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Effectiveness of natural inhibitors against oil pipeline corrosion under corrosive conditions in the Berkaoui Region

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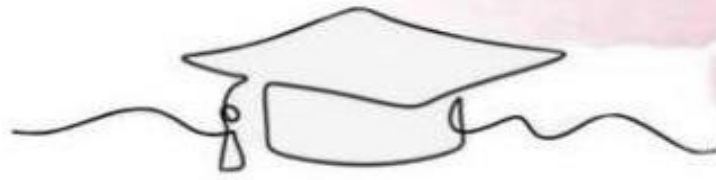
Appreciation

At first, we thank God for enabling us to complete this modest work, and we extend our sincere thanks and gratitude to everyone who contributed, from near and far, to the development of this work.

Our gratitude goes to our supervisors, Mr. Laabidi Saad Issa and Ms. Chouicha Samira, for their guidance and expertise, which were invaluable throughout this process. Their constructive feedback and encouragement contributed to the improvement of the quality of our work. We would also like to extend our sincere gratitude to the faculty members and instructors who contributed their knowledge and provided us with valuable resources throughout our academic journey.

Finally, we would like to express our sincere appreciation to our family for their continued financial and moral support and their belief in our ability to accomplish this excellent work.





Dedication

In the name of Allah, the Most Gracious, the Most Merciful. Praise be to Allah who granted me the strength and guidance to complete this humble work.

I dedicate the fruit of my efforts to the dearest people in my life, my beloved mother and dear father, who have always been my source of support and strength throughout my academic journey. To them, I express my deepest love, gratitude, and appreciation.

To my sister Sara, and to Diaa, Wisal, and Rawan.

To my beloved aunts, especially Naima and Sahlia, and to my uncles, particularly Abdelrazak.

To my dear uncles and aunts.

To my dear friends: Aya, Nassiba, Ahmed, Safi, and Abderrahman.

To my respected teachers, whose knowledge and guidance have greatly contributed to my academic development.

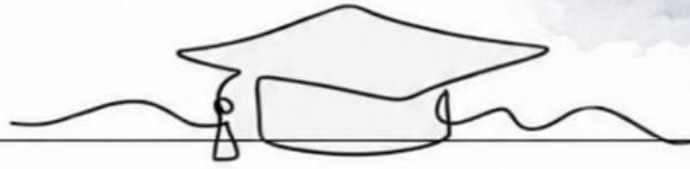
And to myself, for believing in my dreams and striving to achieve them despite all challenges.

And to everyone who contributed, directly or indirectly, to the completion of this work.

I dedicate this humble work with sincere love, appreciation, and respect.

Sadjida Benhamed





Dedication

In the name of Allah, the Most Gracious, the Most Merciful. Praise be to Allah for granting me the strength and perseverance to complete this work.

I dedicate this work to my beloved parents, for their endless support and sacrifices.

To my family, teachers, friends, and everyone who contributed, directly or indirectly, to the completion of this work.

To the one who supported me emotionally throughout this journey, I express my sincere gratitude and dedicate this achievement to her.

And to myself, for never giving up and for striving to reach this moment.

With sincere appreciation and gratitude, I dedicate this work.

Abdelrahman



Abstract:

Microbiologically Influenced Corrosion (MIC) represents a major challenge to the integrity of oilfield infrastructure, particularly in the Haoud Berkaoui oil field, where chemical factors such as carbon monoxide (CO) and hydrogen sulfide (H₂S), together with corrosive bacterial species such as Sulfate-Reducing Bacteria (SRB), accelerate equipment degradation. This study investigates the corrosion inhibition properties of oregano, rosemary, and neem extracts as natural and environmentally friendly alternatives to conventional chemical inhibitors.

The extracts, rich in bioactive compounds such as thymol, carvacrol, and flavonoids, were tested at different concentrations on X52 steel specimens under simulated oilfield conditions. Weight-loss measurements and microscopic analysis revealed that the addition of oregano, rosemary, and neem extracts significantly reduced the corrosion rate and shifted corrosion potentials toward more negative values, indicating a cathodic inhibition behavior. These extracts formed a protective barrier against corrosive species and inhibited the activity of sulfate-reducing bacteria (SRB).

The results indicate that oregano, rosemary, and neem extracts provide effective corrosion protection while contributing to sustainable and environmentally responsible corrosion management practices in the hydrocarbon sector. Further optimization and field testing are recommended to validate their industrial applicability and long-term performance.

Keywords: Microbiologically Influenced Corrosion (MIC), Natural Inhibitor, Oregano, Rosemary, Neem, X52 Steel, Chemical Inhibitor.

الملخص:

يمثل التآكل المتأثر بالكائنات الحية الدقيقة (MIC) تحدياً كبيراً لسلامة البنية التحتية لحقول النفط، لا سيما في حقل حوض بركاوي النفطي، حيث تعمل العوامل الكيميائية مثل أول أكسيد الكربون (CO) وكبريتيد الهيدروجين (H₂S)، إلى جانب الأنواع البكتيرية المسببة للتآكل مثل البكتيريا المختزلة للكبريتات (SRB)، على تسريع تدهور المعدات. تهدف هذه الدراسة إلى تقييم خصائص تثبيط التآكل لمستخلصات الأوريغانو وإكليل الجبل والنيم باعتبارها بدائل طبيعية وصديقة للبيئة للبهبطات الكيميائية التقليدية.

تم اختبار هذه المستخلصات، الغنية بالمركبات النشطة بيولوجياً مثل الثيمول والكارفاكرول والفلافونويدات، بتركيزات مختلفة على عينات من فولاذ X52 تحت ظروف تحاكي بيئة الحقول النفطية. وأظهرت قياسات فقدان الوزن والتحليل المجهرية أن إضافة مستخلصات الأوريغانو وإكليل الجبل والنيم أدت إلى انخفاض ملحوظ في معدل التآكل وتحول جهود التآكل نحو قيم أكثر سلبية، مما يدل على سلوك تثبيط كاثودي. كما شكلت هذه المستخلصات حاجزاً واقياً ضد العوامل المسببة للتآكل وساهمت في تثبيط نشاط البكتيريا المختزلة للكبريتات (SRB).

تشير النتائج إلى أن مستخلصات الأوريغانو وإكليل الجبل والنيم توفر حماية فعالة ضد التآكل، مع المساهمة في تبني ممارسات مستدامة وصديقة للبيئة لإدارة التآكل في قطاع المحروقات. ويوصى بإجراء مزيد من الدراسات والاختبارات الميدانية للتحقق من قابليتها للتطبيق الصناعي وأدائها على المدى الطويل.

الكلمات المفتاحية: تآكل متأثر بالكائنات الحية الدقيقة (MIC)، مثبط طبيعي، أوريغانو، إكليل الجبل، النيم، فولاذ X52، مثبط كيميائي.

Résumé :

La corrosion influencée par les micro-organismes (MIC) représente un défi majeur pour l'intégrité des infrastructures pétrolières, en particulier dans le champ pétrolier de Haoud Berkaoui, où des facteurs chimiques tels que le monoxyde de carbone (CO) et le sulfure d'hydrogène (H₂S), ainsi que des espèces bactériennes corrosives telles que les bactéries sulfato-réductrices (SRB), accélèrent la dégradation des équipements. Cette étude examine les propriétés inhibitrices de corrosion des extraits d'origan, de romarin et de neem en tant qu'alternatives naturelles et écologiques aux inhibiteurs chimiques conventionnels.

Les extraits, riches en composés bioactifs tels que le thymol, le carvacrol et les flavonoïdes, ont été testés à différentes concentrations sur des éprouvettes d'acier X52 dans des conditions simulant un environnement pétrolier. Les mesures par perte de masse et l'analyse microscopique ont montré que l'ajout des extraits d'origan, de romarin et de neem réduisait considérablement la vitesse de corrosion et déplaçait les potentiels de corrosion vers des valeurs plus négatives, indiquant un comportement d'inhibition cathodique. Ces extraits ont formé une barrière protectrice contre les espèces corrosives et ont inhibé l'activité des bactéries sulfato-réductrices (SRB).

Les résultats montrent que les extraits d'origan, de romarin et de neem assurent une protection efficace contre la corrosion tout en contribuant à des pratiques de gestion durable et respectueuse de l'environnement dans le secteur des hydrocarbures. Des études complémentaires et des essais sur le terrain sont recommandés afin de confirmer leur applicabilité industrielle et leurs performances à long terme.

Mot-Clé: Corrosion influencée par les micro-organismes (MIC), Inhibiteur naturel, Origan, Romarin, Neem, Acier X52, Inhibiteur chimique.

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List of Abbreviations

List of abbreviations

Abbreviation	Significance
CFPA	Haoud Berkaoui Authority
MIC	Microbiologically influenced corrosion
HBK	Haoud Berkaoui
SRB	Sulfate-Reducing Bacteria
CFU	Colony Forming Units
pH	Potentiel d'Hydrogène
SCE	Saturated calomel electrode

List of Symbols

Symbol	Signification	Unit
β_a	Anodic Tafel Coefficient	mV
β_c	Cathodic Tafel Coefficient	mV
C	Concentration	mg/L or ppm
E _{corr}	Corrosion Potential	mV
I _{corr}	Corrosion Current	mA/cm ²
N	Normality	mol/L
P	Pressure	bar
R _p	Polarization Resistance	kΩ.cm ²
S	Salinity	g/L
T	Temperature	°C
t	Time	s
V	Volume of the prepared solution	mL

General Introduction

General Introduction

This study evaluates the possibility of using natural plant extracts to reduce bacterial corrosion of pipeline steel under conditions that simulate the environment of Algeria's Haoud-Berkaoui oil field. The main objective is to test the effectiveness of natural inhibitors against microbiologically influenced corrosion (MIC) of pipeline steel, compare the performance of three selected plant extracts, examine the influence of different extraction methods, and propose practical strategies for corrosion control in oil-field conditions.

To achieve this objective, API 5L X52 steel coupons were immersed in separator water collected from the Haoud-Berkaoui field and inoculated with sulfate-reducing bacteria (SRB) in order to reproduce realistic MIC conditions. Six natural extracts were tested, including oil-based and aqueous extracts of rosemary, oregano, and neem. The performance of these extracts was evaluated using the weight-loss method, which allowed the calculation of corrosion rate and inhibition efficiency in comparison with an uninhibited blank sample. The results were further supported by optical microscopy and crystal-violet staining to observe biofilm formation on the steel surface.

The originality of this work lies in its field-relevant experimental approach. Instead of testing the inhibitors in idealized laboratory acid solutions, this study uses a medium that reproduces the actual produced-water chemistry and microbiological conditions of the field. It also compares two extraction routes for each plant and combines gravimetric analysis with microscopic observation, providing more reliable results that may be useful for corrosion-control practices in Sonatrach operations.

This dissertation is organized into four chapters. The first chapter presents the background of biocorrosion, focusing on sulfate-reducing bacteria, MIC mechanisms, influencing factors, detection methods, and control strategies. The second chapter discusses corrosion inhibitors, including their definitions, modes of action, industrial families, and the selected natural plants used in this study. The third chapter introduces the Haoud-Berkaoui field context by describing the corrosion problems observed in surface and buried installations, as well as the current mitigation practices. The fourth chapter is devoted to the experimental work, including the materials used, weight-loss results, corrosion rates, inhibition efficiencies, and microscopic observations used to identify the most effective inhibitor.

Overall, this study provides a field-relevant and multi-method comparison of rosemary, oregano, and neem extracts as eco-friendly inhibitors against SRB-driven pipeline corrosion.

Chapter I:
General Information of
Biocorrosion

I. Introduction

Corrosion is the process by which metallic materials degrade due to chemical or electrochemical reactions with the surrounding environment. This causes metals to change into more stable forms such as oxides or rust, especially in the presence of oxygen and water [1]. This process is characterized by the gradual removal of metal atoms from the surface by dissolution or by the formation of corrosion products that can accumulate and cause serious problems in operation as clogging of pipelines and weakening of structures [2]. The importance of corrosion is well known and especially for steels that are widely used in engineering structures and are highly vulnerable to aggressive environments [3]. Corrosion can lead to degradation of infrastructures such as pipelines, storage systems and industrial equipment, and can cause serious failures.

I.1. Bacterial Corrosion:

Bacterial corrosion, also known as microbiologically influenced corrosion (MIC), is a form of material degradation resulting from the interaction of microorganisms, particularly bacteria, in metallic surfaces under certain environmental conditions [4][5]. It generally occurs in the presence of water, nutrients and suitable physicochemical conditions, in which microorganisms adhere to the surface of the material and form biofilms that modify the electrochemical reactions involved in corrosion [4].

These microbial activities can trigger or accelerate the corrosion processes already in progress by producing corrosive metabolites such as acids or sulfides, plus by creating differential aeration cells on the surface of the metal[4][5] .

As such, MIC results in localized corrosion forms like pitting corrosion, which are difficult to detect and can seriously impair the integrity of industrial systems, especially in aqueous and low-oxygen environments [5].



Figure I.1: Biochemical corrosion [6].

I.2 Microorganisms Involved in Biocorrosion:

Biocorrosion is mainly associated with the activity of different bacteria that interact with metal surfaces and alter electrochemical processes causing material degradation. Some of the major microbes involved are:

a) Sulfate reducing bacteria (SRB):

Sulfate reducing bacteria are anaerobic bacteria that use sulfate or other sulfur compounds as electron acceptors in their metabolism, and produce hydrogen sulfide (H_2S) as a by-product. They mainly metabolize organic substrates such as lactate, acetate and ethanol, and grow better under anoxic conditions, particularly in biofilms and in oil reservoir systems that are exposed to seawater input [7][8]. Sulfide generation is a major contributor to corrosion, accelerating metal degradation and forming corrosive compounds.

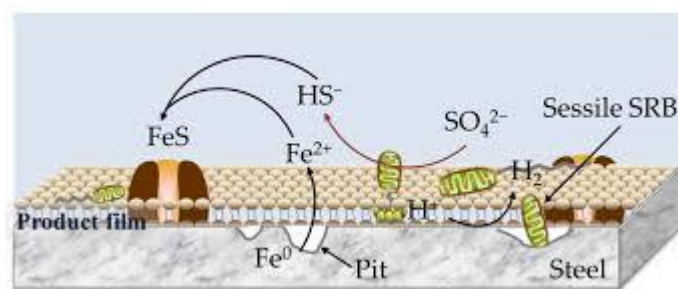


Figure I.2: Effect of Sulfate-Reducing Bacteria (SRB) on the Corrosion of Buried Pipe Steel in Acidic Soil Solution

b) Iron-Oxidizing Bacteria (IOB):

Iron-oxidizing bacteria are aerobic microbes that derive energy from the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) and generate insoluble iron hydroxides. These deposits form differential oxygen concentration cells on metallic surfaces which accelerate localized corrosion. They are also responsible for fouling and operational problems such as pipeline blockage. They are commonly found in aquatic natural and industrial environments [8].

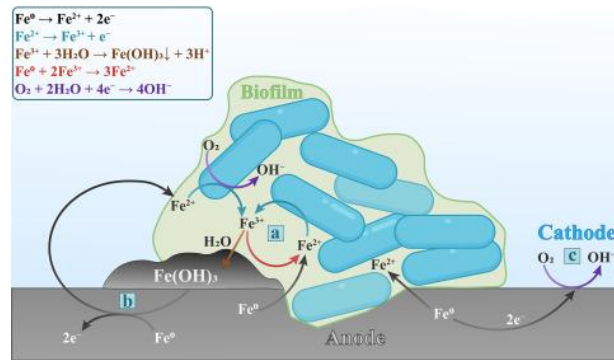


Figure I.3: Iron-Oxidizing Bacteria (IOB)

c) Acid-Producing Bacteria (APB):

Aerobic acid producing microorganisms usually produce organic acids by fermentation of organic matter. These acids lower the pH of the environment and favor the metal depolarization, therefore increasing the corrosion processes. Moreover, they feed other bacteria e.g. sulfate reducing bacteria (SRB), and therefore increase biocorrosion indirectly[9].

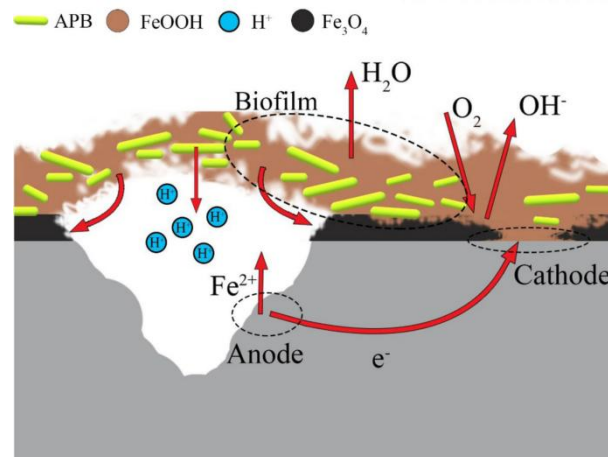


Figure I.4: Mechanistic Representation of Pitting Corrosion Induced by Acid-Producing Bacteria (APB) under Biofilm Formation [9].

I.3 Mechanisms of Biocorrosion in Pipeline:

The activity of microorganisms in certain conditions (for example, the availability of water, hydrocarbons and limited oxygen) is the main factor of biocorrosion in oil pipelines. These conditions promote the development of microbial communities that interact with the materials in pipelines, altering electrochemical reactions and accelerating corrosion processes[10] .

I.3.1 Formation of biofilms in pipelines:

Microorganisms can easily attach to the internal metal surfaces and produce biofilms of extracellular polymeric substances (EPS) in pipeline systems [10]. Biofilms trap water, nutrients and corrosion products, thus creating localized microenvironments that are different from the bulk fluid. This results in differential aeration conditions and encourages localized corrosion, especially in stagnant zones and low flow areas of pipelines [10][11].

I.3.2 Metabolic activity of microorganisms in the pipeline:

Microbial metabolites are corrosive and have a considerable impact on the integrity of metals [10]. In anaerobic zones, bacteria produce hydrogen sulfide (H_2S) which reacts with iron to form deposits of iron sulfide (FeS) leading to increased corrosion rates. In addition to this acid-producing bacteria produce organic acids that lower the local pH making the environment even more aggressive. These processes are highlighted in pipelines transporting hydrocarbons where nutrients are available [10][12].

I.3.3 Electrochemical Processes in Pipe Lines:

Microbial activity in pipelines modifies the anodic and cathodic reactions at the surface of the metal [13]. Electrochemical heterogeneity and localized galvanic cell formation are caused by the formation of deposits such as FeS and biofilms. These conditions increase the rate of electron transfer and encourage localized corrosion forms, like pitting, which are especially hazardous in pipeline systems due to their detection difficulty [13].

I.3.4 Corrosion by Sulfides:

The production of hydrogen sulfide by anaerobic bacteria in oil pipelines is one of the main causes of corrosion [10]. The formation of iron sulfide layers forms cathodic sites which leads to the formation of galvanic cells and thus accelerates the metal dissolution and causes severe localized corrosion.

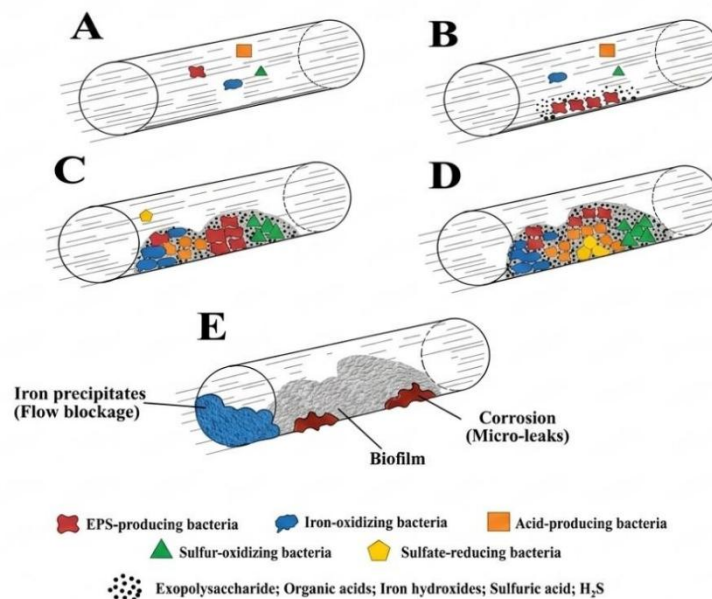


Figure I-5: Biorrosion process promoted by some types of corrosive bacteria[14]

Stage (A): Initial colonization and formation of a conditioning film

The process begins when aerobic bacteria from fresh water, sea water or industrial systems contact the surface of the pipeline. These microorganisms face a conditioning film of organic and inorganic material, which enables the first transition from a planktonic cell to a sessile community.

Stage (B): EPS secretion and biofilm maturation

Bacteria that produce EPS adhere to the pipe walls and produce an extracellular polymeric matrix. This EPS functions as a biological cement providing a stable environment for the attachment of secondary microbial communities.

Stage (C): Microbial growth and metabolic stratification

The matrix is populated by diverse groups of corrosive bacteria that form microcolonies and quickly deplete the available oxygen. The metabolic activity of IOB results in high accumulation of ferric precipitates. This can lead to blockage of flow. At the same time, SOB release sulfuric acid which starts to acidify the local environment.

Stage (D) Synergistic Acidification and Growth of SRB

The removal of oxygen and organic acids produced by APB create an ideal niche for SRB. The SRB produce hydrogen sulfide (H₂S) which causes a drastic reduction of pH and accelerates the electrochemical corrosion process at the metal interface.

Stage (E): Structural Failure and Loss of Function

In the last stage, sophisticated MIC with mature biofilm and iron precipitates impact the pipeline. Localized pitting causes partial flow obstruction and micro-leaks that compromise the structural integrity of the system.

I.4 Factors Affecting Biocorrosion:

The rate of biocorrosion in oil pipelines is governed by a number of environmental and operational factors which determine the growth and activity of microorganisms and the rate of electrochemical reactions at the metal surface [15][16].

Temperature : Temperature is a very important factor controlling the microbial activity . The majority of the microorganisms associated with corrosion have an optimal growth range of moderate temperature . The increase in temperature may increase the rate of metabolism up to a certain limit, and thus accelerate the corrosion processes in pipeline systems [15].

Ph: The pH of the medium has a significant effect on microbial populations and corrosion behaviour. Acidic conditions generally increase the rate of metal dissolution, while neutral to slightly alkaline conditions may favor the establishment of specific microbial communities involved in biocorrosion [16].

Availability of Nutrients : Presence of nutrients like organic compounds, hydrocarbons and sulfur containing substances promote the microbial growth. In oil pipelines, these compounds are energy sources for bacteria and thus stimulate biofilm formation and corrosion activity [15][16].

Presence of Water: Water is a basic requirement for biocorrosion as it provides the medium for microbial survival and electrochemical reactions. Water phases (free or emulsified) in pipelines provide favorable conditions for microbial colonization and initiation of corrosion [15].

Flow Conditions in Pipelines : The flow regime in a pipeline is an important factor in biocorrosion. Low flow or stagnation zones promote biofilm accumulation and microbial growth, although turbulent flow can remove deposits to some extent and induce localized shear stress, which can promote localized corrosion such as pitting [16].

Table I.1: Factors influencing corrosion

Nature of the metal	Nature of the environnement
Volatile corrosion products.	Polarization of electrodes
Solubility of products	Flow velocity of process steam
Nature of the surface film	Formation of oxygen concentration cell
Position of metals in EMF series	Conductance of the corroding medium
Overvoltage	Nature of dissolved gases, dissolved salts, pollutants, etc. Presence of suspended particles in atmosphere
Physical nature of the metal	Influence of pH
Purity of the metal	Impurities in water
Relative area of anodic and cathodic parts of the metal	Humidity of air
	Temperature range

I.5 Consequences of Biocorrosion in Oil Pipelines:

The microbial activity causes localized corrosion, forming deep pits and honeycomb-like structures on the metal surface [17][19].

Pipeline Leakage and Failure: Rapid localized corrosion can cause perforations and catastrophic structural failures [17][18].

Loss of Mechanical Strength: Bacterial metabolites can cause the degradation of metal integrity, thus reducing the overall durability of the infrastructure [18][19].

Economic Losses: The stoppages in the industry, replacement of equipment and environmental restoration cause large financial losses [17][22].

I.6 Detection and Monitoring of Biocorrosion:

Microbiological analysis: Identification and quantification of some corrosive species such as sulfate-reducing bacteria (SRB) from water and soil samples [20][21].

Method of weight loss The use of metal coupons to measure the rate of degradation of the material over a specified period of time [20].

Electrochemical Techniques: Electrochemical workstations for real-time measurements of corrosion currents and potentials [20][21].

Biofilm Analysis: Evaluating pipe interiors for presence of biological slime and microbial metabolites [21].

I.7 Biocorrosion Control and Regulation:

The use of biocides, such as glutaraldehyde, helps to control or eliminate harmful bacteria in pipeline systems [23][26].

Pigging Operations: Mechanical cleaning procedures are used to remove biofilms, deposits and accumulated debris from pipeline walls [22][24].

Corrosion Inhibitors: Industrial inhibitors and green ones such as botanical extracts are used to form protective layers on metal surfaces and reduce corrosion rates[25].

Continual Monitoring: For the integrity of pipelines, the regular monitoring with sensors, ultrasonic devices, and corrosion inspection techniques is essential[20][26].

Table I-2 : Methods used to control bacterial corrosion and how they work

Method	Examples	Mode of action
Physical	- Washing with brushes - Injection of air or gas - Manual cleaning	Removes physical deposits
Biocides	- Chlorine - Ozone - Bromine - Aldehydes - Acrolein - THPS	Prevention, inhibition or elimination of microorganisms.
Protective or antifouling coatings	- Silicones - Resins - Antifouling paints	Formation of a protective film
Corrosion inhibitors	1. Amines 2. Fatty acids 3. Phosphate esters 4. Ammonium nitrate	Formation of a protective film

References [27,28,29,30,31,32]

Conclusion:

In conclusion, biocorrosion is a serious industrial threat, resulting in fast and localized metal failure and huge economic losses [33][35]. Mitigation has to be proactive in order to be effective mainly through the use of tailor-made corrosion inhibitors providing a protective barrier on the metal surfaces [34]. Ultimately, the sustainability of petroleum infrastructure depends on the continuous awareness of environmental conditions and the selection of appropriate and sustainable prevention methods [33][35].

Chapter II:
Corrosion Inhibitors in Oil
Pipelines

II. Introduction:

Corrosion is a major problem in oilnments of water, dissolved salts, and corrosive gases. Such conditions speed up metal deterioration leading to equipment failure, leakage, and huge financial loss.

Corrosion inhibitors are widely employed as an efficient and realistic approach to counteract such effects. Ch-pipeline systems as a result of the interaction of the metals with the hostile enviroemical compounds are used in minimal proportions to treat the fluid in the pipes, creating a protective film on the metal surface and reducing the corrosion rate. This coating decreases the interaction of metal with the corrosive substances and slows down the electrochemical reactions.

Corrosion inhibitors are considered as a basic protection in the oil and gas industry as they are effective, flexible and economically feasible. Their performance is dependent on such factors as chemical composition, concentration, and compatibility with the environment in which they operate. It is essential to apply corrosion inhibitors to preserve pipeline integrity and extend their operational life[36_45].

II.1 Definition of Corrosion Inhibitors:

A corrosion inhibitor is a chemical substance or a mixture of substances that, when added in small amounts (generally from 1 to 15,000 ppm) to a corrosive environment, can prevent or slow down the deterioration of materials. Importantly, these substances achieve this protective effect without significant reactions with other components of the environment. They can be in the solid, liquid, or gaseous state and can be used in different media such as concrete, aqueous solutions and gaseous atmospheres, which leads to a wide range of applications [46][47][48].

II.2. Role and Mechanism[49]:

Such inhibitors are primarily employed as a “first line of defense” in industrial systems such as oil extraction, refining, and water treatment. They act by forming a film on the surface of the metal which protects the metal from contact with aggressive agents in the environment. For the inhibitor to be effective it must be able to reach the metal surface and either adsorb on the surface or react with the products of the electrochemical reaction. The adsorption may be Physical (Physisorption): It is based on weak Coulomb forces between inhibitor and metal atoms.

Chemical (Chemisorption) Strong chemical bonds are formed.

II.3 Industrial (Chemical) Inhibitors:

Inhibitors are important in industry to maintain the integrity of infrastructure such as pipelines. Music:

Organic Compounds: Modern industrial inhibitors of organic molecules with polar groups containing heteroatoms such as Nitrogen (N), Sulfur (S), Oxygen (O) and Phosphorus (P). The most common industrial compositions are amines, imidazolines and their salts. These nitrogen-containing compounds have a diphilic structure (colloidal cationic surfactants) and are capable of adsorbing as protective films in aggressive media such as those found in oil recovery[50_55].

II.3.1 Amines-based inhibitors:

Among the most widely used corrosion inhibitors are organic amines, which adsorb strongly on metal surfaces. The lone electron pair on the nitrogen atom in their molecular structure makes them able to react with the metal leading to the formation of a protective layer that limits the contact with corrosive species and reduces the corrosion rates



Figure II.1.Amines-based inhibitors Cyclohexylamine.

II.3.2 Phosphate-based inhibitors:

Phosphate compounds are predominantly anodic inhibitors. They react with metal ions at the surface to form insoluble phosphate layers that act as a barrier against further metal dissolution and corrosion processes

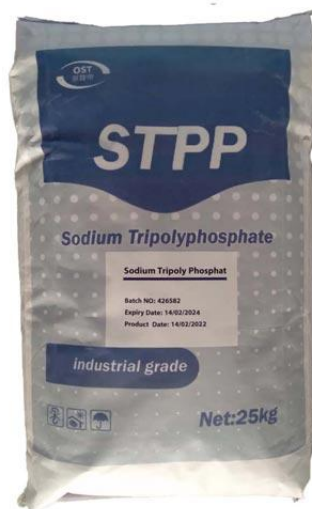


Figure II.2 Phosphate-based inhibitors Sodium Tripolyphosphate (STPP)

II.3.3 Zinc-based inhibitors:

Zinc salts are cathodic inhibitors since they react with the electrochemical reactions occurring at cathodic sites. In particular, zinc ions can react with hydroxide ions, forming insoluble compounds such as Zn(OH)_2 that deposit on the surface and decrease the overall corrosion rate

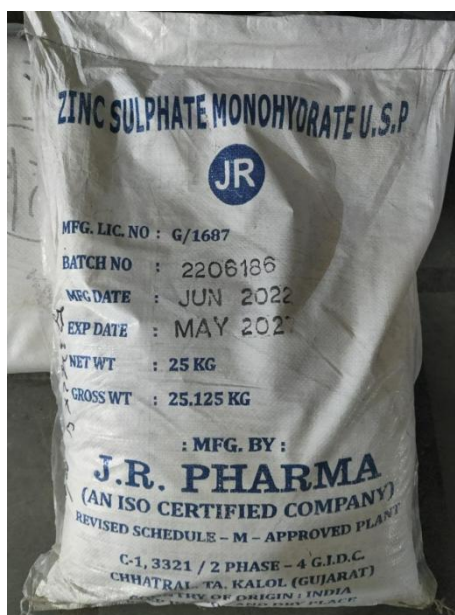


Figure II.3 Zinc-based inhibitors ZINC SULFATE MONOHYDRATE

II.3.4 Filming corrosion inhibitors:

Filming inhibitors are generally organic compounds which adsorb on the metal surface and form a continuous hydrophobic film. This film acts as a physical barrier against the penetration of aggressive species such as water, oxygen and dissolved ions .



Figure II.4 Filming corrosion inhibitors Octadecylamine (ODA)

II.4 Advantages and Limitations:

Industrial corrosion inhibitors are generally highly effective and provide rapid protection even at relatively low concentrations. However, their use may be associated with several drawbacks, including toxicity, environmental concerns, and relatively high operational costs, which limit their long-term sustainability

II.5 Natural (Green) Inhibitors:

Green corrosion inhibitors represent a sustainable and environmentally conscious alternative to traditional, often toxic, chemical treatments. These substances are primarily derived from renewable biological sources and are characterized by their low cost and high availability[56][57][58][59][60]

II.5.1 Leaves of rosemary:[61] [62] [63] [64]

II.5.1.1 Facility Description:

Rosemary is an aromatic evergreen herbaceous plant currently classified as a member of the genus *Salvia*, so it is sometimes referred to as *Salvia rosmarinus*. It grows in many areas and

requires full sun and well-drained soil. It is drought tolerant and is thought to be an easy plant to grow in the home garden.

II.5.1.2 Systematic Classification of the Plant:

- Scientific Name: *Rosmarinus officinalis*
- Family: *Salvia*
- Type: Herbaceous plant
- Appearance: Evergreen, woody shrub, with narrow, dark green leaves above, and silvery below, strong, fragrant fragrance.
- Flowers: Most bloom in spring and summer, light blue or purple



Figure II.5 Rosemary plant

II.5.1.3 Rosemary plant chemical composition:

Rosemary has many active chemicals that are responsible for its distinctive inhibitory properties.

The main components are Aromatherapy oils:

It constitutes 27 per cent of the dry weight of the plant. Its most important constituents are :

- Camphor: 5-21%
- Cineole (eucalyptol): 15-55% -1.8
- Borneol : 1.5-5% α -Pinene : 9-26% - Limonene : 1.5-5% - Pinene: 2-9% -- β

- Carnosol: Antioxidant, comprising 17%
- Carnosic acid: 30%
- Rosmarinic acid: 12%
- Ursolic acid: 6%
- Other compounds : 8%

The most effective of the chemical compounds mentioned in the components of rosemary against bacterial corrosion is : **Carnosic Acid**

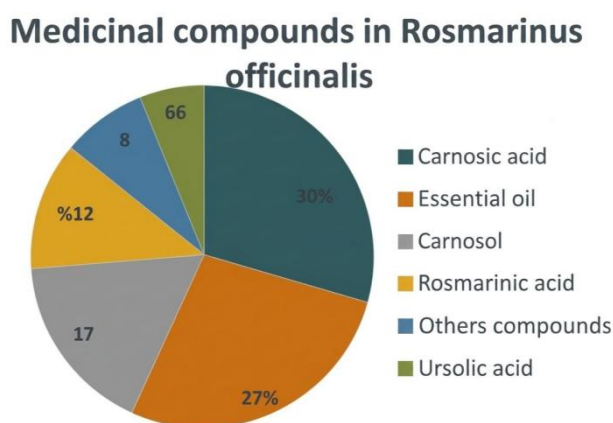


Figure II-6: Chemical components of rosemary [65]

II.5.1.4 Method of extraction of rosemary plant:

1- Harvesting rosemary plant material.

- Dry the material in the absence of light at a controlled temperature for preservation of active principles.

3- Pulverize the dried plant material into a fine powder using a clean, dry grinder or mill.

4-Weigh the powder.

- Add 100 ml of S2D MP separator water or oil for every 10 grams of plant powder

6-Put into a distillation vessel, to boil in a pot of water

7- The oil is then separated from the water and filtered through a separating funnel .

8-Store rosemary extract in a dark and tightly sealed bottle.



Figure II-7: Rosemary powder



Figure II-8 : Mixing rosemary powder in a magnetic stirrer



FigureII-9: Solution Filtration



Figure II-10 : Rosemary oil extraction process



Figure II-11 : Rosemary Ultimate Extract

II.5.1.5 Use of rosemary as bacterial corrosion inhibitor:

Scientific researches have proven Rosemary (*Rosmarinus officinalis*) to be a good inhibitor of corrosion of metals especially in acidic environments. This study reveals that the leaf of rosemary

The extracts and essential oils have mostly organic compounds like carnosic acid and carnosol, which are responsible for the formation of a protective layer on the metal surface and decrease the corrosion rate.

Rosemary has anti-bacterial properties. Research has shown that rosemary extracts containing carnosic acid and carnosol can inhibit the quorum sensing of *Staphylococcus aureus* bacteria, thus reducing their corrosion potential.

The studies were carried out on the plant rosemary:

- Rosemary leaf extract was studied for corrosion inhibitive property of mild steel in sulfuric acid solution in acidic medium . The inhibition efficiency was observed to increase with increase in extract concentration. - In a study of aluminum alloys, aluminum alloys (EN AW-2011) were used as a green corrosion inhibitor (acidic media) for aluminum alloys because the organic compounds present in the oil form a protective layer on the aluminum surface . - Rosemary oil as a corrosion inhibitor for steel in phosphoric acid Rosemary oil was found to be an effective corrosion inhibitor for steel in phosphoric acid with efficiency of up to 73% at the concentration of 10 g/L . - Study of the anticorrosive action of the essential oils of the rosemary and the myrtle on the corrosion of the copper in a sodium chloride medium The present study was carried out in Tunisia to assess the effect of essential rosemary and myrtle Eco-friendly inhibitors of copper corrosion in sodium chloride medium: oils. The results have showed that the essential oils could be used as effective corrosion inhibitors .

II.5.2 Oregano (*Origanum vulgare*)

II.5.2.1 Definition

Oregano is a perennial herb with an aromatic smell, belonging to the Lamiaceae or mint family, and native to the Mediterranean region. It is now grown throughout the world. It grows to about 60-90 cm tall, with erect, branching stems, ovate to oblong leaves (1-4 cm long) and small white to purplish flowers in terminal corymbose clusters. The leaves of the plant are rich in essential oils, this makes the plant strongly aromatic and it is used in the cuisine, folk medicine, as antioxidant, and antimicrobial agent.[66_74]

II.5.2.2 Systematic Classification:

Scientific Name: *Origanum vulgare*

Family: Lamiaceae

Type: Perennial herb

Appearance: Small green leaves with strong aromatic scent

Flowers: Purple to pink clustered flowers



Figure II-12: Origanum plant

II.5.2.3 Chemical Composition[75_85]:

Oregano contains a rich profile of essential oils and phenolic compounds:

5. Carvacrol: 40–70%
6. Thymol: 0–25%
7. p-Cymene: 5–15%
8. γ -Terpinene: 5–10%
9. Flavonoids: 3–7%
10. Other compounds: 5–10%

Carvacrol and thymol are the most active compounds responsible for corrosion inhibition.

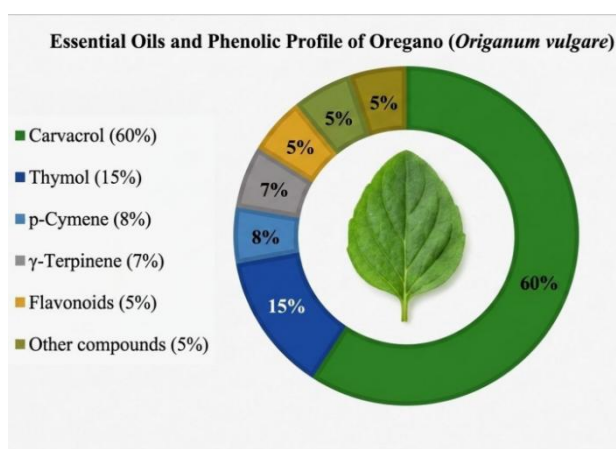


Figure II-13 :Chemical components of Oregano plant

II.5.2.4 Methods of Extraction

Steam distillation (hydrodistillation) Fresh or dried aerial parts are subjected to steam distillation. The essential oil contains large amounts of carvacrol and thymol.

Solvent extraction: Dried leaves can be extracted with ethanol or methanol to obtain polyphenol rich extracts, which are mostly used for antioxidant and antimicrobial studies.

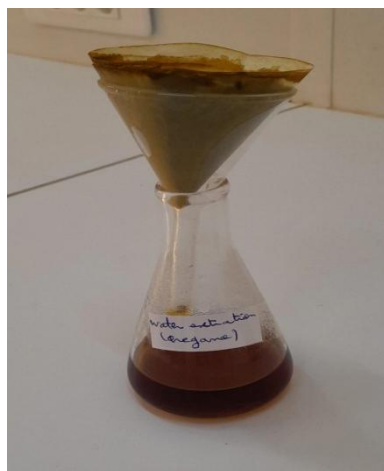
Supercritical fluid extraction (SFE) with CO₂ has also been employed to obtain higher-purity oils and lipid-soluble compounds, although it is less common on a small scale.



Figure II-14: Oregano powder



Figure II-15: Mixing Oregano powder in a magnetic stirrer



FigureII-15: Solution Filtration



Figure II-17: Oregano oil extraction process

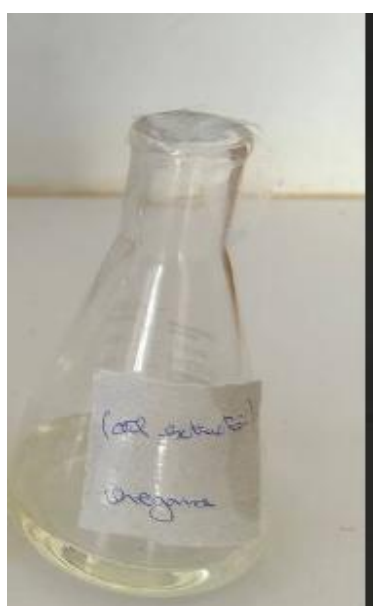


Figure II-18: Oregano Ultimate Extract

II.5.2.5 Use as Corrosion Inhibitor[86_96]:

Several studies confirm that oregano essential oil acts as an efficient green corrosion inhibitor, especially for steel and copper in acidic and saline environments. The active compounds adsorb on the metal surface and form a protective hydrophobic layer.

II.5.3 Neem leaf[94_112].

II.5.3.1 General description

Neem is a fast-growing evergreen tree of the mahogany family (Meliaceae) which is extensively cultivated in tropical and subtropical Asia, Africa and the Middle East. The tree grows to 15–20 m high, with pinnate leaves, small white flowers in fragrant clusters and olive-like fruit. The neem leaves are glabrous, dark green, lanceolate-ovate, strongly aromatic and traditionally used for their insecticidal, antimicrobial, anti-inflammatory and anti-diabetic properties.

II.5.3.2 Systematic Classification of the Plant:

Division: Tracheophyta Class: Magnoliopsida Order Sapindales Family: Meliaceae Genus: *Azadirachta* Species: *Azadirachta indica* A. Juss.



Figure II-19: Neem plant

II.5.3.3 Chemical Composition:

Neem leaves have a complex mixture of primary and secondary metabolites:

- Liminoids (triterpenoid tetranortriterpenes) such as azadirachtin, nimboesterol, nimbin and their derivatives responsible for the insecticidal and growth regulating effects.

Flavonoids and polyphenols like quercetin that provide antioxidant and anti-inflammatory activities.

- Leaf extracts have also been reported to contain alkaloids, tannins, saponins, glycosides and terpenes.
- Neem leaves essential oil is rich in sesquiterpene-type compounds, and exhibits antifungal activity.

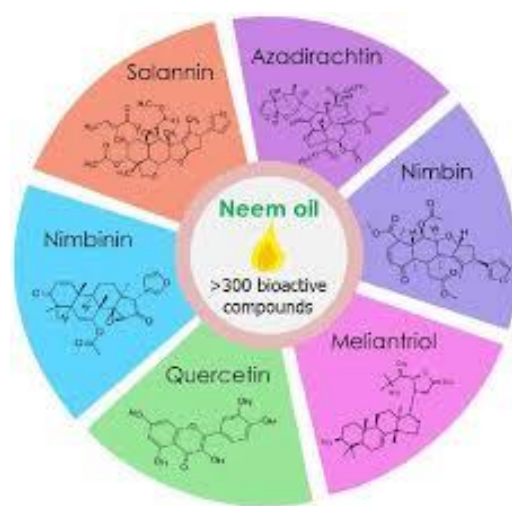


Figure II-20: Chemical components of Neem plant

Extraction techniques

Solvent extraction (maceration or Soxhlet) Dried ground leaves are usually extracted with solvents such as ethanol, methanol or n-hexane to obtain total crude extracts containing limonoids, flavonoids and terpenes.

Steam distillation: Fresh or dried leaves are hydrodistilled to obtain essential oil; yields are usually low (around 0.1–0.6 wt%).

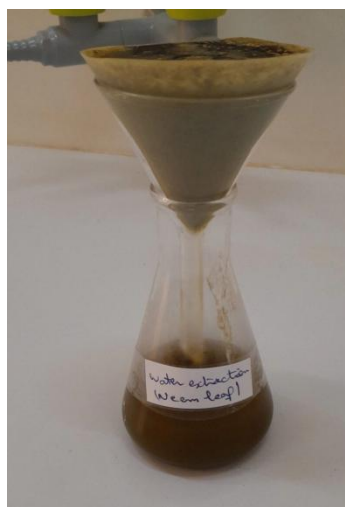
Hydrodistillation has been the most common method used for extraction of essential oils from different aromatic plants. This method has shown to give higher oil yields (up to ~0.6 wt%) in comparison to supercritical fluid extraction (SFE) with CO₂ and is considered more environmentally friendly.



Figure II-21: Neem powder



Figure II-22: Mixing Neem powder in a magnetic stirrer



FigureII-23: Solution Filtration



Figure II-24 :Neem oil extraction process



Figure II-25 : Neem Ultimate Extract

Conclusion:

Comparison of industrial and natural corrosion inhibitors shows different merits and limitations by class. Industrial Inhibitors Generally Provide High efficiency, repeatable performance and capability to operate under a wide range of environmental conditions. However, natural inhibitors extracted from plant or biological origins offer environmentally friendly options with biodegradability and low toxicity.

The selection among these options will depend on operational requirements, environmental impact assessments, cost considerations and compliance with regulatory norms. A thorough assessment of these factors provides the best and longest-lasting corrosion prevention in a variety of industrial

Chapter III:
Bacterial Corrosion Problem
in HBK

III.1 Introduction:

The Saharan Platform, located in southern Algeria, forms part of the North African Craton. It consists of a Precambrian basement unconformably overlain by a thick sedimentary cover. During the Paleozoic era, this platform was structured into several sedimentary basins separated by structural highs.

The Haoud Berkaoui (HBK) oil field is situated in the northern Algerian Sahara and represents one of the key hydrocarbon-producing zones in the region. It covers an area of approximately 6,300 km², with estimated reserves of 347.5×10^6 m³. Geologically, it belongs to a complex structural system forming the northern extension of the Triassic province [113].

III.1.1 Problem of Bacterial Corrosion in HBK:

Microbially influenced corrosion (MIC) presents a significant operational challenge in HBK facilities. It leads to pipeline perforation, leakage, and production interruptions. This phenomenon is complex and is mainly associated with the presence of salts (NaCl), hydrogen sulfide (H₂S), and carbon dioxide (CO₂), combined with favorable environmental and operational conditions.

III.1.2 Mechanisms of Bacterial Corrosion:

Certain microorganisms accelerate corrosion through metabolic activity:

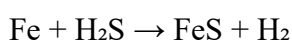
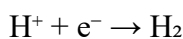
Sulfate-Reducing Bacteria (SRB)

These bacteria reduce sulfate into hydrogen sulfide (H₂S), which strongly promotes corrosion.

Anodic reaction:



Cathodic reactions:



Effect of NaCl

Sodium chloride significantly increases corrosion rates by:

Enhancing electrolyte conductivity

Promoting aggressive corrosive environments at concentrations up to ~5%

Influencing protective scale formation (FeCO_3), where Mg^{2+} may inhibit and Ca^{2+} may accelerate scale development

III.1.3 Corrosion in Surface Installations:

Corrosion impact is generally limited in stainless steel components such as tubing and wellheads. However, carbon steel systems are highly vulnerable, especially in:

- Surface well equipment exposed to turbulence and erosion-corrosion
- Manifolds subjected to multiphase flow
- Collectors carrying produced fluids with high water cut
- The presence of H_2S , CO_2 , and chloride-rich water significantly increases degradation rates.



Figure III-1: Corrosion Of above-Ground Production Installations

III.1.4 MIC in Buried Pipelines:

Buried pipelines are highly susceptible to MIC due to soil conditions. Major causes include:

Formation of electrochemical cells due to soil heterogeneity

Chemical contamination from industrial or drilling activities

Galvanic coupling between protected and unprotected pipelines

This leads to localized and accelerated corrosion in underground systems [95][96].



Figure III-2 : Bacterial corrosion of pipes

III.2 Detection and Inspection of MIC:

MIC monitoring in HBK relies on integrated techniques combining microbiological, chemical, and physical methods:

Microbiological sampling and analysis

Soil and water testing

Non-destructive testing (UT, eddy current)

Corrosion rate sensors

Electrochemical monitoring

X-ray fluorescence (XRF) analysis

Visual inspection and thickness measurements



Figure III-3 :Perforation Level of 4" pipe

III.3 Mitigation of Bacterial Corrosion:

To control MIC, HBK implements combined mitigation strategies:

- Chemical injection of corrosion inhibitors (e.g., ALPHA175INT)
- Use of biocides such as glutaraldehyde and THPS
- Mechanical cleaning using pipeline pigs.
- Cathodic protection systems
- Maintenance of internal and external coatings

III.3.1 Chemical Products Used:

Prochinor AP104: demulsifier improving oil-water separation and reducing corrosion risk [113][114].

Chimec 2935: antiparaffin agent preventing wax deposition [115].

MC MX 6-3116: film-forming corrosion inhibitor effective against MIC and acid gas corrosion [116].

CORR21154A: inhibitor for saline and acidic environments with MIC resistance [117].

III.3.2 Physical and chemical properties of inhibitors prochinor AP104,

Chimec2935, ALPHA 175INT , MX 6-3116 :

III.3.3 Injection of chemical product in oil facilities :



Figure III-4 : ALPHA 175INT injection Device

Conclusion

The Haoud Berkaoui field represents a complex operational environment where corrosion phenomena are influenced by multiple interacting factors, including microbial activity, salinity, gas composition, and environmental conditions.

The study highlights that corrosion in this field is multifactorial and difficult to control without integrated management strategies. Therefore, effective mitigation requires continuous monitoring, advanced chemical treatment, and robust maintenance programs. The combination of industrial practices and technological innovation is essential to ensure asset integrity and extend the operational life of production facilities in the HBK region.

Chapter IV:
Electrochemical Study of the
Inhibitors

IV.1 Experimental Products and Procedures:

The products used:

Steel X52 :was rolled into discs of diameter 1 cm and thickness 1 cm, cut into squares with a saw and welded to copper conductors and covered with thermosetting resin. Resin mold is plastic. Leave the mold open for 24 hours for the resin to harden. Before use, the working electrode should be polished on the working surface with low-grit silicon carbide sandpaper under running water. degrease with acetone and distilled water after polishing

Table IV-1: Chemical composition (in %) of X52 steel:

Chemical Composition %							
C	Mn	P	S	Si	V	Nb	Ti
≤ 0.28	≤ 1.40	≤ 0.030	≤ 0.030	0.15–0.45	≤ 0.10	≤ 0.05	≤ 0.04

Corrosive environment: a sample of HBK suparator water taken from suparator MP S2D, with a salinity of 1.69 g/L and pH of 5.66 and Fe 2+ of 258 mg/L.



Figure IV-1 : Corrosive environment (HBK suparator water)

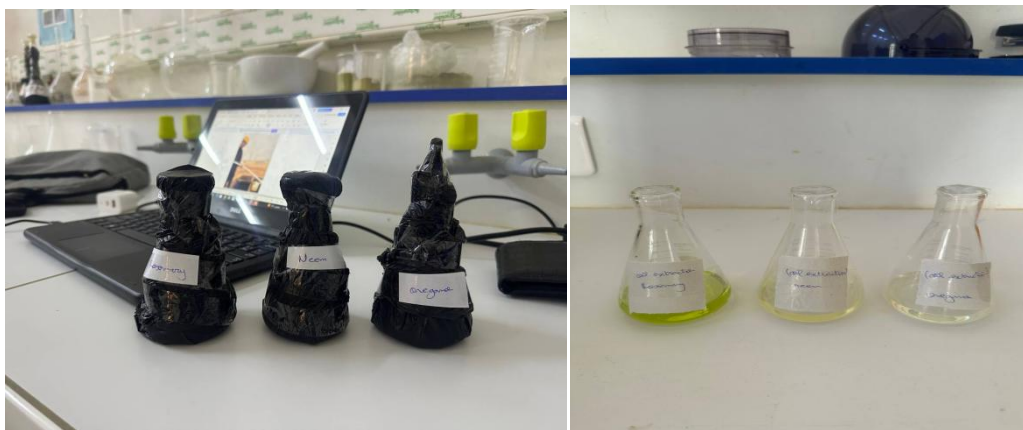


Figure IV-2: Plants Extract

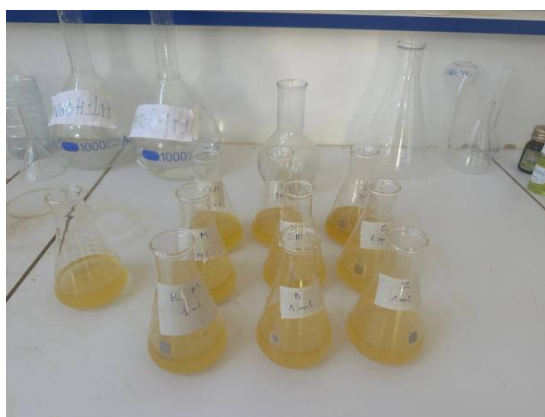


Figure IV-3: Corrosive Solutions with Oil and Aqueous Extracts



Figure IV-4 Microscope

IV.2 Weight-loss method

A complementary gravimetric (weight-loss) study was conducted to evaluate the corrosion behaviour of API 5L X52 steel in a simulated Haoud-Berkaoui (HBK) produced-water medium, both in the absence and in the presence of natural plant-derived inhibitors. The weight-loss method was selected because it provides a direct, integral measure of the total metal consumed over an extended exposure period, and it remains the reference technique for validating the trends observed by instantaneous electrochemical measurements. Mass measurements were performed after 24 h, 48 h and 72 h of immersion at a controlled temperature of 30 °C, reproducing the thermal conditions of the HBK separator water.

The corrosive medium was the HBK separator water (MP S2D) characterised by a salinity of 1.69 g/L, a pH of 5.66 and a ferrous-iron content of 258 mg/L, inoculated with sulfate-reducing bacteria (SRB) to reproduce the microbiologically influenced corrosion (MIC) conditions prevailing in the field. Seven coupons were examined: three oil extracts, three aqueous extracts, and one inhibitor-free blank used as the reference for the calculation of the inhibition efficiency.

IV.2.1 Sample Identification

To allow an unambiguous interpretation of the results, the seven X52 coupons are identified in Table IV-2 according to the nature of the inhibitor added to the 60 mL of corrosive medium. Samples A1–A3 correspond to the oil (hydrophobic) extracts, samples A4–A6 to the aqueous extracts, while A7 is the uninhibited blank used as the corrosion reference.

IV.2.2 Weight Evolution of the X52 Steel Coupons

The masses of the seven coupons were recorded before immersion and after each exposure interval. The corrected data set is reported in Table IV-3. The value of sample A5 (neem aqueous extract) at 72 h has been corrected with respect to the raw laboratory record for the reasons detailed in Section IV.5.

Table IV-2: Weight evolution of X52 steel samples (corrected)

Sample	Before (g)	After 24 h (g)	After 48 h (g)	After 72 h (g)
A1	3.5018	3.5018	3.5016	3.5013
A2	4.9984	4.9984	4.9982	4.9976
A3	3.9811	3.9811	3.9810	3.9809
A4	3.3700	3.3695	3.3678	3.3676
A5 *	3.7562	3.7560	3.7537	3.7528
A6	3.0257	3.0255	3.0250	3.0250
A7	2.8548	2.8538	2.8521	2.8508

IV.2.3 Quantitative Corrosion Parameters

Three quantitative descriptors were derived from the gravimetric data to characterise the corrosion process and to rank the inhibitors: the cumulative weight loss, the corrosion rate, and the inhibition efficiency.

IV.2.3.1 Weight loss

For each coupon and each exposure time, the cumulative weight loss is the difference between the initial mass and the mass measured after immersion:

$$\Delta W = W_0 - W_t$$

where W_0 is the initial mass (g) and W_t the mass (g) after exposure time t .

IV.2.3.2 Corrosion rate

The corrosion rate was expressed in millimetres per year (mm/yr) using the standard relation:

$$CR = (K \times \Delta W) / (A \times t \times \rho)$$

where $K = 8.76 \times 10^4$ is the unit-conversion constant for mm/yr, ΔW is the weight loss (g), A is the exposed coupon area (cm^2), t is the exposure time (h) and $\rho = 7.85 \text{ g/cm}^3$ is the density of carbon steel. An exposed area $A = 2.0 \text{ cm}^2$ was adopted for the X52 coupons.

IV.2.3.3 Inhibition efficiency and surface coverage

The inhibition efficiency IE (%) quantifies the protection conferred by each extract relative to the uninhibited blank (A7):

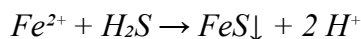
$$IE (\%) = [(CR_{\text{blank}} - CR_{\text{inh}}) / CR_{\text{blank}}] \times 100$$

The fractional surface coverage of the adsorbed inhibitor film is $\theta = IE / 100$, an indicator of the proportion of the metal surface effectively shielded by the protective layer.

IV.3 Microscopic Evidence of Antibacterial Efficacy:

IV.3.1. Introduction

Sulfate-reducing bacteria (SRB) are the principal microbial agents responsible for microbiologically influenced corrosion (MIC) of carbon steel in anaerobic aquatic environments such as oilfield produced waters, ballast tanks and water-injection systems. Their dissimilatory metabolism reduces sulfate to hydrogen sulfide, which reacts with dissolved ferrous ions according to



to produce a characteristic black ferrous-sulfide deposit. Beyond the direct chemical attack by HS^- , biogenic sulfide acidifies the local environment, depolarises the steel cathode, and creates the conditions for cathodic depolarisation and direct extracellular electron transfer between the metal substrate and the SRB consortium. These mechanisms operate almost exclusively within sessile biofilm aggregates, where local concentrations of metabolic intermediates can be orders of magnitude higher than in the bulk medium. The control of SRB-driven corrosion therefore requires the simultaneous suppression of planktonic growth and of biofilm establishment, the latter being the more critical of the two.

The progressive restrictions imposed on synthetic biocides — notably glutaraldehyde, tetrakis(hydroxymethyl)phosphonium sulfate (THPS) and quaternary ammonium compounds — for reasons of aquatic toxicity, regulatory compliance and bacterial resistance have stimulated active research on natural plant-derived alternatives. Rosemary (*Rosmarinus officinalis*), neem (*Azadirachta indica*) and oregano (*Origanum vulgare*) have been identified in the literature as promising candidates owing to their content of antimicrobial diterpenoids, limonoids and phenolic monoterpenes. The relative efficacy of these candidates, however, depends critically on the extraction solvent: lipophilic bioactive compounds such as carnosic acid, carvacrol, thymol and azadirachtin are efficiently recovered into vegetable-oil carriers, while aqueous extracts retain only polar derivatives of these compounds whose antibacterial potency is generally lower.

The present section reports the optical-microscopy evaluation of the antibacterial and antibiofilm activity of six such natural extracts against an SRB culture, and the systematic correlation of these visual data with the gravimetric inhibition efficiency obtained in parallel on X52 steel coupons. The combined approach provides a rigorous, multi-method validation of the antimicrobial ranking and identifies oregano essential oil as the most effective natural inhibitor of the series.

IV.3.2 Objectives

The specific objectives of the microscopic investigation were:

- To document the bacterial density, biofilm aggregate morphology and FeS precipitation pattern in each of the seven culture conditions after 72 h of incubation;
- To establish a semi-quantitative visual scoring of the three microscopic indicators (cell density, biofilm, FeS) and to test its statistical correlation with the gravimetric inhibition efficiency;
- To interpret the observed differences mechanistically in terms of (i) the chemical nature of the bioactive compounds, (ii) the partition behaviour of these compounds between oil and aqueous phases, and (iii) the resulting capacity to disrupt the planktonic and sessile phases of SRB populations;
- To rank the six extracts in order of antibacterial / anti-corrosion efficacy and to identify the most promising candidate for further development.

IV.3.3 Materials and Methods

IV.3.3.1 Bacterial culture and growth medium

A mixed sulfate-reducing bacterial consortium isolated from production-water of the Haoud-Berkaoui field was maintained in modified Postgate B medium of the following composition (g L^{-1}): KH_2PO_4 0.5; NH_4Cl 1.0; $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ 1.0; $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2.0; sodium lactate 3.5; yeast extract 1.0; $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 0.5; sodium thioglycolate 0.1; ascorbic acid 0.1; resazurin 1 mg L^{-1} . The pH was adjusted to 7.5 ± 0.1 with 1 M NaOH and the medium was sterilised at 121°C for 20 min. Strict anaerobic conditions were maintained throughout the procedure: the medium was boiled, cooled and dispensed under a continuous N_2/CO_2 (80/20) atmosphere, the colour of the resazurin indicator (pink $\rightarrow$ colourless) confirming the establishment and persistence of the anaerobic state. Each Erlenmeyer flask received 100 mL of medium and was inoculated with 2 mL of an actively growing pre-culture ($\approx 10^7 \text{ cells mL}^{-1}$).

IV.3.3.2 Preparation and addition of the natural inhibitors

Six natural inhibitors were tested in parallel, supplemented to the inoculated medium at a single nominal dose of 2 mL (corresponding to 2 % v/v):

IV.3.3.3 Incubation and sampling

The flasks were sealed with rubber stoppers and aluminium crimps and incubated at 30 ± 1 °C in a static atmosphere for 72 h. At the end of the incubation period, the macroscopic state of each flask was recorded (medium colour, turbidity, presence of black FeS precipitate, sediment), and three 1-mL aliquots were withdrawn aseptically for microscopic observation.

IV.3.3.4 Crystal-violet staining and optical microscopy

A 20 μ L droplet of each aliquot was deposited on a clean microscope slide, heat-fixed at 60 °C for 2 min, and stained with 0.5 % w/v crystal-violet solution for 1 min, rinsed twice with deionised water, blotted dry and mounted in immersion oil. Observations were carried out with an upright optical microscope equipped with achromatic objectives ($\times 40$ and $\times 100$, the latter with oil immersion) and a 5-megapixel digital camera. Three independent fields per condition were imaged at $\times 400$ (overall density assessment) and three additional fields at $\times 1000$ (biofilm morphology), totalling 42 micrographs.

IV.3.4 Conclusion

The optical-microscopy evaluation of six natural plant extracts against a sulfate-reducing bacterial consortium, conducted in parallel with a gravimetric corrosion study on X52 steel, has established the following conclusions:

- Crystal-violet staining followed by observation at $\times 400$ and $\times 1000$ provides a fast, low-cost and discriminating screening of the antibacterial / antibiofilm activity of natural inhibitors against SRB, fully consistent with the much slower gravimetric weight-loss procedure.
- A very strong inverse linear correlation (Pearson $r = -0.986$, $R^2 = 0.972$) is established between the mean microscopic visual density score and the gravimetric inhibition efficiency, validating the use of optical microscopy as a quantitative screening tool.
- Oregano essential oil (A3) is the most effective of the six extracts tested, achieving an inhibition efficiency of 95.0 %, a corrosion rate reduced 20-fold relative to the inhibitor-free control, and complete eradication of the biofilm aggregates. Its activity is attributed to

the membrane-targeting action of carvacrol and thymol coupled to the formation of a hydrophobic protective film at the steel surface.

- Rosemary essential oil (A1, IE = 87.5 %), oregano aqueous extract (A6, IE = 82.5 %) and neem essential oil (A2, IE = 80.0 %) produce similarly high efficiencies through complementary mechanisms.
- The oregano aqueous extract (A6) is a noteworthy exception to the general "oil-better-than-aqueous" rule and offers an industrially attractive option, combining good antibacterial performance with an environmentally and economically favourable formulation.
- The aqueous extracts of rosemary (A4, 40 %) and especially of neem (A5, 15 %) are inadequate as stand-alone inhibitors, the latter being almost indistinguishable from the inhibitor-free control in both visual and gravimetric data.
- In the SRB system, the antibiofilm action is the controlling parameter of corrosion inhibition, more so than the antiplanktonic action; screening protocols for new natural inhibitors should therefore concentrate on the suppression of biofilm aggregate formation rather than on the reduction of free-swimming cells.

The final efficiency ranking established jointly by the microscopic and gravimetric methods is:

A3 (95.0 %) > A1 (87.5 %) > A6 (82.5 %) > A2 (80.0 %) > A4 (40.0 %) > A5 (15.0 %)

and identifies oregano essential oil as the most promising natural inhibitor for the mitigation of microbiologically influenced corrosion of carbon steel in SRB-laden produced waters.

IV.4 Economic Feasibility of Plant-Derived Bio-Inhibitors for SRB Corrosion Control in Oil-Field Pipelines

This industrial economic feasibility report evaluates the possibility of producing plant-derived bio-inhibitors for controlling sulfate-reducing bacteria (SRB) and reducing microbiologically influenced corrosion (MIC) in API 5L X52 oil-field pipelines at the Haoud-Berkaoui (HBK) field. The proposed inhibitors are based on rosemary, oregano, and neem oils. The technical foundation of the project comes from experimental results showing strong inhibition performance: oregano oil achieved 95.0% inhibition efficiency, rosemary oil 87.5%, and neem oil 80.0% against SRB-induced corrosion. The report combines these technical results with an engineering-economic assessment covering capital costs, operating costs, profitability, sensitivity, scale-up strategy, environmental impact, and risk management. All values are presented in US dollars, with an indicative exchange rate of 1 US\$ $\approx$ 135 DZD.

The proposed local-production facility requires an estimated capital expenditure (CAPEX) of about US\$320,100, equivalent to approximately 43.2 million DZD. The largest investment item is the extraction system, including steam-distillation and cold-press equipment, costing US\$95,000 and representing 29.7% of total CAPEX. Other major costs include the quality-control laboratory at US\$38,000, utilities infrastructure at US\$34,000, buildings and civil works at US\$30,000, land preparation and first cultivation cycle at US\$28,000, storage tanks at US\$26,000, formulation equipment at US\$22,000, and safety systems at US\$18,000. A 10% contingency of US\$29,100 is also included. The report considers this total capital requirement modest by oil-field industrial standards, which supports the attractiveness of the project.

The annual operating expenditure (OPEX) at the design capacity of approximately 3,000 liters per year is estimated at US\$215,530, or about 29.1 million DZD. Raw materials are the dominant operating cost, reaching US\$96,000 per year and representing 44.5% of total OPEX. This is mainly due to the low essential-oil yield of herbs, estimated at around 1.5% by weight. Labour is the second-largest cost, at US\$54,000 per year, or 25.1% of OPEX. Utilities cost US\$23,000 annually, while quality-control operations, overheads, transportation, waste management, and maintenance make up the rest. The cost structure shows that project profitability depends strongly on securing affordable biomass and improving extraction yield.

The profitability analysis is based mainly on avoided corrosion costs, reduced repair and maintenance, reduced downtime, and replacement of synthetic biocides. The annual economic value created by the project is estimated at US\$685,000, including US\$650,000 in avoided corrosion-related costs and US\$35,000 from by-product revenue such as hydrosol and spent biomass. After subtracting annual OPEX, the project generates a gross profit of US\$469,470 per year. Depreciation is calculated on a straight-line basis over ten years at about US\$32,010 per year, resulting in a pre-tax net profit of approximately US\$437,460 per year. The annual operating cash flow used in the discounted-cash-flow analysis is US\$469,470.

The break-even analysis confirms that the project has a large safety margin. The break-even deployment volume is estimated at approximately 824 liters per year, while the planned production capacity is 3,000 liters per year. This means the facility would operate at about 3.6 times its break-even volume. The value per liter is estimated at US\$228.3, while variable cost is about US\$27.3 per liter. This margin indicates that the project can remain profitable even if demand or value creation is lower than expected.

Over a ten-year horizon and using a 12% discount rate, the discounted-cash-flow analysis gives highly favorable investment indicators. The net present value (NPV) is approximately US\$2.33

million, the internal rate of return (IRR) is around 146.6%, the profitability index is about 8.29, and the accounting return on investment is around 137% per year. The simple payback period is approximately 0.68 years, or about 8.2 months, while the discounted payback period is approximately 0.76 years, or about 9.1 months. These indicators suggest that the project is financially attractive, but the report stresses that the results depend strongly on the assumed corrosion-saving benefit.

The sensitivity analysis identifies the corrosion-saving benefit as the most important driver of project value. A $\pm 30\%$ change in corrosion-saving benefit changes the NPV from US\$1.353 million to US\$3.313 million, compared with the base case of US\$2.333 million. Other important variables include extraction yield, market demand, treatment efficiency, and raw-material price. Energy cost has the smallest impact. Importantly, the NPV remains positive under all tested adverse scenarios, remaining above US\$1.3 million even in the weakest case. This suggests that the project is economically robust, although field validation remains essential.

The report proposes a phased industrial scale-up strategy. The first phase is a pilot-scale implementation using ready-made oregano oil purchased from the market and applied to a selected HBK pipeline section through existing chemical-injection points. This pilot would use corrosion coupons and electrochemical probes to confirm real field performance under actual flow, temperature, and pressure conditions. The estimated pilot CAPEX is around US\$45,000. The second phase is a demonstration-scale extraction unit producing several hundred liters per year from contract-farmed biomass. This phase would test agronomic supply, extraction yield, product consistency, and local production costs. The final phase is full industrial deployment, with a facility producing around 3,000 liters per year to serve HBK and potentially other Sonatrach fields. Capacity could later be expanded by adding modular distillation trains.

The proposed supply chain connects contract farms, drying and collection, central extraction, quality control and formulation, distribution, and application in HBK/Sonatrach fields. The agricultural layout includes approximately 65 hectares, with oregano occupying around 33 hectares, rosemary around 28 hectares, neem around 4 hectares, and additional space for extraction, quality control, storage, utilities, safety systems, access roads, irrigation, and firebreak buffers. The production workflow includes cultivation and harvest, drying and preparation, steam distillation or cold pressing, crude essential-oil separation, by-product recovery, GC-MS quality verification, formulation, storage, and field injection. A key operational constraint is that producing one liter of oregano oil at 1.5% yield requires around

67 kg of dried herb, making yield optimization and by-product valorization central to the project.

Compared with conventional biocides, plant oils are more expensive on a direct efficiency-adjusted cost basis. Synthetic biocides such as glutaraldehyde and THPS remain cheaper, while neem oil appears more competitive than oregano and rosemary. However, the report argues that the higher cost of oregano and rosemary is partly justified by their better environmental and safety profile, lower toxicity, biodegradability, and potential reduction in regulatory and compliance costs. The environmental assessment highlights several benefits: reduced use of toxic chemicals, lower pollution risk, alignment with green chemistry principles, valorization of hydrosol and spent biomass, and contribution to Sustainable Development Goals related to responsible production, industry and innovation, local employment, and life on land.

The main risks are technical, economic, supply-chain, regulatory, and market-related. The most serious risk is economic: the possibility that the real field corrosion-saving benefit is lower than the model assumes. Other risks include reduced field efficiency compared with laboratory results, variable extraction yield, biomass shortage or price volatility, regulatory approval for a new oil-field chemical, and dependence on Sonatrach as a single major buyer. The proposed mitigation measures include pilot validation, dosage optimization, monitoring, process optimization, chemotype selection, conservative financial assumptions, phased deployment, contract farming, multiple biomass sources, buffer stocks, early regulatory engagement, and long-term off-take agreements.

Overall, the report concludes that plant-derived bio-inhibitors are technically feasible, economically viable, environmentally sustainable, and industrially scalable for SRB control and corrosion mitigation in oil and gas pipelines. The project shows strong financial indicators, including low CAPEX, high NPV, high IRR, a profitability index far above one, and payback in less than one year. However, before investment, the report recommends confirmatory field trials and a detailed front-end engineering design. If field results confirm the expected corrosion-saving benefit, the technology could provide an effective alternative to conventional synthetic biocides while supporting industrial performance, environmental protection, and local value creation.

Project Website and Digital Access

Website link:

<https://bsp-cost-study.netlify.app/>

QR Code:



Website link:

<https://bio-inibitors-mechanism.netlify.app/>

QR Code:

BSP امسحني للدراسة الاقتصادية



General Conclusion

General Conclusion:

This study was carried out to address the problem of microbiologically influenced corrosion of pipeline steel caused by sulfate-reducing bacteria in the produced water of the Haoud-Berkaoui field. The main objective was to evaluate the ability of natural plant extracts to inhibit bacterial corrosion under conditions close to those encountered in the field and to assess their potential as sustainable alternatives to synthetic chemical inhibitors.

The work began with a theoretical examination of biocorrosion and the role of sulfate-reducing bacteria in the deterioration of steel pipelines. It also reviewed the main types of corrosion inhibitors and presented the selected natural sources, namely rosemary, oregano, and neem. The corrosion situation in the Haoud-Berkaoui installations was then discussed in order to link the theoretical background to the industrial context of the study. Finally, an experimental investigation was conducted using API 5L X52 steel coupons immersed in sulfate-reducing bacteria-inoculated separator water. The protective effect of three oil-based extracts and three aqueous extracts was evaluated by the weight-loss method and supported by microscopic observation of bacterial cultures.

The experimental results showed that oil-based extracts were generally more effective than aqueous extracts. Among all the tested inhibitors, oregano essential oil provided the highest protection, reaching an inhibition efficiency of about 95% after 72 hours of immersion. It was followed by rosemary oil, oregano aqueous extract, and neem oil. In contrast, rosemary aqueous extract and especially neem aqueous extract showed weaker and less durable protection. Overall, the oil-based extracts achieved an average inhibition efficiency close to 88%, whereas the aqueous extracts reached an average of about 46%. These results confirm the important role of the extraction route in determining the anticorrosion performance of plant-based inhibitors. The gravimetric results also showed a clear decrease in corrosion rate when effective inhibitors were used. The blank sample recorded the highest corrosion rate, while the oregano oil extract reduced it from 0.3100 mm/year to 0.0155 mm/year after 72 hours, corresponding to a reduction of about 95%. The final ranking of the inhibitors was oregano oil, followed by rosemary oil, oregano aqueous extract, neem oil, rosemary aqueous extract, and neem aqueous extract. This ranking demonstrates that not all natural extracts have the same protective capacity and that the chemical nature of the extract strongly affects its ability to form a protective layer on the steel surface.

The microscopic observations supported the gravimetric findings. Oregano essential oil showed near-complete suppression of bacterial biofilm formation, while the less effective extracts allowed higher bacterial density. The correlation between microscopic bacterial density and

General Conclusion

gravimetric inhibition efficiency was very strong and negative, with a Pearson correlation coefficient of $r = -0.986$. This means that the samples showing lower bacterial growth also presented higher inhibition efficiency. The agreement between the two methods strengthens the reliability of the results and confirms that the protective action of the best extracts is closely related to their antibiofilm effect.

The statistical comparison between the oil-based and aqueous extract families showed a large difference in average inhibition efficiency. The oil-based extracts reached a mean efficiency of 87.5%, while the aqueous extracts reached 45.8%. However, this difference did not reach conventional statistical significance at the 5% level, mainly because of the small number of samples in each group and the high variability among the aqueous extracts. Therefore, the statistical result should be interpreted with caution. It does not cancel the observed trend, especially because the ranking remained consistent and was confirmed by microscopic observations.

The findings of this study allow the main objectives to be considered achieved. The corrosion problem in the Berkaoui context was examined, the selected natural inhibitors were evaluated and ranked, and the influence of the extraction method was demonstrated. The working hypothesis was also confirmed, since the hydrophobic oil-based extracts provided better protection than the aqueous extracts. This superiority can be explained by their ability to form a more stable protective film on the steel surface and to reduce bacterial adhesion and biofilm formation.

From a scientific perspective, this work provides experimental evidence that plant extracts can reduce microbiologically influenced corrosion of pipeline steel under realistic produced-water conditions. It also clarifies the importance of the extraction route and highlights the role of antibiofilm activity in the inhibition process. From a practical perspective, the study identifies oregano essential oil as the most promising natural inhibitor among the tested extracts. Its high inhibition efficiency, low toxicity, renewability, and potential environmental advantages make it a credible candidate for further development in the protection of petroleum infrastructure.

When compared with conventional chemical inhibitors used in the Haoud-Berkaoui installations, oregano essential oil showed a level of protection that falls within the range commonly associated with industrial film-forming inhibitors. However, this comparison remains indicative, because the synthetic inhibitors were not tested under exactly the same experimental conditions in this study. A direct side-by-side comparison between oregano essential oil and the chemical inhibitors currently used on site would therefore be necessary before making a definitive industrial performance claim.

General Conclusion

From an industrial standpoint, the results suggest that oregano essential oil could be tested progressively within the Haoud-Berkaoui corrosion-management program. A practical implementation could begin with the production of a standardized extract of controlled composition and concentration, followed by pilot trials on a limited pipeline section or a secondary produced-water circuit. The extract could be injected through existing chemical-injection systems and monitored using weight-loss coupons, electrochemical probes, and periodic inspection. If field trials confirm the laboratory results, oregano essential oil could be introduced alone or combined with reduced doses of synthetic inhibitors as part of a more sustainable corrosion-control strategy.

This study also has some limitations. The experiments were conducted under controlled laboratory conditions and over a limited immersion period. The number of tested concentrations was restricted, and the long-term stability of the protective films was not fully investigated. In addition, the behavior of the inhibitors under real flow conditions, high temperature, high pressure, and extended exposure times was beyond the scope of this work. These limitations define the boundaries of the conclusions and indicate the need for further investigation.

Based on the obtained results, future research should focus on optimizing the concentration and injection protocol of the most effective extract, especially oregano essential oil. It is also recommended to identify the active molecules responsible for inhibition and to study their adsorption mechanism using electrochemical and surface-analysis techniques. Further tests should be carried out under dynamic-flow, high-temperature, and high-pressure conditions in order to reproduce the real operating environment more accurately. In addition, the possibility of combining several plant extracts or using green inhibitors with reduced doses of conventional products should be explored to improve protection and reduce environmental impact.

In conclusion, this study demonstrates that natural plant extracts, particularly oregano essential oil, can provide effective protection against the bacterial corrosion of API 5L X52 pipeline steel under sulfate-reducing bacteria conditions similar to those of the Haoud-Berkaoui field. By combining high inhibition efficiency with environmental advantages, green inhibitors represent a promising path toward sustainable corrosion control in the oil and gas industry. Further development, optimization, and field validation could allow these natural products to contribute to safer, cleaner, and more durable petroleum infrastructure.

Bibliography

Bibliography:

1. Jones, D. A. (1996). *Principles and prevention of corrosion* (2nd ed.). Prentice Hall.
2. Fontana, M. G. (1986). *Corrosion engineering*. McGraw-Hill.
3. NACE International. (2006). *Corrosion basics: An introduction*.
4. Tang, K., Baskaran, V., & Nemati, M. (2009). Bacteria of the sulphur cycle: An overview of microbiology, biokinetics and their role in petroleum and mining industries. *Biochemical Engineering Journal*, 44, 73–94.
5. Bogan, B. W., Lamb, B. M., Husmillo, G., Lowe, K., Paterek, R. J., & Kilbane, J. J. (2004). *Development of an environmentally benign microbial inhibitor to control internal pipeline corrosion*. Gas Technology Institute, 1–18.
6. Enning, D., & Garrelfs, J. (2014). Corrosion of iron by sulfate-reducing bacteria. *Applied and Environmental Microbiology*.
7. Little, B. J., & Lee, J. S. (2007). *Microbiologically influenced corrosion*. Wiley.
8. Beech, I. B., & Sunner, J. (2004). Biocorrosion: Towards understanding interactions between biofilms and metals. *Current Opinion in Biotechnology*.
9. Pereira, C. I., Crespo, M. T. B., & Romão, M. V. S. (2001). Evidence for proteolytic activity and biogenic amines production in *Lactobacillus curvatus* and *L. homohiochii*. *International Journal of Food Microbiology*, 68, 211–216.
10. Sheikh, I. A., & Sheikh, N. A. (2025). Microbiologically influenced corrosion in uncoated and coated mild steel. *Scientific Reports*, 12629, 1085.
11. Panda, S. S. *Mini-Reviews in Organic Chemistry*. MPS Powered by Eureka, 1875-6298. Insufficient data to verify full reference.
12. Wendt-Potthoff, K., & Neu, T. (1998). Microbial processes for potential in situ remediation of acidic lakes. In W. Geller, H. Klapper, & W. Salomons (Eds.), *Acidic mining lakes* (pp. 269–284). Springer.
13. Johnson, D. B., Rowe, O., Kimura, S., & Hallberg, K. B. (2004). Development of an integrated microbiological approach for remediation of acid mine drainage and recovery of heavy metals. In A. P. Jarvis, B. A. Dudgeon, & P. Younger (Eds.), *Proceedings of the IMWA Symposium Mine Water* (pp. 151–157). University of Newcastle.
14. Videla, H. A., & Herrera, L. K. (2005). Microbiologically influenced corrosion: Looking to the future. *International Microbiology*.
15. Javaherdashti, R. (2008). *Microbiologically influenced corrosion: An engineering insight*. Springer.
16. Rajasekar, A., et al. (2010). Biocides and their applications in the oil and gas industry. *Journal of Petroleum Science and Engineering*.
17. Little, B. J., Lee, J. S., & Ray, R. I. (2008). The influence of marine biofilms on corrosion. *Electrochimica Acta*.

Bibliography

18. Verma, C., et al. (2018). Plant extracts as green corrosion inhibitors. *Journal of Molecular Liquids*.
19. Javaherdashti, R. (1999). MIC control strategies. *Anti-Corrosion Methods and Materials*.
20. Videla, H. A. (2002). Prevention and control of biocorrosion. *International Biodeterioration & Biodegradation*, 49, 259–270.
21. Videla, H. A. (2003). Biocorrosion and biofouling of metals and alloys of industrial usage: Present state of the art at the beginning of the new millennium. *Revista de Metalurgia*, Extra volume, 256–264.
22. Kumar, C. G., & Anand, S. K. (1998). Significance of microbial biofilms in food industry: A review. *International Journal of Food Microbiology*, 42, 9–27.
23. Maruthamuthu, S., Mohanan, S., Rajasekar, A., Muthukumar, N., Ponmarippan, S., Subramanian, P., & Palaniswamy, N. (2005). Role of corrosion inhibitor on bacterial corrosion in petroleum product pipelines. *Indian Journal of Chemistry Technology*, 12, 567–575.
24. Greene, E. A., Brunelle, V., Jenneman, G. E., & Voordouw, G. (2006). Synergistic inhibition of microbial sulfide production by combinations of the metabolic inhibitor nitrite and biocides. *Applied & Environmental Microbiology*, 72, 7897–7901.
25. Muthukumar, N., Mohanan, S., Maruthamuthu, S., Subramanian, P., Palaniswamy, N., & Raghavan, M. (2003). Role of *Brucella* sp. and *Gallionella* sp. in oil degradation and corrosion. *Electrochemistry Communications*, 5, 421–426.
26. Revie, & Uhlig. *Corrosion and corrosion control*. Insufficient data to verify full reference.
27. Mekhloufi, & Rebih. *Corrosion inhibitors in petroleum units*. Insufficient data to verify full reference.
28. Ghrissi, & Chriffi. *Bio-inhibitors against bacterial corrosion*. Insufficient data to verify full reference.
29. Bentiss, F., Traisnel, M., & Lagrenee, M. (2000). *Corrosion Science*, 42, 127.
30. Sharma, S., & Chaudhary, R. S. (2000). *Bulletin of Electrochemistry*, 16, 267.
31. Bentiss, F., Lagrenee, M., Traisnel, M., & Hornez, J. C. (1999). *Corrosion*, 55, 968.
32. Bregman, J. J. (1963). *Corrosion inhibitors*. MacMillan.
33. Boffardi, B. P. (1987). Control of environmental variables in water-recirculating systems. In *Corrosion, ASM Handbook*. ASM International.
34. Yurt, A., Balaban, A., Kandemir, S. U., Bereket, G., & Erk, B. (2004). *Materials Chemistry and Physics*, 85, 420.
35. Stone, P. J. (1987). Corrosion inhibitors for oil and gas production. In *Corrosion, ASM Handbook* (Vol. 13). ASM International.
36. Zaim, S., Muralidharan, S., Iyer, S., Muralidharan, B., & Vasudevan, T. (1998). *British Corrosion Journal*, 33, 297.

Bibliography

37. Cisse, M. B., Zerga, B., El Kalai, F., Touhami, M. E., Sfaira, M., Taleb, M., Hammouti, B., Benchat, N., El Kadiri, S., & Benjelloun, A. T. (2011). *Surface Review and Letters*, 18, 303.
38. Musa, A. Y., Jalgham, R. T. T., & Mohamad, A. B. (2012). *Corrosion Science*, 56, 176.
39. Nataraja, S. E., Venkatesha, T. V., & Tandon, H. C. (2012). *Corrosion Science*, 60, 214.
40. Rosenfeld, I. L. (1977). *Corrosion inhibitors*. McGraw-Hill.
41. Thomas, J. G. N. (1994). *The mechanism of corrosion*. Butterworths Heinemann.
42. Hackerman, N., & Snaveley, E. S. (1984). *Corrosion basics*. NACE International.
43. Van Delinder, L. S. (1984). *Corrosion inhibitors basics: An introduction*. NACE International.
44. Sastri, V. S., Roberge, P. R., & Perumareddi, J. R. (1992). *Selection of inhibitors based on theoretical considerations*. Canadian Institute of Mining, Metallurgy and Petroleum.
45. Ash, M., & Ash, I. (2001). *Handbook of corrosion inhibitors*. NACE.
46. Schweitzer, P. A. (2007). *Fundamentals of metallic corrosion* (2nd ed.). CRC Press.
47. Sastri, V. S. (1998). *Corrosion inhibitors: Principles and applications*. Wiley-VCH.
48. Nathan, C. C. (1973). *Corrosion inhibitors*. NACE.
49. Mercer, A. D. (1994). *Corrosion inhibition: Principles and practice*. Butterworths Heinemann.
50. Andrade, J. M., Faustino, C., Garcia, C., Ladeiras, D., Reis, C. P., & Rijo, P. (2018). *Rosmarinus officinalis* L.: An update review of its phytochemistry and biological activity. *Future Science OA*, 4.
51. Papastavropoulou, K., Oz, E., Oz, F., & Proestos, C. (2022). Polyphenols from plants: Phytochemical characterization, antioxidant capacity, and antimicrobial activity of some plants from different sites of Greece. *Separations*, 9, 186. <https://doi.org/10.3390/separations9080186>
52. Tjitraresmi, A., Moektiwardoyo, M., Susilawati, Y., & Shiono, Y. (2020). Antimalarial activity of Lamiaceae family plants. *Systematic Reviews in Pharmacy*, 11, 324–333.
53. Fidan, H., Stankov, S., Ivanova, T., Stoyanova, A., Damyanova, S., & Ercisli, S. (2019). Characterization of aromatic compounds and antimicrobial properties of four spice essential oils from family Lamiaceae. *Ukrainian Food Journal*, 8, 227–238. <https://doi.org/10.24263/2304-974X-2019-8-2-3>
54. da Silva, L. R. R., Ferreira, O. O., Cruz, J. N., Franco, C. D. J. P., Dos Anjos, T. O., Cascaes, M. M., da Costa, W. A., de Aguiar Andrade, E. H., & de Oliveira, M. S. (2021). Lamiaceae essential oils, phytochemical profile, antioxidant, and biological activities. *Evidence-Based Complementary and Alternative Medicine*, 2021, 6748052. <https://doi.org/10.1155/2021/6748052>
55. Moshari-Nasirkandi, A., Alirezalu, A., Alipour, H., & Amato, J. (2023). Screening of 20 species from Lamiaceae family based on phytochemical analysis, antioxidant activity and

Bibliography

- HPLC profiling. *Scientific Reports*, 13, 16987. <https://doi.org/10.1038/s41598-023-44337-7>
56. Ashfaqullah, S., & Tamta, S. (2018). Studies on high value medicinal plant: *Origanum vulgare* L.: A review. *IJRAR*, 6(1).
57. Guner, A., Ozhatay, N., Ekim, T., & Baser, K. H. C. (2000). *Flora of Turkey and the East Aegean Islands* (2nd ed., Vol. 11). Edinburgh University Press.
58. Skoufogianni, E., Solomou, A. D., & Danalatos, N. G. (2019). Ecology, cultivation and utilization of the aromatic Greek oregano (*Origanum vulgare* L.): A review. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 47, 545–552. <https://doi.org/10.15835/nbha47311296>
59. Alekseeva, M., Zagorcheva, T., Atanassov, I., & Rusanov, K. (2020). *Origanum vulgare* L.: A review on genetic diversity, cultivation, biological activities and perspectives for molecular breeding. *Bulgarian Journal of Agricultural Science*, 26, 1183–1197.
60. Chalchat, J.-C., & Pasquier, B. (1998). Morphological and chemical studies of *Origanum* clones: *Origanum vulgare* L. ssp. *vulgare*. *Journal of Essential Oil Research*, 10, 119–125. <https://doi.org/10.1080/10412905.1998.9700861>
61. Comba, L., Corbet, S. A., Hunt, L., & Warren, B. (1999). Flowers, nectar and insect visits: Evaluation of British plant species for pollinator-friendly gardens. *Annals of Botany*, 83, 369–383. <https://doi.org/10.1006/anbo.1998.0835>
62. Verma, R. S., Padalia, R. C., Chauhan, A., Verma, R. K., Yadav, A. K., & Singh, H. P. (2010). Chemical diversity in Indian oregano (*Origanum vulgare* L.). *Chemistry & Biodiversity*, 7, 2054–2064. <https://doi.org/10.1002/cbdv.200900419>
63. Hussain, A. I., Anwar, F., Rasheed, S., Nigam, P. S., Janneh, O., & Sarker, S. D. (2011). Composition, antioxidant and chemotherapeutic properties of the essential oils from two *Origanum* species growing in Pakistan. *Revista Brasileira de Farmacognosia*, 21, 943–952. <https://doi.org/10.1590/S0102-695X2011005000165>
64. Nykanen, I. (1986). High resolution gas chromatographic–mass spectrometric determination of the flavour composition of wild marjoram (*Origanum vulgare* L.) cultivated in Finland. *European Food Research and Technology*, 183, 267–272.
65. Nurzyńska-Wierdak, R. (2009). Herb yield and chemical composition of common oregano (*Origanum vulgare* L.) essential oil according to the plant's developmental stage. *Herba Polonica*, 55, 55–62.
66. Naquvi, K. J., Ahamad, J., Salma, A., Ansari, S. H., & Najmi, A. K. (2019). A critical review on traditional uses, phytochemistry and pharmacological uses of *Origanum vulgare* Linn. *International Research Journal of Pharmacy*, 10, 7–11. <https://doi.org/10.7897/2230-8407.100370>
67. Khan, S. T., Khan, M., Ahmad, J., Wahab, R., Abd-Elkader, O. H., Musarrat, J., Alkhathlan, H. Z., & Al-Kedhairi, A. A. (2017). Thymol and carvacrol induce autolysis, stress, growth inhibition and reduce the biofilm formation by *Streptococcus mutans*. *AMB Express*, 7, 49. <https://doi.org/10.1186/s13568-017-0344-y>
68. Arámbula, C. I., Diaz, C. E., & Garcia, M. I. (2019). Performance, chemical composition and antibacterial activity of the essential oil of *Ruta chalepensis* and *Origanum vulgare*.

Bibliography

- Journal of Physics: Conference Series*, 1386, 012059. <https://doi.org/10.1088/1742-6596/1386/1/012059>
69. Şahin, F., Güllüce, M., Daferera, D., Sökmen, A., Sökmen, M., Polissiou, M., Agar, G., & Özer, H. (2004). Biological activities of the essential oils and methanol extract of *Origanum vulgare* ssp. *vulgare* in the Eastern Anatolia region of Turkey. *Food Control*, 15, 549–557. <https://doi.org/10.1016/j.foodcont.2003.08.009>
70. Jianu, C., Lukinich-Gruia, A. T., Rădulescu, M., Mioc, M., Mioc, A., Şoica, C., Constantin, A. T., David, J., Bujancă, G., & Radu, R. G. (2023). Essential oil of *Origanum vulgare* var. *aureum* L. from Western Romania: Chemical analysis, in vitro and in silico screening of its antioxidant activity. *Applied Sciences*, 13, 5076. <https://doi.org/10.3390/app13085076>
71. Yildiz, S., Turan, S., Kiralan, M., & Ramadan, M. F. (2021). Antioxidant properties of thymol, carvacrol, and thymoquinone and its efficiencies on the stabilization of refined and stripped corn oils. *Journal of Food Measurement and Characterization*, 15, 621–632. <https://doi.org/10.1007/s11694-020-00665-0>
72. Hajibonabi, A., Yekani, M., Sharifi, S., Nahad, J. S., Dizaj, S. M., & Memar, M. Y. (2023). Antimicrobial activity of nanoformulations of carvacrol and thymol: New trend and applications. *OpenNano*, 13, 100170. <https://doi.org/10.1016/j.onano.2023.100170>
73. Kachur, K., & Suntres, Z. (2020). The antibacterial properties of phenolic isomers, carvacrol and thymol. *Critical Reviews in Food Science and Nutrition*, 60, 3042–3053. <https://doi.org/10.1080/10408398.2019.1675585>
74. Radusiene, J., Ivanauskas, L., Janulis, V., & Jakstas, V. (2008). Composition and variability of phenolic compounds in *Origanum vulgare* from Lithuania. *Biologija*, 54, 45–49. <https://doi.org/10.2478/v10054-008-0009-5>
75. Bernstein, N., Chaimovitch, D., & Dudai, N. (2009). Effect of irrigation with secondary treated effluent on essential oil, antioxidant activity, and phenolic compounds in oregano and rosemary. *Agronomy Journal*, 101, 1–10. <https://doi.org/10.2134/agronj2007.0144>
76. Benchikha, N. B., Menaceur, M. M., & Barhi, Z. (2013). Extraction and antioxidant activities of two species *Origanum* plant containing phenolic and flavonoid compounds. *Journal of Fundamental and Applied Sciences*, 5, 120–128. <https://doi.org/10.4314/jfas.v5i1.10>
77. Capecka, E., Mareczek, A., & Leja, M. (2005). Antioxidant activity of fresh and dry herb of some Lamiaceae species. *Food Chemistry*, 93, 223–226. <https://doi.org/10.1016/j.foodchem.2004.09.020>
78. Jussieu, A. (1830). Mémoire sur la famille de Myrsinacées. *Mémoires du Muséum National d'Histoire Naturelle*, 19, 133.
79. The Plant List. (2014). *The Plant List, Version 1.1*. Retrieved October 22, 2014, from <http://www.theplantlist.org/tp1.1/record/kew-2667002>
80. Morgan, E. D. (2009). Azadirachtin, a scientific gold mine. *Bioorganic & Medicinal Chemistry*, 17(12), 4096–4105.
81. Khare, C. P. (2007). *Indian medicinal plants: An illustrated dictionary*. Springer.

Bibliography

82. Tiwari, R., Verma, A. K., Chakraborty, S., Dhama, K., & Singh, S. V. (2014). Neem (*Azadirachta indica*) and its potential for safeguarding health of animals and humans: A review. *Journal of Biological Sciences*, 14(2), 110–123.
83. Biswas, K., Chattopadhyay, I., Banerjee, R. K., & Bandyopadhyay, U. (2002). Biological activities and medicinal properties of neem (*Azadirachta indica*). *Current Science*, 82(11), 1336–1345.
84. Seddiek, S. A., Khater, H. F., El-Shorbagy, M. M., & Ali, A. M. (2013). The acaricidal efficacy of aqueous neem extract and ivermectin against *Sarcoptes scabiei* var. *cuniculi* in experimentally infested rabbits. *Parasitology Research*, 112(6), 2319–2330.
85. Hashmat, I., Azad, H., & Ahmed, A. (2012). Neem (*Azadirachta indica* A. Juss): A nature's drugstore: An overview. *International Research Journal of Biological Sciences*, 1(6), 76–79.
86. Kaur, G., Sarwar Alam, M., & Athar, M. (2004). Nimbidin suppresses functions of macrophages and neutrophils: Relevance to its anti-inflammatory mechanisms. *Phytotherapy Research*, 18(5), 419–424.
87. Koul, O., Multani, J. S., Singh, G., Daniewski, W. M., & Berlozecki, S. (2003). 6 β -Hydroxygedunin from *Azadirachta indica*: Its potentiation effects with some non-azadirachtin limonoids in neem against lepidopteran larvae. *Journal of Agricultural and Food Chemistry*, 51(10), 2937–2942.
88. Pandey, I. P., Ahmed, S. F., Chhimwal, S., & Pandey, S. (2012). Chemical composition and wound healing activity of volatile oil of leaves of *Azadirachta indica* A. Juss. *Advances in Pure and Applied Chemistry*, 1(3), 62–66.
89. Ngure, R. M., Onger, B., Karori, S. M., Wachira, W., Maathai, R. G., Kibugi, J., et al. (2013). Anti-trypanosomal effects of *Azadirachta indica* neem extract on *Trypanosoma brucei rhodesiense*-infected mice. *Eastern Journal of Medicine*, 14(1), 2–9.
90. Luo, X., Ma, Y., Wu, S., & Wu, D. (1999). Two novel azadirachtin derivatives from *Azadirachta indica*. *Journal of Natural Products*, 62(7), 1022–1024.
91. Siddiqui, B. S., Ali, S. T., Rajput, M. T., Gulzar, T., Rasheed, M., & Mehmood, R. (2009). GC-based analysis of insecticidal constituents of the flowers of *Azadirachta indica* A. Juss. *Natural Product Research*, 23(3), 271–283.
92. Kusari, S., Verma, V. C., Lamshoeft, M., & Spiteller, M. (2012). An endophytic fungus from *Azadirachta indica* A. Juss. that produces azadirachtin. *World Journal of Microbiology and Biotechnology*, 28(3), 1287–1294.
93. Ley, S. V. (2005). Development of methods suitable for natural product synthesis: The azadirachtin story. *Pure and Applied Chemistry*, 77(7), 1115–1130.
94. Simescu-Lazar, F., Slaoui, S., Essahli, M., Bohr, F., Lamiri, A., Vanoye, L., & Chopar, J. P. (2023). Title not provided in source. *Lubricants*, 11(2), 56. <https://doi.org/10.3390/lubricants11020056>
95. Boudouda, K. (1999). *Sonatrach document*. Geology Department.
96. Selka, K., & Kelaiaia, A. (n.d.). *Study of bacterial corrosion in buried pipelines*. Kasdi Merbah Ouargla University. Retrieved from <https://dspace.univ-ouargla.dz/jspui/bitstream/123456789/14905/3/Selka-Kelaiaia-.pdf>

Bibliography

97. Chimec S.p.A. (n.d.). *Flow assurance chemicals: Chimec 2935 technical data sheet*. <https://www.chimec.com>
98. Al-Amiery, A. A., Wan Isahak, W. N. R., & Al-Azzawi, W. K. *Product technical card*. Insufficient data to verify full reference.
99. Universiti Kebangsaan Malaysia. (2023). *Corrosion inhibitors: Natural and synthetic organic inhibitors*. Insufficient data to verify full reference.
100. NACE International (DNV GL, APQC), International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) Study, NACE International, Houston, TX, 2016.
101. G. H. Koch et al., Corrosion Cost and Preventive Strategies in the United States, Report FHWA-RD-01-156, NACE International / U.S. Federal Highway Administration, 2002.
102. B. J. Little and J. S. Lee, Microbiologically Influenced Corrosion, John Wiley & Sons, Hoboken, NJ, 2007.
103. H. A. Videla, Manual of Biocorrosion, CRC Press / Lewis Publishers, Boca Raton, FL, 1996.
104. V. S. Sastri, Corrosion Inhibitors: Principles and Applications, Wiley-VCH, Weinheim, Germany, 1998.
105. M. A. Quraishi, D. S. Chauhan and E. E. Ebenso, "Vegetal and green corrosion inhibitors," in Corrosion Inhibitors in the Oil and Gas Industry, Wiley-VCH, 2020.
106. C. Verma, E. E. Ebenso and M. A. Quraishi, "Plant extracts as eco-friendly corrosion inhibitors: a review," Journal of Molecular Liquids, vol. 266, pp. 577–590, 2018.