draw the corresponding line chart. In doing so, we have ensured that each of the individual entities counted in

Table 1 and their numbers are accurately included in the analysis. During the in-depth analysis phase, we considered all the authors listed in the paper, whether as the first author or other contributors, to be included in the analysis of author publications and author partnerships. For the attribution of countries, regions and institutions, we strictly follow all relevant information marked in the paper for statistics to ensure the completeness and accuracy of the data. For the visual analysis session, we used CiteSpace 6.1. The R6 (64-bit) Basic version provides in-depth visual exploration of key nodes such as "Author", "Institution", "Country", "Keyword", "Cited Author", and "Cited Journal" through carefully set filters and keywords. Specifically, we may set filter parameters such as "Minimum Frequency" or "Time Span" to focus on the most representative and influential entities. At the same time, through the careful selection of keywords, we ensure that the analysis accurately captures and reflects the core issues and dynamics of the research field. The above process not only realizes the deduplication of literature and independent entity statistics, but also deeply reveals the research pattern and dynamics of multiple dimensions such as authors, institutions, countries, and keywords through visual analysis, which provides solid data support and visual insights for subsequent in-depth research.

Table 1. *Counts and number of independent entities.*

Category	Quantities
Articles	880
Journals	331
Authors	3708
Institutions	2002
Countries/Regions	221

3. Results and Discussion

3.1. Number of Posts

Considering the annual number of high-temperature corrosion inhibitors in oil and gas fields in the Web of Science core collection database from 2008 to 2024 (Figure 1), the results show that the overall number of annual papers increased first and then decreased. From 2018 to 2021, the number of articles on high-temperature corrosion inhibitors in oil and gas fields increased significantly, with the most significant number of articles published in 2021, from 19 in 2008 to 107 / year in 2021. However, the overall number of relevant publications is relatively tiny.

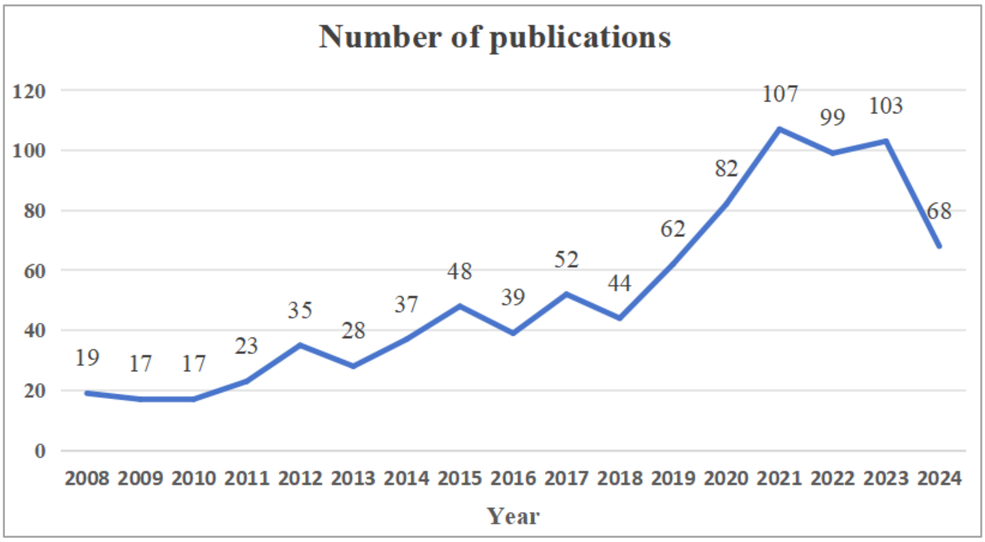

Figure 1. *Annual publication volume of research on high temperature corrosion inhibitor in oil and gas fields in 2008-2024.*

3.2. Institutional and National Communications

Through the analysis of authors by CiteSpace software, authors were distributed in 437 institutions between 2008 and 2024. The top 10 institutions are shown in Table 2, among which the China University of Petroleum has the most significant number of articles, and 9 of the top 10 institutions are from China. The institutional cooperative relationship chart (Figure 2) provides 437 nodes and 453 connections, and the centrality is small, indicating less research cooperation among the institutions on high-temperature corrosion inhibitors in oil and gas fields.

Table 2. *Top 10 institutions by publication volume.*

Rankings	Mechanism	Quantities	Percentage/(%)
1	China Univ Petr (China University of Petroleum)	69	7.84
2	Russian Acad Sci (Russian Academy of Sciences)	59	6.70
3	PetroChina (CNPC Corporation Limited)	35	3.98
4	Southwest Petr Univ (Southwest Petroleum University)	35	3.98
5	China Univ Petr East China (China University of Petroleum (East China))	27	3.07
6	Chinese Acad Sci (Chinese Academy of Sciences)	22	2.50
7	China Univ Geosci (China University of Geosciences (Wuhan))	21	2.39
8	Yangtze Univ (Yangtze River University)	20	2.27
9	Xian Shiyou Univ (Xi'an Petroleum University)	17	1.93
10	PetroChina Res Inst Petr Explorat & Dev (China Petroleum Exploration and Development Research Institute)	11	1.25

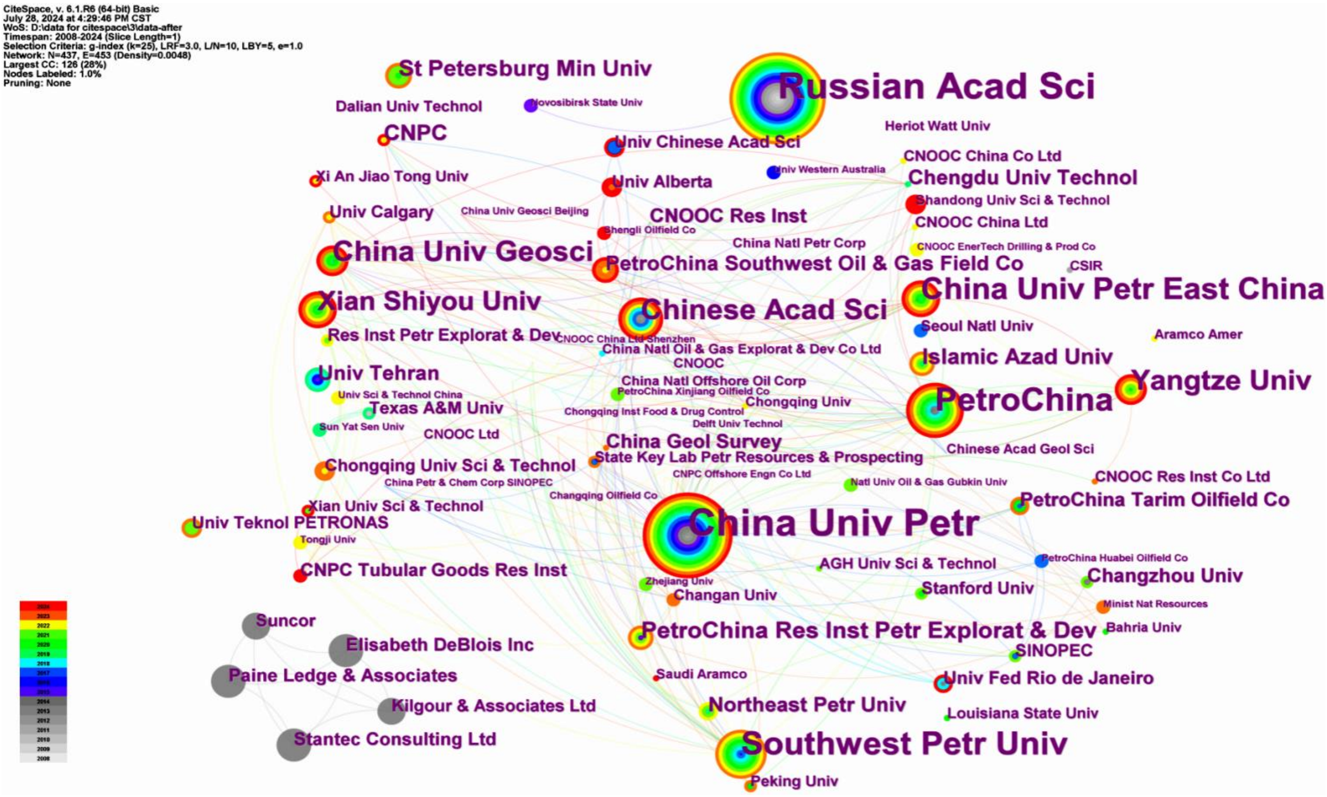

Figure 2. *Partnership diagram of the research institutions.*

According to CiteSpace statistics, there are 80 relevant countries/regions, and the top 10 countries/regions in the number of publications are shown in Table 3. China has the most significant number of research papers on high-temperature corrosion inhibitors in oil and gas fields, accounting for 40%, primarily related to the large number of Chinese universities, research institutions, and researchers engaged in related fields. N=80 and E=101 are available in the national partnership chart (Figure 3), and the centre degree is much larger than that of the research institution, indicating that the study of high-temperature corrosion inhibitors in oil and gas fields is closer than that between institutions.

Table 3. *Top 10 countries / regions by publication volume.*

Rankings	Countries	Quantities	Percentage/ (%)
1	PEOPLES R CHINA	357	40.57
2	USA	131	14.89
3	RUSSIA	108	12.27
4	IRAN	50	5.68
5	CANADA	43	4.89
6	NORWAY	38	4.32
7	ENGLAND	35	3.98
8	BRAZIL	28	3.18
9	SAUDI ARABIA	24	2.73
10	AUSTRALIA	21	2.39

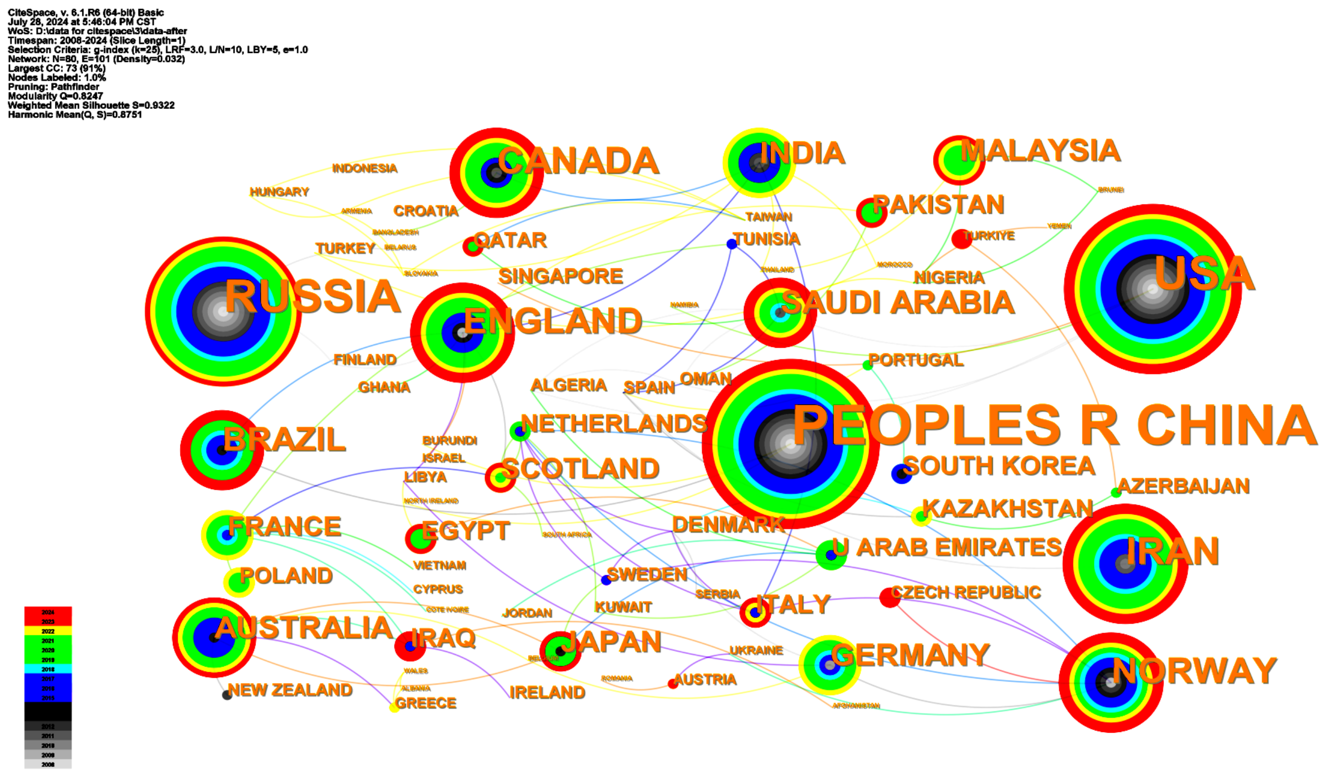

Figure 3. *National / regional cooperation diagram.*

3.3. Analysis of the Authors in the Research Field

Through a detailed statistical analysis of authors who have published in the field of corrosion inhibitors in oil and gas fields, we are able to identify a core group of authors who have made significant contributions to the field and reveal the collaborative links between them. According to statistics, between 2008 and 2024, the authors of published articles in this field formed a cooperative network of 497 nodes and 349 connections, and its network density (Density) was 0.0028. In the visualization in Figure 4, the size of the nodes intuitively reflects the number of authors' publications, while the connections between nodes represent the cooperative relationship between the authors, and the thickness of the connections further reflects the closeness of the cooperation [3]. These data suggest that a total of 497 authors have published in this research area over the past 16 years, but it is worth noting that the authors' collaborations are relatively fragmented, with the majority of authors tending to work independently.

According to the analysis of several authors with a large number of publications, in 2022, Farhadian, Abdolreza et al. [4] study overcame the compatibility problem between inhibitors by effectively mixing the inhibition of natural gas hydrate and corrosion and reducing the production and transportation costs of the oil and gas industry. The newly synthesized waterborne polyurethane (WPUs) are evaluated through experimental and calculation methods as highly efficient dual-use gas, hydrate and corrosion inhibitor. Experimental and computational results show that WPUs can serve as potent bifunctional inhibitors to prevent gas hydrate formation and CO within oil and gas pipelines2/H2Corrosion of S while also having the potential as an antiaggregate hydrate inhibitor. Tang, Cuiping, Farhadian, Abdolreza et al. [5] developed a new biosurfactant to effectively inhibit gas hydrate agglomeration and corrosion of offshore oil and gas pipelines, where oleic acid was used for the development of the class I biosurfactant as an anticonvulsant and corrosion inhibitor, using click chemistry technology for flow assurance applications. The autoclave results show that the bio-based anti-agglomeration agents (BAAs) can significantly inhibit the gas hydrate agglomeration, and the torque value remains unchanged during the hydrate formation process. The hydrate particles were effectively dispersed in liquid paraffin wax in the presence of 1 wt% of either BAA 1 or BAA 2.

Furthermore, molecular dynamics simulations show that the head group of BAA 1 is adsorbed on the hydrate surface, and its alkyl chains disperse the hydrate formed in the hydrocarbon phase into a slurry. The electrochemical tests showed that both BAAs prevent saturating H_2S and CO_2, are highly efficient, and are inhibitors of carbon steel corrosion in oilfield water. BAA 1 and BAA 2 fully protected 99% and 98.8% of the steel at 0.1 wt%, respectively.

Moreover, the adsorption of BAA 1 molecules on the steel surface is almost parallel to the surface in the physical and chemical directions. This adsorption provides the maximum surface coverage and prevents corrosion. These findings suggest that oleic acid can be used as a potential starting feedstock to develop environmentally friendly inhibitors for flow assurance in oil and gas pipelines. Gao Jiancun, Feng Li et al. [6] study showed that adding an acidified corrosion inhibitor can significantly reduce the corrosion rate of oil tubing. Under different media conditions, a series of new acid corrosion inhibitors in oil and gas fields are synthesized to meet the requirements of N80 steel pipe under high temperatures and concentrated acid conditions. The hanging sheet weight loss and electrochemical kinetic potential scanning methods evaluate the corrosion suppression effect, and the corrosion suppression mechanism is preliminarily discussed. The corrosion inhibitors synthesized in aqueous systems also have good corrosion suppression properties, which opens up a new way to synthesize corrosion inhibitors.

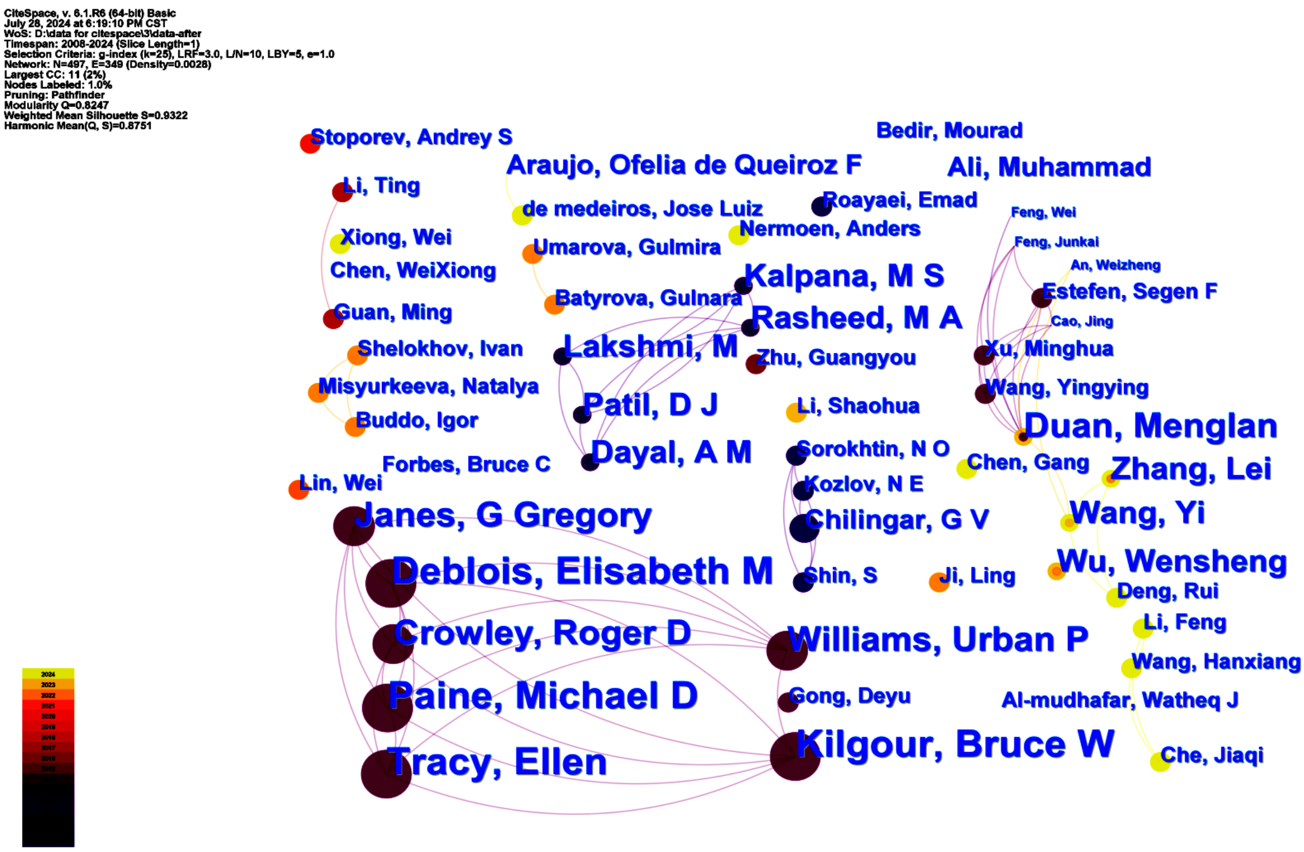

Figure 4. *Author partnership diagram.*

3.4. Keyword Cluster Analysis

Keywords are the concise embodiment of the content of the article, which can deeply reflect the core theme of the article, and the high frequency of keywords indicates that they are of significant importance in the field of research. By using Citespace software to visually analyze the keywords in the research on "High temperature corrosion inhibitors", we counted a total of 487 keywords, of which 41 keywords reached a frequency of 10 times or more. These high-frequency keywords are clearly divided into 16 clusters in Figure 5, and the keywords within the same cluster show strong correlation with each other.

Initially, L. Egghe introduced the g index [7] as an enhancement to the H index, aiming to better elucidate the impact of an author's most widely read articles. The g-index is highly responsive to the frequency of citations. In our cluster and timeline map analyses, we adjust the g-index within the Selection Criteria from the default value of 25 to 15. This adjustment helps to account for articles with fewer citations while still managing the influence of those with higher citation counts.

By examining keywords, we can grasp the central ideas of an article. CiteSpace employs an algorithm to group tightly related keywords, assigns a score to each, and identifies the median value with the highest significance within a cluster as its representative category. The keyword clustering depicted in Figure 5 is achieved using CiteSpace, which streamlines the keyword network through the pathfinder shear algorithm and emphasizes its crucial structural characteristics. As indicated by the graph, the cluster structure with Q=0.8247 > 0.3 is notable, and the cluster with S=0.9322 > 0.7 is highly reliable [8] and efficient. The analysis can be categorized into 16 areas: oil and natural gas storage with CO_2 sealing, the Tarim Basin, associated petroleum gas, machine learning, flow, condensed matter, adsorbed soil gas, carbonate reservoirs, carbon steel, oil and gas fields, corrosion resistance, mass spectrometry, water cut, produced water, and hydrocarbon accumulation.

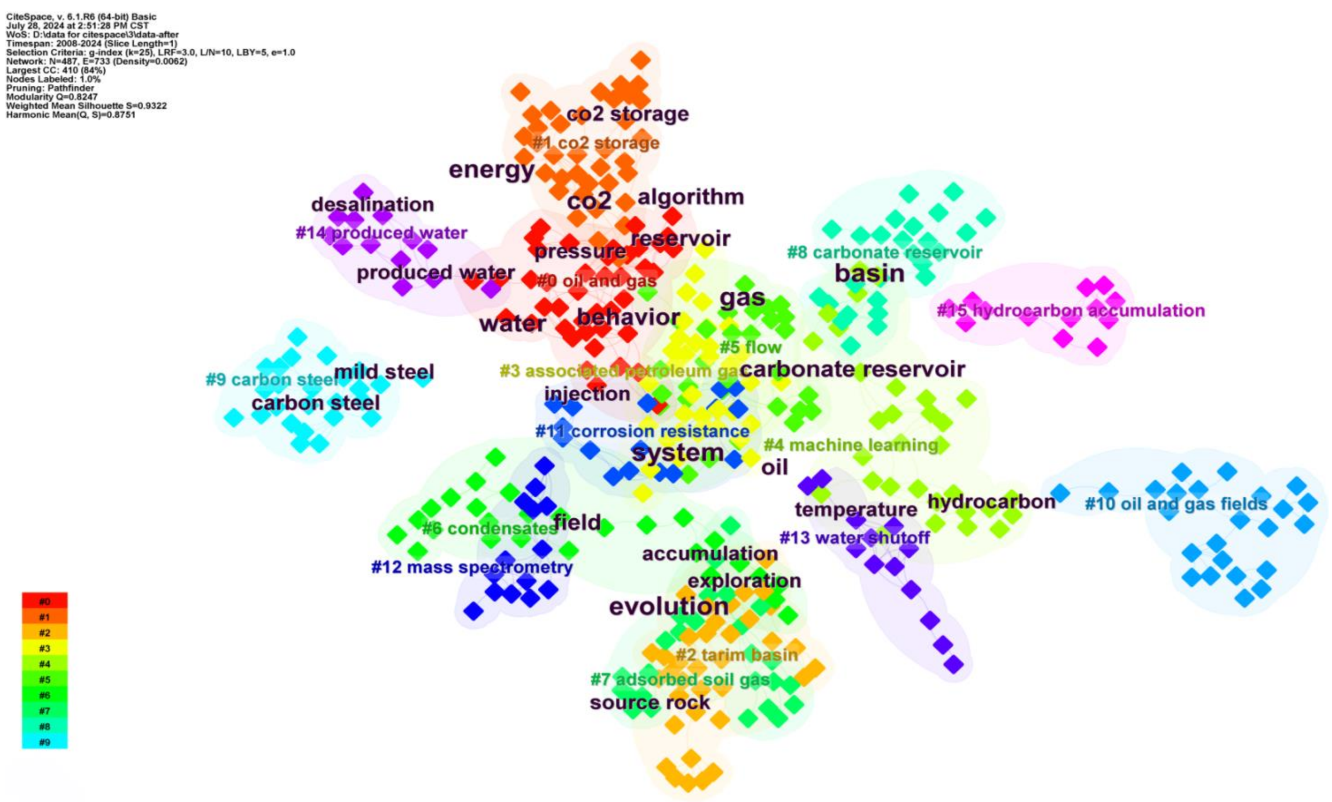

Figure 5. *Keyword cluster analysis plot.*

For high-temperature and high-pressure CO_2 Oil and gas field underground environment, foreign corrosion inhibitor research and development technology are relatively mature; research direction mainly focuses on phosphates, alkyl pyridine, imidazoline and ethoxysulfonates organic corrosion inhibitor, domestic high-temperature corrosion inhibitor, its main components, aldehyde, ketone, amine condensate, imidazoline derivatives, pyridine, quinoline quaternary ammonium salt, heteropolyamines and compound added synergists such as formaldehyde, alkyne alcohol and polymer, etc. As far as the current situation is concerned, the high-temperature corrosion inhibitors (mainly acid corrosion inhibitors) developed at home and abroad generally have the problems of large dosage (the addition of acid corrosion inhibitors is generally 1% -2%) and high cost, and the research work in the application of corrosion inhibitors is relatively scarce. The corrosion inhibitors for high temperature and high-pressure conditions in oil and gas fields are rare [9].

In the next few years, in high-temperature and high-pressure environments, inhibitor research mainly focuses on attaching great importance to the inhibitor compound technology, exploring more suitable for gas, liquid, and solid corrosion environments, developing low toxicity, high efficiency, sound biological degradation of environmental protection corrosion inhibitor, constantly explore new types of corrosion inhibitor, enrich the existing inhibitor product system, field experiments, test the field feasibility of laboratory products [9], etc.

3.5. Keywords Timeline Mapping

The study of the timing atlas can deduce the evolution of oil field inhibitor research and predict the future development trend, and through multidimensional clustering and keyword information, with the year of hot spots in chronological order and set in the specified area, help researchers understand the time path of the evolution of essential keywords, [10]. In the graph, the square represents the keyword node, and the larger the square, the higher the frequency of the corresponding theme. The colour node ring's colour and thickness indicate the ring's occurrence time; that is, the thicker the inner colour ring of the square and the higher the frequency of the colour appearing in the corresponding year [11]. As shown in Figure 6, # 1 CO_2 Storage has been studied for nearly two decades, and the number of # 3 associated LPG studies has gradually decreased in recent years.

In recent years, future research may focus on molecular dynamics simulation, reservoir simulation, completion fluid, polymer, post-combustion carbon capture, and constructed wetlands. A Roua et al. studied the corrosion inhibition properties of isoxazole-derived organic compounds, namely series Iso (a), Iso (b), Iso (c), Iso (d), Iso (e), Iso (f), Iso (g) and Iso (h), which may have affected [12] for materials science and industrial applications, and performed molecular dynamics simulations. SunA, Cui G et al. synthesized a new environment-friendly corrosion inhibitor (HCTS) through modified chitosan, which effectively inhibited CO_2-NaCl corroding the pipeline, and the corrosion inhibitor (HCTS) loaded bentonite/acrylamide capsule [13] was prepared according to the downhole corrosion environment. Elyor Berdimurodov et al. developed a novel drug active compound (GCU) as CO in 1 M NaCl of St3 steel2 and H_2S saturated green inhibitor; study shows that the inhibitor is an excellent inhibitory molecule with maximum protection of 95.62% at 100mg/L/0.08mM; the adsorption behaviour of the inhibitor is characterized by Langmuir isotherm; electrochemical study shows that the molecule is a mixed corrosion inhibitor; theoretical calculation shows a good correlation with the experimental results and confirm that the adsorption-inhibition characteristics depend on the molecular structure of the inhibitor, and the inhibitor in the protonated form is more inhibited [14] than the intrinsic form.

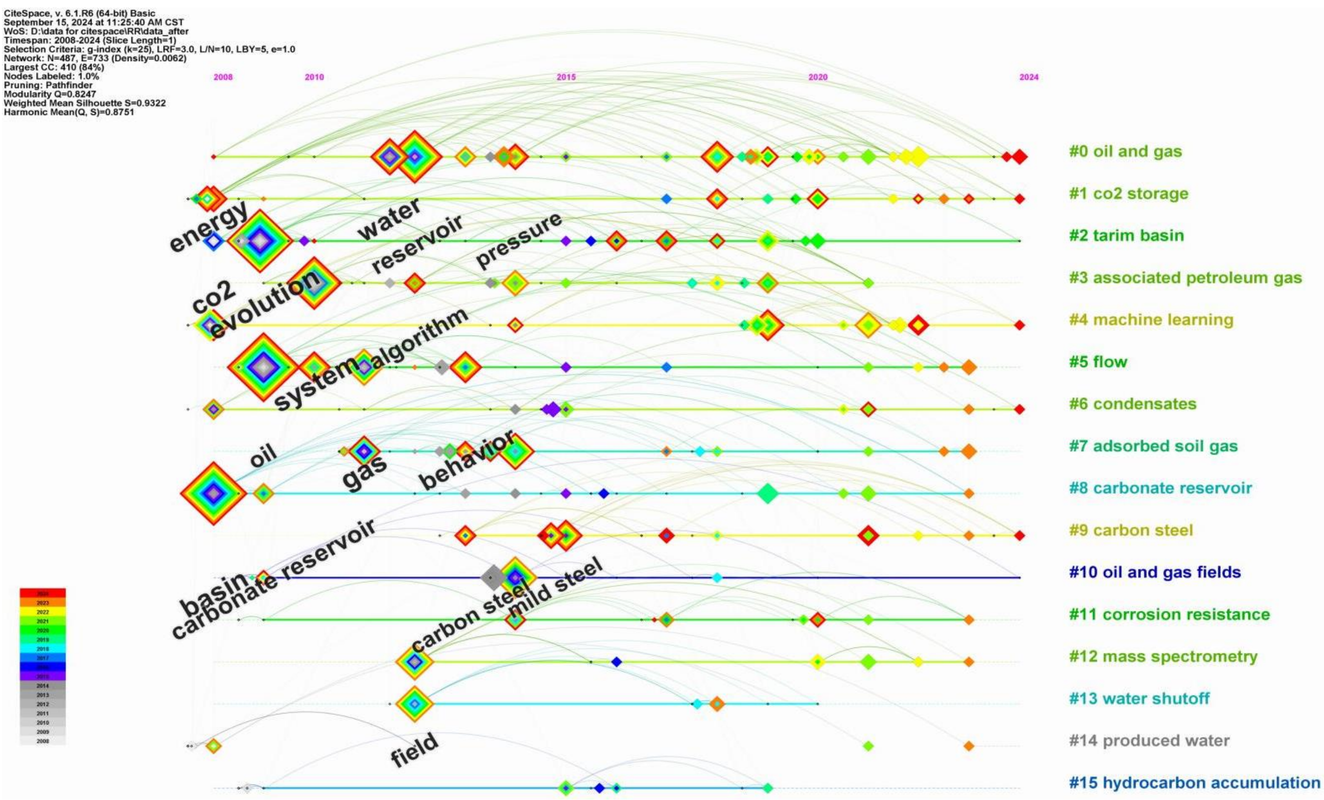

Figure 6. *Keywords timeline spectrogram.*

3.6. Keyword Highlighting Analysis

By conducting a prominent analysis of keywords, we can ascertain the frequency of a specific word's usage during a particular period in the statistical timeframe, which reveals the research frontier and the historical progression of development over a specified duration. As depicted in Figure 7, the top 22 keywords exhibiting the strongest citation bursts are "oil and gas fields," with the highest reference strength, and the research frontier persisted from 2014 to 2016.

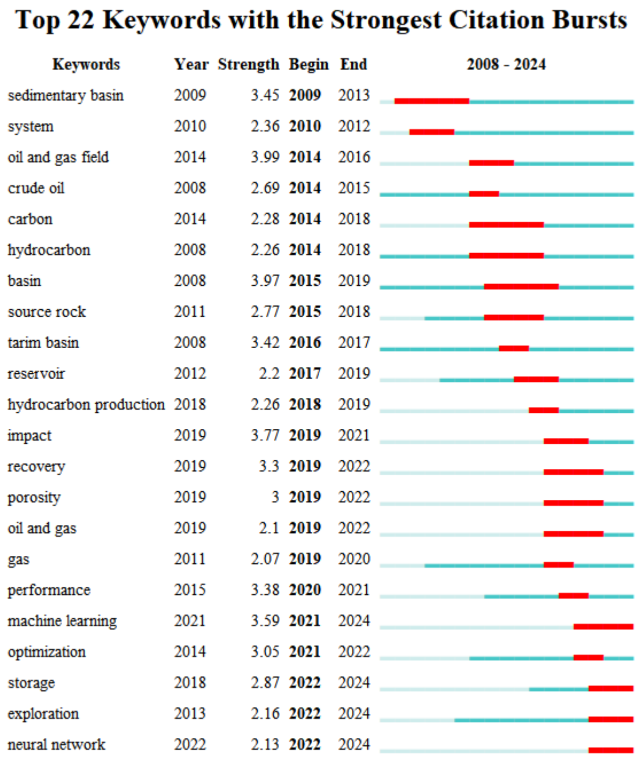

Figure 7. *Keywords highlight the analysis diagram.*

In oil and gas fields, steel alloys are typically utilized for casing and pipes in oil and gas wells. However, the presence of various corrosive gases, organic acids, salts, and pollutants in well fluids can negatively impact productivity, efficiency, and continuous production. Common corrosive substances such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), water (H_2O), organic acids (HCOOH, CH_3COOH, etc.), and salts (NaCl, $CaCl_2$, $MgCl_2$, NH_4Cl, etc.) can cause metal corrosion during any stage of production, purification, storage, and transportation. One of the most widely used techniques to address this issue is the use of corrosion-resistant materials. Additionally, anticorrosion and wear-resistant coatings are applied to prevent internal pipe corrosion. Another common method of corrosion protection is the use of scavengers, primarily for H_2S and O_2, to reduce the corrosive effects of well fluids. One popular technique for H_2S removal involves the use of an alkaline solution and activated carbon. Triazine and aldehydes are potent and commonly used non-productive H_2S scavengers. Furthermore, utilizing corrosion inhibitors is a practical and cost-effective approach to preventing corrosion of well sleeves and tubing. These inhibitors adsorb at the interface between the corrosive fluid and the internal pipe, effectively preventing corrosion. [15].

4. Conclusions

This study analyzed samples from the core collection database of Web of Science, with 880 articles on the progress of oil and gas field corrosion inhibitors published in 2008-2024, through the use of a scientific knowledge map, a lot of digital and language information visualization, visually shows the research progress in oil and gas field.

First, the results show that the overall number of annual papers showed a trend of rising first and then declining. Among them, the most significant number of relevant articles was published in 2021, but the overall number of relevant articles was relatively small. Secondly, the authors, institutions and countries are not closely related, and there is little research cooperation on high-temperature corrosion inhibitors in oil and gas fields, so they are in a state of independent research. The China University of Petroleum has the largest publication among the top 10 institutions from China, and the country has the most significant publication, indicating that China has made a relatively significant contribution to this field. Thirdly, the study of mass spectrometry in oil and gas is prominent, while the literature on high-temperature corrosion inhibitors is minimal. Finally, corrosion is the natural continuous degradation of materials caused by chemical, mechanical, or electrochemical reactions, and corrosion rates are higher at high temperatures.

With the enhancement of environmental awareness and the concept of sustainable development, the research and application of corrosion inhibitors in oil and gas fields have paid more and more attention to environmental performance. Modern corrosion inhibitors not only require efficient anti-corrosion performance, but also need to meet environmental protection requirements such as low toxicity, non-toxicity, and biodegradability. By using environmentally friendly corrosion inhibitors, oil and gas field companies can achieve sustainable development while ensuring production safety while reducing their environmental impact. The importance of oil and gas field corrosion inhibitors in contemporary times is self-evident. It is not only an important means to ensure the safety of equipment and prolong the service life, but also an effective way to reduce economic losses and improve economic benefits. At the same time, with the enhancement of environmental awareness and the concept of sustainable development, the research and application of corrosion inhibitors in oil and gas fields will also pay more attention to environmental performance.

Through the visual display of CiteSpace, the scientific community can intuitively understand the content, methods and conclusions of these important research results, so as to promote the promotion and application of research results. By analyzing the publication year and citation relationship of the literature, we can predict the future development trend of the field of corrosion inhibitors in oil and gas fields. This helps the scientific community to lay out the research direction in advance and seize the commanding heights of technology.

Future research may include the study of corrosion inhibitors in oil and gas fields under high temperatures and high pressure, more multiphase corrosion inhibitors suitable for various corrosion environments, and developing green corrosion inhibitors with low toxicity, high efficiency, and good biodegradation. The development and application of these new corrosion inhibitors will provide a strong guarantee for the safe production and sustainable development of oil and gas fields.

Abbreviations

CO_2	Carbon Dioxide
WOS	Web of Science
WPUs	Waterborne Polyurethane
CO	Carbon Monoxide
BAAs	Bio-based Anti-agglomeration Agents
H_2S	Hydrogen Sulfide
LPG	Liquefied Petroleum Gas
NaCl	Sodium Chloride
H_2O	Water

Conflicts of Interest

There is no conflict of interest with other units, businesses, affiliates, and other authors in the work of this study.

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