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Inhibitors for Corrosion by H_2S and the Effects on Oil Pipelines: Bibliometric Analysis

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ABSTRACT

Hydrogen sulphide (H_2S) corrosion is a significant problem in the oil industry. It affects pipeline integrity and generates high maintenance and repair costs. This work aims to evaluate global trends and the effectiveness of different types of H_2S corrosion inhibitors applied in oil pipelines through bibliometrics and a systematic review, analysing their future implications for developing anticorrosion strategies during the last decade. This process was developed in three phases: (i) baseline data and focusing, (ii) scientific metrics, and (iii) literature review using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method. The results show sustained growth in publications, focusing on green inhibitors and nanotechnology-based technologies that achieve efficiencies of more than 90% in the laboratory. However, gaps persist in field validation and designing multifunctional composites for extreme environments. These findings suggest prioritising applied research into new self-healing materials and coatings, as well as industrial-scale evaluation protocols to optimise the protection of critical infrastructure in the oil industry.

1. INTRODUCTION

In recent decades, global energy use has increased exponentially [1]. By the year 2050, this increase in energy demand is expected to pose a significant challenge for energy companies [2]. According to Liu et al. [3], in a case study conducted in China, they mention that the oil and gas industry plays a key role in the energy and economic development of a country, representing approximately 31.8% of the demand worldwide, being the livelihood of various sectors [4]. The oil industry influences the energy supply and has a profound impact on economic stability and geopolitical dynamics worldwide [5]. Oil transportation and mobilisation are fundamental to the global energy industry and the world economy [6], and their importance lies in moving crude oil from extraction sites to refineries and then distributing refined products to consumer markets [7, 8].

Oil and gas pipelines are key in the energy industry value chain [9], facilitating transportation and several critical processes from extraction to refining [10]. From the oilfields, crude oil and natural gas are transported through extensive pipeline networks to refineries, where they undergo transformation processes to obtain refined products such as petrol, diesel, and other petrochemical derivatives [11]. In addition to their primary transport function, these pipelines are essential within refinery systems [12], where they efficiently distribute intermediate products between various processing units, such as distillation columns, cracking reactors, and gas treatment plants [13]. This continuous and controlled flow is vital to optimise operations and ensure the safety of the refining process [14]. Likewise, pipeline integrity is crucial to minimise operational risks, prevent leaks, and reduce environmental impact [7, 15].

These pipelines are subjected to extreme physical and chemical conditions due to the nature of the fluids they transport and the environments in which they operate [16]. One of the most critical challenges in operating these pipelines is the presence of phenomena such as corrosion and scaling [17]. Scaling is the accumulation of solids such as salts, minerals, and other deposits on the internal walls of pipelines [18]. Corrosion is the deterioration of metal due to chemical reactions with the environment, mainly water and acid gases such as carbon dioxide (CO_2) and hydrogen sulphide (H_2S) [19]. This process can lead to the formation of iron oxide and other corrosive compounds, which weaken the pipeline structure and cause leaks and system failures [20].

Pitting corrosion is one of the most critical challenges facing oil pipelines, directly affecting their integrity and operational safety [21]. It accounts for 20% to 40% of corrosion failures depending on the environment and specific operating conditions [22]. Several oil fields worldwide face significant pitting corrosion problems, such as those in the Gulf of Mexico, the North Sea (including Kuwait and Saudi Arabia), and the Amazon Basin [23]. This type of corrosion is characterised by forming small cavities or “pits” on the internal or external surface of pipelines, which can perforate the metal locally [24]. Although the pits are small, they can rapidly deepen and lead to catastrophic failures, such as oil leakage or even complete pipeline rupture [25]. In oil pipelines, pitting corrosion is often caused by chlorides, saline water, or corrosive gases such as H_2S in oil [26]. These conditions create a highly aggressive environment for steel, which is the material commonly used in these pipelines. A clear example of this is oil fields located in coastal or marine areas, where contact with chloride-rich seawater can accelerate the pitting process, affecting the durability of the pipelines [9]. In 2006, a significant pipeline leak in the Prudhoe Bay oil field in Canada was caused by internal corrosion, including that induced by H_2S, leading to the spill of more than 200,000 gallons of oil into the Arctic tundra [27]. The control and prevention of H_2S corrosion in oil pipelines are essential to avoid catastrophic failures and high costs in the industry [28]. Due to the complexity of the mechanisms involved in iron sulphide formation, pitting corrosion, and sulphide stress cracking under extreme pressure and temperature conditions, this study focuses on a comprehensive review of the literature, integrating global trends both quantitatively and qualitatively to develop more effective anticorrosive strategies in real-life operating contexts [29]. In bibliometric analysis, several specialised software tools are used to facilitate the collection, analysis, visualisation, and presentation of data on scientific production [30]. These tools are essential for transforming data from publication databases into graphs, networks, and maps, enabling a better understanding of trends, impacts, and collaborations in specific fields of study [31]. VOSviewer is widely employed for creating and visualising co-authorship networks, citation patterns, and keyword co-occurrence maps. It is beneficial for identifying subject clusters and illustrating relationships between articles, authors, or institutions [32].

Corrosion in petroleum pipelines, mainly caused by H_2S generated pitting, represents a significant challenge for the energy industry [33]. Despite advances in materials technology and protection methods, there is a considerable gap in developing and applying corrosion inhibitors effective against this specific type of corrosion [24, 34]. Corrosion inhibitors are chemicals that can reduce or prevent metal deterioration when added to a pipeline environment. Although research on corrosion inhibitors for oil pipelines is extensive, it has mainly focused on their efficacy and cost. However, there are few studies on developing and applying new inhibitors that are environmentally sustainable and biodegradable [35].

The relationship between the importance of using H_2S corrosion inhibitors in oil pipelines and the literature review allows for the generation of research questions: What are the global trends in research on H_2S corrosion inhibitors in the last decade? What types of inhibitors dominate the recent literature? And what gaps or limitations are evident in practical application?

This work aims to evaluate the global trends and effectiveness of different types of H_2S corrosion inhibitors used in steel oil pipelines through a bibliometric and systematic review (PRISMA method) of the existing literature published in Scopus, analysing their future implications for the development of sustainable anticorrosive strategies over the last decade.

2. MATERIALS AND METHODS

Literature reviews are key to supporting research and its practical applications with a detailed study of the available evidence. Thus, they promote the advancement of knowledge and provide solid and reliable support for decision-making [36, 37]. By combining bibliometric methods and a systematic review, an important research focus can be generated, as it allows the analysis of the most critical trends and researchers in the field of research [38]. Furthermore, this bibliometric analysis permitted tracking the main trends and advances in research on H_2S-induced corrosion in oil pipelines, identifying the effects of inhibitors on oil pipelines and new coating technologies. This process was developed in three phases: (i) baseline data and focusing, (ii) scientific metrics and (iii) literature review-PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method (Figure 1).

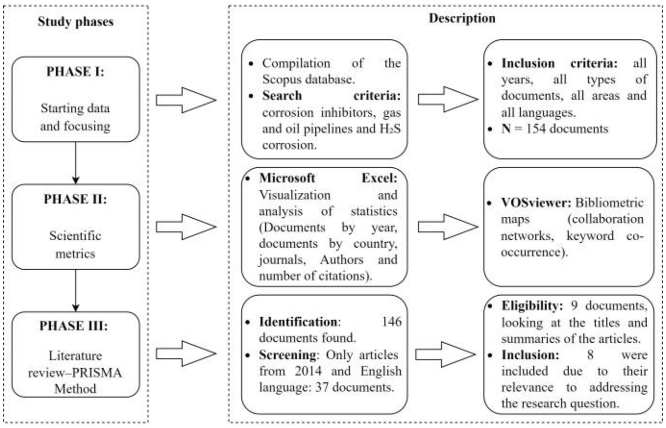

Figure 1. Methodological scheme of the study on inhibitors for H_2S corrosion

2.1 Phase I: Starting data and targeting

This article analyses the research approaches and trends related to inhibitors for H_2S corrosion in oil pipelines based on a bibliometric analysis and literature review. Corrosion is one of the main problems that occurs in oil industries worldwide, generating a significant economic and environmental impact due to the leaks that can result [39]. Due to this term, the keywords "Corrosion inhibitors" [40] and "corrosion mitigators" were selected [41]. Oil pipelines are essential for ensuring the safe, efficient and continuous transportation of hydrocarbons over long distances [42]. Therefore, the keyword "oil and gas pipelines" was chosen as the second term [43]. The Scopus database was selected because of its extensive coverage and relevance to the scientific literature. Scopus has become an indispensable resource for high-quality literature reviews, enabling researchers to consolidate knowledge and identify gaps in existing research [44, 45]. The search algorithm was built using Boolean operators (OR and AND) to refine the results and ensure the relevance of the retrieved documents. (OR and AND) to refine the results and ensure the relevance of the retrieved documents. The final equation applied was the following: (TITLE-ABS-KEY ("oil pipeline" OR "gas and oil pipeline" OR "underground oil pipeline" OR "underground gas pipeline") AND TITLE-ABS-KEY ("H_2S corrosion" OR "corrosion mitigation" OR "corrosion prevention" OR "corrosion inhibitors" OR "corrosion blockers")). This formula was applied to the title, abstract, and keyword fields, allowing the retrieval of relevant scientific literature on H_2S-induced corrosion in oil pipelines and associated inhibition strategies. Once the search was defined, data were downloaded in comma-separated value (CSV) formats for further processing and generation of graphs to visualise phase two field behaviour [46].

2.2 Phase II: Scientific metrics

Bibliometric analysis has become a fundamental tool for evaluating and understanding scientific production in various disciplines [47, 48]. This quantitative approach allows researchers to measure the impact of research, identify emerging trends, and map collaboration networks between authors and institutions [49, 50]. The data collected in the previous phase were exported to a Microsoft Excel spreadsheet for further analysis and organisation, with bibliographic data such as authors, title, year of publication, source title, authors' affiliations, keywords, number and citation data. Subsequently, cleaning was performed, and eight documents that did not contain complete bibliographic information were identified. Therefore, the documents were reduced to 146 publications. The VOSviewer software was used to construct the bibliometric mapping because it is easy for data processing, construction, and visualisation of bibliometric networks [51]. In this phase, co-authorship analyses were performed to identify collaborations between authors and countries, and keyword co-occurrence analyses allowed us to detect central themes and emerging trends in the literature. The generated maps reflect the intellectual structure of the field and facilitate the interpretation of research dynamics.

2.3 Phase III: Literature review–PRISMA method

Following the bibliometric analysis conducted in Phase II, the findings were refined through a systematic review using the PRISMA method, which examined the most relevant studies identified in the scientific network. Although PRISMA is traditionally applied as an independent technique, it was used as a phase after the bibliometric mapping. This method allowed for the document selection refinement and the analysis's focus on high impact works. The review consisted of four stages. In the "identification" stage, the 146 documents retrieved from the Scopus database were used. In the "screening" phase, the following inclusion criteria were applied: articles published since 2014 and in English, which reduced the set to 37 publications. The 2014-time cutoff was established due to the notable increase in research focused on protecting oil infrastructure through more sustainable strategies over the last decade [52]. This change responds to the industry's growing regulatory and social pressure to reduce environmental impact by promoting more environmentally friendly corrosion inhibitors, biopolymers, nanoparticles, and less toxic materials. In the "eligibility" stage, the titles and abstracts of the papers were reviewed in detail to assess their relevance and alignment with the research topic. This resulted in the selection of nine documents that showed a high impact in the area according to the number of citations. Finally, in the "inclusion" stage, a thorough evaluation of the full content of the papers was carried out, selecting eight studies that offered the most relevant answers and perspectives, such as efficiency and mechanism of action, to address the research question.

3. RESULTS

3.1 Evolution of scientific contribution

According to research related to corrosion inhibitors in oil pipelines, it can be evidenced through Scopus that this began in 1977, with the study by Laird [53], which reflects the deterioration of oil pipelines due to both internal and external corrosion as well as the importance of developing more efficient methods to control the problem and better corrosion inhibitors to stop its effects. The number of publications has varied, with some significant peaks in the 2000s and 2020s. This change is due to the development of new technologies or materials and increasing scientific production. However, it should be noted that as of 2010, the percentage of publications was 63%, showing a growth trend. In 2024, there was a decrease in production because data collection closed in September of that year (Figure 2).

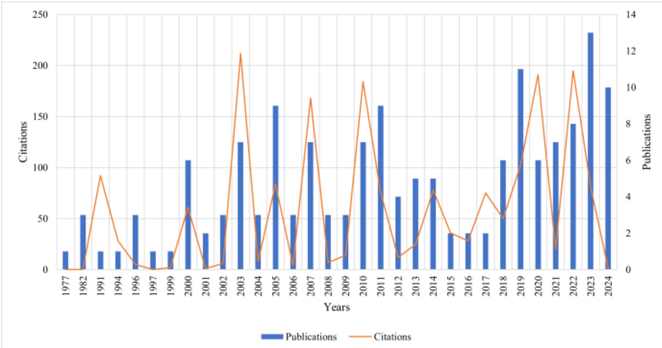

Figure 2. Scientific production of corrosion inhibitors in oil pipelines in Scopus over time

The citations show a fluctuating behaviour over the years, with significant peaks in specific periods. Citations fluctuate over the years, with significant peaks in particular periods. The highest number of citations was recorded in 2003, with over 200 associated with seven publications, most notably the study by Papavinasam et al. [54] on evaluating corrosion inhibitors in oil and gas pipelines. The article was widely cited for its rigorous comparison of various laboratory methods for assessing corrosion inhibitors, aligning them with real-world field conditions. Its practical approach made it a key reference for engineers and scientists. Furthermore, it coincided with pipeline incidents in the United States, which increased interest in preventive solutions [55]. Relevant increases were also identified in 2007, 2010, 2020, and 2022, with six to eight publications exceeding 150 citations yearly. Notable among these are the studies by Azevedo [56], focused on analysing pipeline failures; Rajasekar et al. [57], on characterising corrosive bacterial consortia; and Ijaola et al. [42], on the use of coatings for protecting steel pipes. All of them mark significant advances in the field. Current research (2023-2024) has not yet accumulated citations. However, the next few years will likely increase, reflecting the impact of these studies, which focus on developing advanced real-time monitoring technologies to detect and evaluate corrosion at early stages. They also apply new materials and coatings with improved resistance properties.

3.1.1 Contribution by country

According to the bibliometric analysis, 42 countries published at least one study on corrosion inhibitors in oil pipelines, of which 13 reached a minimum of three articles (Figure 3). The three central countries stand out in terms of their scientific production: China leads with 30 documents, focusing its research on environmentally friendly inhibitors such as imidazoline quaternary salts and chitosan derivatives, which are generally validated by weight loss and electrochemical polarisation tests [58]. The United States, with 28 publications, has specialised in advanced nanocomposite coatings such as self-healing films enriched with zinc oxide nanoparticles and C_{60} fullerene, evaluated by electrochemical impedance spectroscopy and accelerated corrosion tests with sodium chloride [59]. Canada contributed 17 studies focusing on corrosion microbiology studies, examining how fluid flow influences biofilm formation in closed-loop reactors and using gravimetric methods to measure inhibitor efficacy [60]. Finally, the United Kingdom has delved into the adsorption mechanisms of imidazoline-based inhibitors and the molecular characterisation of corrosive bacterial consortia. These countries are recognised as among the most cited worldwide in this field (Table 1).

Table 1. Top 10 countries by number of documents

Ranking	Country	Region	Documents	Citations
1	China	Asia	30	264
2	United States	America	28	374
3	Canada	America	17	361
4	Russian Federation	Europe	15	63
5	Mexico	America	9	60
6	Saudi Arabia	Asia	8	105
7	Australia	Oceania	7	190
8	Nigeria	Africa	5	118
9	United Kingdom	Europe	5	283
10	India	Asia	4	225

Figure 3 shows the bibliographic analysis by country, where the nodes represent each nation and vary in size depending on the number of registered documents. The links in the graph reflect international collaborations and their thickness indicates the intensity of each relationship. In total, 13 countries connected through 42 links were identified, with a cumulative relationship strength of 929, organized into six groups differentiated by colour.

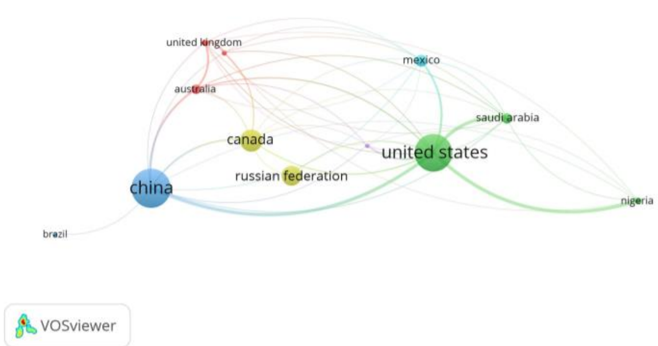

Figure 3. Bibliometric map of contribution by country during the period 1977-2024

Table 2 shows the countries that produce the most by cluster and the three central countries with which they collaborate. For example, the first group (red) contains eight countries, with Australia leading in production and collaborating mainly with China, the United States, and the United Kingdom. The associations between countries in each cluster are due to strategic and economic factors in the energy industry. Australia, for example, collaborates intensively with China, the United States and the United Kingdom due to its role as a natural resource supplier, strengthening its commercial ties with these large markets [61].

Table 2. The leading country in production by cluster and the first three countries with which it collaborates

Cluster	Country	Countries it Collaborates with	Link Strength
1	Australia	China	55
		United Kingdom	52
		United States	16
2	United States	Nigeria	171
		Saudi Arabia	168
		China	157
3	China	United States	157
		Australia	55
		Canada	36
4	Canada	China	36
		India	17
		United States	15
5	France	United States	42
		China	5
		Australia	5
6	Mexico	United States	60
		Saudi Arabia	3
		China	2

3.2 Lines of research inhibitors for corrosion in oil pipelines

According to the co-occurrence analysis of the author's words, connections and construction of a domain structure, 28 keywords with a minimum of three occurrences were established. Table 3 shows the top 10 words with the highest frequency in the study area, highlighting "corrosion", "corrosion inhibitor", and "oil pipeline" as the three most frequent keywords.

Table 3. The ten keywords with the highest appearance in studies of inhibitors for corrosion in oil pipelines

Ranking	Keywords	Occurrences	Total Link Strength
1	Corrosion	19	24
2	Corrosion inhibitor	12	10
3	Oil pipeline	9	11
4	pipeline	9	10
5	inhibitor	6	9
6	Internal corrosion	6	10
7	pipelines	6	5
8	inhibition	5	12
9	Pitting corrosion	5	5
10	Oil pipelines	5	9

The bibliometric map generated in the VOSviewer software grouped the different keywords into five clusters, representing the research areas of inhibitors for corrosion in oil pipelines (Figure 4). Changes in node size reflect the number of keyword occurrences, while the links represent relationships with other topics.

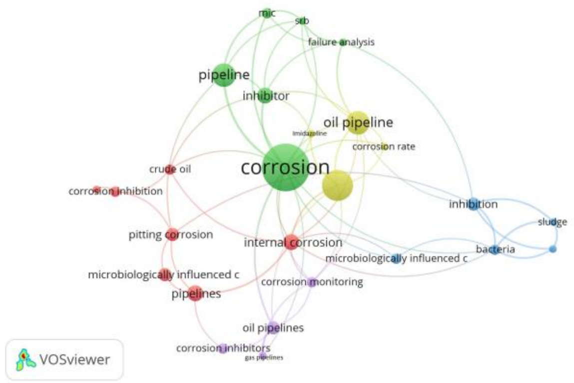

Figure 4. Bibliometric map of co-occurrence of author keywords in Inhibitors for corrosion in oil pipelines

Cluster 1 (red), titled "Internal Corrosion and Monitoring in Oil Pipelines," focuses on understanding the importance of corrosion inhibitors. This cluster brings together studies on specific types of corrosion, in particular "internal corrosion" [62] and "pitting corrosion" [63], both serious problems in the petroleum industry. The term "microorganism-induced corrosion" is also mentioned in this context, pointing to a particular interest in the internal microbiological factors that influence corrosion processes [60].

The area called "corrosion rate prevention and analysis" covers cluster 2 (green), which includes representative contributions of the most common and broad concepts about corrosion in the context of oil pipelines, highlighting terms such as "corrosion" [64] and "pipeline" [65] that are in the centre, which suggests that most of the studies deal with corrosion mechanisms and their effects on oil pipelines, as well as the search for materials and compounds that protect them pipes of internal and external corrosion [59, 66].

Cluster 3 (blue), named "corrosion inhibitors and sediments", is related to specific corrosion inhibition mechanisms; this is reflected by the interconnection between the term "inhibition" [67] and "bacteria" [57, 68], suggesting studies on biological inhibitors or the influence of organisms on corrosion processes. The term "sediments" highlights the importance of sludge or debris accumulation in the corrosive process [69], making it relevant to control these factors and reduce corrosion in pipelines.

Cluster 4 (yellow), called "pipeline corrosion rate", is related to research analysing the influence of crude oil on corrosion mechanisms and inhibition methods, as reflected by the term "internal corrosion" [70], suggesting that a large part of the studies focus on the corrosion that occurs inside the pipes, caused by gases such as H_2S [67], a common problem in the oil and gas industry. Likewise, the interrelationship with "corrosion rate" [71] indicates that these studies evaluate how inhibitors slow the structural deterioration of pipes.

Finally, cluster 5 (purple), called "corrosion inhibitors in oil pipelines", focuses on research on the effectiveness of corrosion inhibitors [72] and their relationship with oil pipelines [73]. It appears in an important position and shows a focus on how these inhibitors act in various conditions within oil pipelines.

3.3 Review using the PRISMA method: Research trends

The review considered eight studies that analysed the effects of H_2S corrosion inhibitors on oil pipelines (Table 4) [58, 59, 67, 74-78]. The information analysis reflects that the contribution is centred on the Asian continent, with China being the country with the most significant contribution. These countries evaluate the effects and efficiency of corrosion inhibitors, reflecting their interest in developing efficient solutions that reduce operating costs and minimise environmental impact. In addition, studies have been conducted to improve the durability of pipelines by reducing the need for costly maintenance.

Corrosion inhibitors play an essential role in protecting oil pipelines against corrosive agents, such as hydrogen sulphide (H_2S) [79], carbon dioxide (CO_2) [80], water and other components present in petroleum fluids. These act by creating a protective layer on the internal surface of the pipes, preventing corrosive agents from coming into direct contact with the metal, reducing the corrosion rate and prolonging the useful life of the pipes, reducing the risk of failures or leaks [81]. In response to this problem, corrosion inhibitors have become one of the most effective and widely used strategies in the oil and gas industry.

Research carried out in recent years has shown that using corrosion inhibitors can reduce the corrosion rate by up to 90% [74, 77], indicating greater operational efficiency and a significant reduction in maintenance costs. However, the success of these inhibitors depends on multiple factors, including the correct selection of the inhibitor, the concentration used, and the way it is applied and monitored over time [82].

The studies reviewed reveal that although the most common and commercial generic inhibitors, such as amine-based ones, phosphonates, imidazoline and sulphur compounds, continue to have good relevance in this field [83] because they are selected based on the operating conditions, such as temperature, pressure and chemical composition of the transported fluids [58]. However, increasing research is focused on minimising the environmental impact by developing more sustainable and environmentally friendly inhibition technologies. According to Badawi and Fahim [40], new inhibitors are being developed that are efficient in protecting pipelines and reducing the environmental impact of the chemicals used. In this sense, Pérez-Miranda et al. [84] state that green corrosion inhibitors are gaining ground as a more sustainable solution because they are products derived from natural or less toxic sources [85], which seek to reduce the ecological footprint of oil activities without compromising protection against corrosion [86]. However, implementing these inhibitors still faces challenges, especially under extreme operating conditions.

Researchers are exploring using plant extracts, agro-industrial waste, and biopolymers as sustainable alternatives to traditional inhibitors. An example is the studies conducted by Mirgorod et al. [77], which use tobacco residues as effective corrosion inhibitors, or Cui et al. [75], who synthesise branched chitosan derivatives as demulsifiers and anticorrosives for steel. This trend reflects the need to reduce the environmental impact of using toxic chemicals in the oil industry.

Table 4. Scientific findings on the effects of H_2S corrosion inhibitors on oil pipelines

Country	Reference	Study Aim	Study Findings
China	[58]	Inhibition Localised Corrosion of N80 Petroleum Pipeline Steel in NaCl-Na_2S Solution Using an Imidazoline Quaternary Ammonium Salt.	Imidazoline quaternary ammonium salt corrosion inhibitor can form a layer of adsorption film on the metal surface to increase the polarisation resistance and reduce the corrosion rate.
	[67]	Simultaneous Inhibition of Natural Gas Hydrate Formation and CO_2/H_2O Corrosion for Flow Assurance inside the Oil and Gas Pipelines.	The inhibitors considerably improved the polarisation resistance, allowing the formation of a protective layer on the metal surface to protect it from corrosion, with an inhibition efficiency of 96.3%.
	[74]	Corrosion Inhibiting Evaluation of β-Cyclodextrin Functionalised Acrylamide Copolymer for X70 Steel in Sulfuric solution.	The copolymer acts as a mixed-type inhibitor; the inhibition efficiency increases with increasing concentration and decreases with increasing temperature, exhibiting maximum values of 94.8% at the highest concentration.
	[75]	Synthesis of Branched Chitosan Derivatives for Demulsification and Steel Anti-Corrosion Performances Investigation.	BH (Branched Chitosan) and CH (Chitosan Hydrogel) at 500 $mg \cdot L^{-1}$ inhibited the corrosion of carbon steel by 85.70% and 83.56%, respectively, from the experiment of weight loss in a saturated NaCl solution with 8% by weight CO_2/H_2O at 60°C.
	[59]	Enhanced Protective Coatings Based on Nanoparticle Fullerene C_{60} for Oil & Gas Pipeline Corrosion Mitigation.	The fullerene-C_{60} loaded composite coatings showed significantly improved corrosion resistance, with 0,5 and 1,0 % of the nanocomposite performing as an intact layer for corrosion protection, with a reduction in severe corrosion damage observed more than 50%.
Indonesia	[76]	Solvent-Free Synthesis of Imidazoline from TETA-Palmitic Acid and Evaluation of Its Corrosion Inhibition Activity.	The 1.5% NaCl solution saturated with CO_2/H_2O showed the performance of imidazoline as a potential corrosion inhibitor, as demonstrated by electrochemistry and gravimetrics.
Russia	[77]	Acid Corrosion Inhibitor from Tobacco Waste for Steel of Oil Pipes.	The inhibitors act as a mixed type inhibitor, affecting both the anodic and cathodic reactions, with efficiency against PSL-1 steel of 92-96%. Gravimetric and electrochemical methods were applied to determine its effectiveness.
Saudi Arabia	[78]	Corrosion Inhibition Properties of Sweet Crude Oil for Carbon Steel 1018 in NaCl Solution.	The results showed that a 144-hour immersion in NaCl crude oil saturated with CO_2/H_2O produced an 88% reduction in corrosion rate, comparable to the efficiency of standard quaternary ammonium-based inhibitors.

The proposed gas hydrate formation is innovative in the oil and gas industry, particularly in subsea pipelines and transportation systems [67]. Qasim et al. [87] mention that these multifunctional inhibitors improve operational efficiency and reduce the need for various chemicals. The combined use of corrosion inhibitors and protective coatings is being investigated as a more effective strategy to extend the useful life of pipelines, exploring how coatings can improve the adhesion and effectiveness of inhibitors, particularly in acidic corrosion environments [88].

Another alternative for protecting oil pipelines is the application of nanotechnology due to its high potential, especially in developing innovative coatings and nanostructures that offer improved protection against corrosion [89]. Among the most notable advances is the study by Wang et al. [59], where C_{60} fullerene is used as an effective physical-chemical barrier to prevent the interaction of corrosive agents with metal surfaces. Likewise, Govardhane and Shende [90] emphasise that innovative coatings have made significant progress, incorporating self-healing, controlled release of inhibitors and the ability to adapt to environmental changes. These functionalities are especially relevant to preserving the integrity of infrastructures in the hostile environments characteristic of the oil sector. However, this bibliometric analysis shows that, despite their high efficiency under laboratory conditions, implementing these technologies still faces significant barriers, mainly related to costs and limited field validation. This highlights the need to move toward applied studies that evaluate their real performance and technical and economic viability in industrial contexts.

4. DISCUSSION

The methodology applied in this study has allowed the integration of two complementary approaches: i) a bibliometric analysis, which demonstrates the evolution of scientific production on H_2S corrosion inhibitors in steel oil pipelines, and ii) a systematic review using the PRISMA method, focusing on the effects, mechanisms of action, and efficiency of these compounds. This methodological combination provides a comprehensive overview of the field, identifies gaps in practical validation, and identifies opportunities to innovate in sustainable solutions. According to the bibliometric analysis, scientific production on this topic has shown an upward trend since 1977, accounting for approximately 63% of all publications in the last 14 years. This increase could be due to the growing pressure to develop more efficient inhibitors with a lower environmental impact in response to stricter regulations and the advancement of new technologies.

The bibliometric analysis showed a sustained increase in publications on inhibitors, particularly over the last 14 years, accounting for approximately 63% of all publications since 1977. This growth is associated with the need for more effective and sustainable alternatives to mitigate corrosion, which aligns with new environmental regulations.

Furthermore, the leadership of countries such as China, the United States, and Canada (Table 1) and the observed international cooperation reflect a global and coordinated concern about protecting oil infrastructure. Figure 4 shows the relationship between inhibitors (green cluster) with oil pipelines (yellow cluster) and the purple cluster of internal corrosion, highlighting the importance of implementing these systems in the industry. According to Hameed et al. [91], the progress of inhibitors lies in minimising the environmental impact of chemical solutions without compromising the internal protection of pipelines.

Table 5. Comparison of the different inhibitors used for corrosion that exist in the oil industry

Inhibitor Type	References	Main Application	Advantages	Disadvantages	Reported Efficiency
Nanoparticles	[59, 92, 93]	High-pressure and temperature environments	High corrosion resistance, long-lasting protection	High costs, still limited development	>92%
Multifunctional Inhibitors	[94, 95]	Subsea systems, hydrate and corrosion mitigation	Efficient in underwater environments, reducing the use of additional chemicals	Greater complexity in its formulation	90-96%
Organics (Amines, Imidazolines)	[76, 96]	Acid and sulphur environments	High efficiency, good adhesion to metal	They can be toxic and require adequate concentration	90-95%
Inorganic (Chromates, Phosphates)	[97, 98]	Protection in aqueous solutions	They form stable passive layers and are easy to apply	Environmental risk: some are highly toxic	85-90%
Biopolymers and Natural Extracts	[99, 100]	A sustainable alternative in moderate environments	Ecological, biodegradable, lower environmental impact	Lower resistance in extreme conditions	75-90%
Agroindustrial Waste	[77, 101]	Ecological alternative in saline environments	Low cost, contribute to the circular economy	Require specific treatments for stability	75-85%

In corrosion protection for oil pipelines, Table 5 summarises various approaches to inhibitor design, classified according to characteristics, mechanisms of action, and application conditions. This diversity reflects the industry's operational complexity, where factors such as acidity, salinity, temperature, and pressure require tailored solutions. Organic inhibitors, such as imidazolines studied by Solomon et al. [96], stand out for their high efficiency in acidic and sulphurous environments due to their ability to form protective layers on metal surfaces. In contrast, inorganic inhibitors, such as phosphates analysed by Bastidas et al. [97], have demonstrated exemplary performance in aqueous and saline media. However, their application in acidic conditions is limited due to risks such as the release of arsine, a toxic byproduct that compromises operational safety and environmental compliance [102].

With these limitations, biopolymers and natural extracts have emerged to moderate the environmental impact with up to 90% efficiency. Most natural inhibitors are non-toxic, biodegradable and abundant in nature [40]. Studies such as Mourya et al. [103] on the extract of Tagetes erecta, known as the Wonder Flower, or Adewuyi et al.'s [104] research with wild pumpkin seed oil (Adenopus breviflorus) have shown good efficiency as inhibitors of carbon steel corrosion. They act as mixed-type inhibitors, cathodic and anodic. Research shows an increase in the development of green inhibitors based on plant extracts and biopolymers [105]. However, unlike organic and inorganic inhibitors, these decrease efficiency under extreme operating conditions such as high temperatures and pressures [106].

In this context, nanotechnology-based technologies open up new possibilities. Inhibitors such as fullerene C_{60}, evaluated by Wang et al. [59] on nanoparticles manufactured by Nano-C (carbon nanostructures), show efficiencies exceeding 95% under high pressure and temperature conditions, although high costs and limited commercialisation hinder its mass adoption.

Most studies evaluated using the PRISMA method report efficiencies exceeding 90% under controlled conditions [67, 77]. However, a gap persists between laboratory efficacy and real-life performance. This gap is accentuated in the case of green inhibitors, whose field validation is still limited. Furthermore, no inhibitor category offers a comprehensive solution on its own: while some stand out for their technical efficacy, others do so for their environmental compatibility. Therefore, a key avenue for progress will be the development of hybrid and multifunctional formulations with experimental validation under real-life industrial conditions. Combining conventional inhibitors with these coatings could effectively protect pipelines in extreme operating environments with severe corrosion.

Finally, the need to move toward formulations that balance efficacy and sustainability, and to design real-life trials that validate the long-term performance of inhibitors, is highlighted. International collaborations, already evident in bibliometric patterns, must be strengthened to accelerate the transition toward more robust, intelligent, and environmentally friendly solutions.

5. CONCLUSIONS

The analysis of H_2S corrosion inhibitors in oil industry pipelines has revealed significant growth in interest and research on this topic, particularly over the past 14 years, making it clear that corrosion remains a critical challenge for the durability and performance of hydrocarbon transportation infrastructure. The publication growth justifies the continued development of more effective solutions, making the development of advanced protection strategies indispensable, especially the search for environmentally friendly inhibitors. The commitment to reducing the environmental impact of the oil industry has driven the development of more robust and sustainable corrosion inhibitors. In collaboration with the United States and Canada, China stands out most in this field, facilitating essential advances in creating highly effective inhibitors under adverse conditions and responding to the need to minimise negative impacts on the environment.

The systematic review identified several types of inhibitors, including organic, inorganic, green, and nanotechnological. Green inhibitors, such as extracts of Tagetes erecta (China), neem leaf (China), or Adenopus breviflorus seed oil (United Kingdom), have demonstrated efficiencies close to 90% in controlled trials and are emerging as sustainable alternatives to more aggressive traditional compounds. Meanwhile, nanomaterials such as C_{60} fullerene and zinc oxide show efficiencies exceeding 90% under harsh conditions, demonstrating their potential for advanced industrial applications, although their industrial use is limited by cost and lack of standardisation.

Finally, a significant gap was identified in validating inhibitors, especially those of plant origin and nanostructured compounds, whose effectiveness has been proven primarily under laboratory conditions but not in real-world operating environments. This limitation hinders their industrial adoption and underscores the need to conduct pilot-scale studies to evaluate their performance under variables such as temperature, pressure, and fluid composition. In this context, it is essential to promote the development of hybrid formulations that integrate technical performance, environmental compatibility, and operational stability. Furthermore, strengthening international scientific cooperation, particularly among leading countries such as China, the United States, and Canada, is recommended to accelerate innovation and field-validate solutions that enable more efficient and sustainable protection against H_2S corrosion in the oil industry.

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