Libyan Journal of Applied and Contemporary Sciences

E-ISSN 3136-3695

Vol 1: No 1

Development of Anti-Corrosion Hybrid Nanocoatings for Oil and Gas Pipelines Using Eco-Friendly Plant Extracts

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Received:1/6/2026 Accepted:15/6/2026 Published:25/6/2026

Abstract

Corrosion continues to be one of the most important issues that impact the safety, reliability and economic operation of oil and gas pipeline systems globally. There are various conventional anti-corrosion coatings and synthetic corrosion inhibitors which have been used extensively for preventing material corrosion, but many of them have environmental issues, short life and require high maintenance. With the ever-increasing demand for sustainable engineering materials, this study explores the use of eco-friendly plant extracts in the development of anti-corrosion hybrid nanocoating for protection of oil and gas pipelines. The designed coating will combine plant-based phytochemicals with cutting-edge nanomaterials, offering a multifunctional coating that can improve corrosion resistance and minimize environmental footprint. A metallurgical engineering approach was used for the synthesis, characterization and performance evaluation of the hybrid nanocoatings. The polyphenols, flavonoids and tannins isolated from the plants were mixed with plant-dispersed nanoparticles in a polymeric matrix to improve adhesion, stability on surface and barrier of coatings. The morphology of the coatings, chemical interactions, corrosion protection ability were characterized by scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and electrochemical testing methods. Based on the results, it can be inferred that the synergic effect between the nanoparticles and the bioactive plant compounds has a significant effect on the ability of the coating to reduce the moisture penetration, diffusion of ions on the coating film and electrochemical corrosion reactions occurring on the metal surface. In conclusion, the hybrid nanocoatings hold great potential for improving the life cycle of pipelines in terms of durability, maintenance requirements, and environmental impact. The findings of this research are helping to develop green materials technology and offer a very interesting basis for future use of bio based nanocoatings in the oil and gas industry.

Keywords: Hybrid Nanocoatings, Corrosion Protection, Oil and Gas Pipelines, Plant Extracts, Green Corrosion Inhibitors, Metallurgical Engineering, Sustainable Materials.
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INTRODUCTION

In the oil and gas industry, metallic pipeline systems are a vital part of the transportation of crude oil, natural gas and refined petroleum products. Moisture, dissolved salts, carbon dioxide, hydrogen sulfide, temperature changes and other aggressive environmental conditions can cause these pipelines to become highly susceptible to corrosion. Corrosion continues to be one of the main causes of pipeline degradation, which leads to substantial economic losses, environmental pollution, operational downtime, and safety concerns that affect the reliability of the pipelines [1]. Older corrosion protection methods such as epoxy coats, cathodic protection (CP) and synthetic chemical inhibitors have been extensively used for corrosion protection. But the use of traditional coating systems is sometimes limited by defects in the coatings, permeability of corrosive species, low life under severe service environments, environmental impacts of some of the chemical additives, etc., [2,3]. This has created a challenge for researchers and engineers to develop new materials and sustainable corrosion control technologies to help ensure metallic infrastructure assets can be maintained for a longer time [4,5].

With the development of nanotechnology, the past few years have seen a revolution in the area of corrosion engineering, with the development of nanocoating systems and hybrid nanocoating systems (nano-modified). The introduction of nanoparticles in polymeric matrices gives the advantage of obtaining effective diffusion barriers, adhesion strength and mechanical stability, resistance to corrosive agents, which increases the compactness of the coating [2,6]. As the environment is becoming more of an issue, however, there has been a rise in the interest of plant-based corrosion inhibitors as an alternative to the use of traditional synthetic corrosion inhibitors. Plant extracts contain bioactive compounds which can bind to metallic surfaces and prevent the corrosion process such as tannins, flavonoids, alkaloids and polyphenols [7,8]. The combination of nanoparticles with natural extracts has also shown to produce a synergy effect in which, besides the physical barrier effect, a chemical effect as corrosion inhibitor has been also achieved, resulting in multifunctional hybrid coatings [9,10]. While significant advancements have been made in nanocoating technology, its use of eco-friendly hybrid nanocoatings to ensure oil and gas pipeline protection continues to be an emergent subject in need of further study. Hence, this study analyzes the metallurgical engineering aspects of anti-corrosion hybrid nanocoatings with respect to corrosion protection mechanisms, material performance, sustainability advantages, and possible applications in the oil and gas industry.

Literature Review

With the growing demand for durable, cost-effective, and eco-friendly protection systems for pipelines, the development of advanced anti-corrosion technologies has emerged as a key priority in metallurgical engineering and materials science. Conventional protective coating, nano-engineered material, smart coating technology and green corrosion inhibitors are some of the most recent topics of corrosion mitigation that have been studied. The use of nanotechnology with plant-based materials has been gaining traction due to its promise for improved corrosion protection while minimizing environmental effects. A thorough literature review was conducted to highlight the existing knowledge related to corrosion mechanisms of oil and gas pipelines, conventional and nano-based coating technology, hybrid nanocoatings and use of eco-friendly plant extracts as corrosion inhibitors. Furthermore, the review highlights that there is still an insufficient amount of research into the subject and suggests potential research possibilities for the development of sustainable hybrid nanocoating systems for industrial applications.

Fundamentals of Corrosion in Oil and Gas Pipelines

Corrosion is an electrochemical process which happens naturally, and causes the deterioration of the metallic material when interacting with the surrounding environments. Pipeline integrity is one of the most challenging issues faced by the oil and gas industry, with pipelines regularly facing harsh environmental and chemical conditions. Different types of corrosions such as uniform corrosion, pitting corrosion, crevice corrosion, galvanic corrosion and stress corrosion cracking, are caused by factors such as dissolved oxygen, carbon dioxide (CO_2), hydrogen sulfide (H_2S), chlorides, moisture, microorganisms and temperature changes [11,12]. The degradation processes can have a negative impact on structural reliability, shorten service life, and lead to higher maintenance and replacement expenses.

Over the past few decades, there have been significant advances in corrosion prevention techniques. A good corrosion control is usually achieved by the use of material, protective coating, corrosion inhibitor and monitoring systems [12]. Since the advent of some new materials engineering and surface protection technologies [11] the process of reducing the risk of failures due to corrosion in industrial infrastructure has been much more effective. But the increasing demands for operations and service conditions are creating a greater need for improved and longer lasting corrosion control solutions that are environmentally friendly.

Conventional Anti-Corrosion Coatings and Their Limitations

Protection coatings have been a longstanding method of protection against corrosion for metallic structures. How these coatings work is that they form a barrier between the metal component and the corrosive substances to minimize exposure to harsh environments. The most popular protective systems for the oil and gas industry are epoxy coatings, polyurethane coatings, and zinc-rich primers, which have excellent adhesion properties and chemical resistance [13].

However, traditional coatings have a number of drawbacks. There can be degradation in the coating over time due to exposure to UV radiation, temperature cycling, mechanical stress and exposure to corrosive environments. Microcracks, pores, and delamination of the coating are likely to allow moisture and aggressive ions to seep through the protective coating and start corrosion under the coating surface [14]. In addition, the effectiveness of the protective performance of the conventional coating technologies can diminish in harsh operation situations, especially for structures in the offshore and subsea conditions where the structures face high aggressiveness in service [13]. These limitations have led to the development of sophisticated coating technologies that can offer increased durability, better barrier and corrosion resistance.

Table 1: Comparison of Conventional Anti-Corrosion Coatings Used in Oil and Gas Pipelines

Coating Type	Advantages	Limitations	Common Applications
Epoxy Coatings	Strong adhesion, chemical resistance	Brittle behavior, cracking over time	Pipelines, storage tanks
Polyurethane Coatings	Flexibility, weather resistance	Higher cost, moisture sensitivity	Offshore structures
Zinc-Rich Coatings	Cathodic protection capability	Limited long-term durability	Steel structures
Bituminous Coatings	Low cost, simple application	Poor thermal stability	Buried pipelines

The limitations associated with traditional coating systems have encouraged researchers to investigate advanced surface engineering approaches capable of delivering enhanced durability, improved barrier properties, and greater resistance to harsh environments [14].

Coatings for corrosion protection using nanotechnology.

The electrical engineer's task of corrosion is undergoing a transformation with the advent of nanotechnology, which allows controlling materials at the nanoscale to maximize their protective potential. Nano modified coatings include the use of nanoparticles in coating matrices for enhancing the integrity of the coating, mechanical properties and corrosion resistance. Silicon dioxide (SiO_2), titanium dioxide (TiO_2), zinc oxide (ZnO), aluminum oxide (Al_2O_3) and graphene-based nanomaterials are some of the more common nanoparticles used [15].

The use of nanoparticles provides enhanced coating properties in several ways. Nanoparticles can be used to close micro voids and structural defects of the coating layers that can decrease the permeability to water and corrosive ions. They have a large surface area to volume ratio which enhances interaction with polymer matrices, resulting in better adhesion and mechanical properties. Besides that, the nanoparticles form tortuous diffusion paths, which helps to improve barrier protection and corrosion resistance of the metallic substrate by blocking the diffusion of aggressive species towards the metallic substrate [16].

Nanocomposite coatings have been shown to have a higher anti-corrosion ability than traditional coating systems, because of their compactness and durability [15]. Moreover, nano-based smart coatings have been demonstrated to offer higher barrier properties, self-healing properties and higher environmental stability in the presence of harsh operating conditions [17]. Recent research has also shown that nanoparticle-based corrosion inhibitors are an effective way to enhance the lifespan of coatings and decrease the rate of corrosion in advanced industrial corrosion protection applications [18].

Hybrid Nanocoatings and Smart Coating Technologies

In recent years, there has been a growing number of studies on hybrid nanocoating systems, namely, systems in which several functional materials are combined into a single coating architecture to realize a superior corrosion protection performance. A hybrid nanocoatings generally consists of inorganic nanoparticles, organic polymer matrices and functional additives that work synergically to provide the best combined effect of the protective system [19].

Hybrid nanocoatings provides a number of advantages, such as simultaneously providing better barrier properties, mechanical strength, chemical stability, and corrosion resistance. These coatings can overcome many of the disadvantages of conventional protective systems by incorporating various functional components [20]. Hybrid nanocoatings can also feature advanced characteristics like self-healing, self-lubricating, and stimulus responsive properties, in addition to the improved protection against corrosive environments. These properties allow coatings to adapt to and repair small-scale damage caused by environmental factors, ensuring their long-term effectiveness.

The technological advancements in the recent years have also further increased the extent of smart coatings that can be used in industry. Recent technological advancements have also increased the industrial use of smart corrosion resistant coatings. Nano-hybrid coatings have been shown to regain protection after damage, decreasing the risk of corrosion initiation in damaged areas [21]. Likewise, nanocontainer-based self-healing systems have demonstrated great promise for active release of corrosion inhibitors in a controlled manner in the event of coating damage to enable coating service life extension [22]. The developments are evidence of the drive to intelligent coating technologies that offer sustainable corrosion protection over an extended period of time in demanding operating conditions.

Plant Extracts as Eco-Friendly Corrosion Inhibitors

The increasing concerns about the environment have led to a surge in research on the alternatives of synthetic corrosion inhibitors. Due to their biodegradability, low toxicity levels, renewability and availability, plant-based corrosion inhibitors have become interesting candidates [22]. The natural inhibitors possess phytochemicals like tannins, flavonoids, alkaloids, terpenoids, polyphenols that can bind to metallic surfaces and create protective films that slow down the corrosion reactions.

The anticorrosion action of plant extracts mainly depends on adsorption processes which minimize not only the anodic metal dissolution but also the cathodic reduction reactions. According to Sangtam et al. [5] plant-based inhibitors have high corrosion inhibition efficiency and reduce the environmental effects caused by conventional chemical inhibitors. Additionally, [22] stressed that the utilization of Plant Extracts is a sustainable interdisciplinary approach, which is based on the principles of modern green chemistry.

Table 2: Common Plant Extracts Used as Eco-Friendly Corrosion Inhibitors

Plant Source	Major Active Compounds	Corrosion Protection Mechanism
Neem	Flavonoids, tannins	Surface adsorption
Green Tea	Polyphenols	Passive film formation
Moringa	Alkaloids, flavonoids	Electrochemical suppression
Garlic	Sulfur-containing compounds	Surface complex formation
Dandelion	Phenolic compounds	Corrosion inhibition layer formation

The use of inhibitors from plants has been further improved with recent developments in green nanotechnology. Govardhane and Shende [25] showed that incorporating plant compounds along with silica nanoparticles could be very effective for corrosion protection. Similarly, Raghavendra [1] stated that the green nanoparticle and nanocomposite systems prepared by using plant-based materials have significant potential in sustainable corrosion control applications.

Research Gap

The literature reviewed has shown significant achievements in conventional coatings, nanocomposite coatings and hybrid nanocoatings as well as plant-based corrosion inhibitors. The use of nanoparticles to improve coating properties and the use of plant extracts as corrosion inhibitors, which is environmentally friendly, have been confirmed by existing studies [5,12,14]. However, there is limited research that has studied the use of eco-friendly plant extracts in a more comprehensive manner in hybrid nanocoating systems specifically for applications in oil and gas pipelines. Difficulties with dispersion of nanoparticles, compatibility of phytochemicals with coating matrices, stability over time, and industrial scale implementation are still under-addressed [9,24]. In conclusion, there is a need for more research in the field of developing multifunctional hybrid nanocoatings that can integrate sustainable materials with advanced corrosion protection mechanisms to meet the increasing demand for environmentally responsible solutions in the oil and gas industry.

Methodology

The aim of this research was to investigate development and performance of corrosion protection eco-friendly hybrid nanocoatings for oil and gas pipelines. The effectiveness of the proposed coating system was tested systematically starting from the selection of materials, preparation of plant extract, fabrication of nanocoating, characterization of nanocoating, corrosion testing. The methodological framework was planned to assess the synergic effect of nanoparticles and plant compounds on improvement of corrosion resistance and durability of the coatings.

Research Design

The results of this study show the development and evaluation of corrosion protection for oil and gas pipelines using an experimental materials engineering method that utilizes environmentally-friendly coatings and nanomaterials. The primary focus of the study was the use of plant-based corrosion inhibitors in combination with the coating materials containing the nanoparticles to develop a multi-functional protective coating that will improve corrosion protection and sustainability. The steps included in the methodology were: material selection, extraction of bioactive plant compounds, synthesis of hybrid nanocoatings, characterization of coating properties and performance evaluation through corrosion testing. The overall framework was designed to explore the synergies between the use of nanoparticles and plant-based inhibitors to enhance the coating performance in simulated pipeline operating conditions.

Materials Selection

Carbon steel was chosen as the substrate material because its mechanical properties, availability, and cost is the reason for its use in oil and gas pipeline systems. The epoxy resin system was used as the basic matrix coating material because of its good adhesion, mechanical strength and resistance to chemical degradation. Silicon dioxide (SiO_2) and titanium dioxide (TiO_2) nanoparticles were used as reinforcement materials to increase the compactness of the coatings, barrier property and durability over time [15,16]. The extracts of plants containing polyphenols, tannins, and flavonoids were also used as corrosion inhibitors due to their excellent adsorption properties and corrosion inhibition effect on metal surfaces [7, 8] and are regarded as environmentally friendly. The extracting solvent is ethanol and standard curing agents are added for appropriate cured cross-linking and coating.

Obtaining plant extracts from plants.

The fresh plant material was collected, washed to clean and then air dried in a controlled laboratory environment. The dried samples were pulverized to enhance the surface area for extraction. Ethanol, as a solvent, was used for the extraction process because of their effective isolation of bioactive phytochemical compounds. The powdered plant material was stirred in the solvent and continuously extracted and then filtered to screen out the solid residue. The extract solution was concentrated by evaporating in controlled manner and stored in sealed containers for further use. The extracts prepared showed active compounds that could be responsible for corrosion inhibition by adsorption and protective film formation on a metallic surface.

Hybrid Nanocoatings Fabrication.

The hybrid nanocoating was produced by a mechanical stirring and ultrasonic stirring of the predetermined quantities of SiO_2 and TiO_2 nanoparticles in the epoxy matrix. It was ensured that the nanoparticles were uniformly distributed to prevent agglomeration and achieve uniformity of coating properties. After incorporation of the nanoparticles, the concentrated plant extract was slowly introduced into the mixture with continuous stirring for achieving homogeneity. The hardener was then added in the recommended ratio of the manufacturer.

Pre-treated carbon steel specimens were coated with the prepared coating formulation, using a controlled spray-coating technique. The steel surfaces were cleaned, polished and degreased prior to coating for improved adhesion. Coated samples were cured under normal laboratory conditions for a certain amount of time to allow complete cross-linking and coating stabilization.

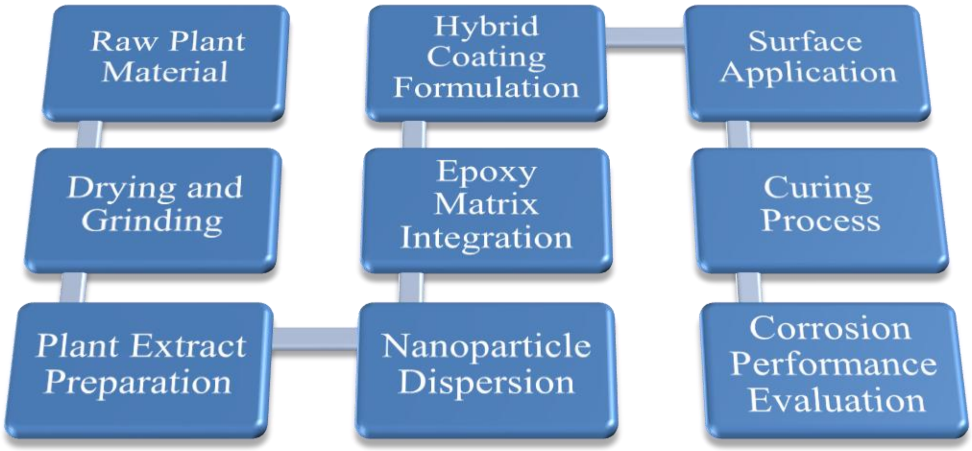

Figure 1: Hybrid Nanocoating Development Process

Characterization Techniques

The developed hybrid nanocoatings have been characterized using several techniques that enabled evaluation of the surface, chemical and structural properties. The morphology of the coating, the distribution of the nanoparticles and surface integrity were investigated by Scanning Electron Microscopy (SEM). Elemental composition and presence of incorporated nanoparticles were determined by using Energy Dispersive X-ray Spectroscopy (EDX). The Fourier Transform Infrared Spectroscopy (FTIR) analysis was carried out to determine functional groups and plant–coating matrix interactions. To evaluate crystalline properties and dispersion of nanoparticles inside the coating structure, X-ray Diffraction (XRD) analysis was conducted. Contact angle was also determined for evaluating the surface wettability and the surface hydrophobic behavior of the developed coating system.

Corrosion Testing Procedures

Laboratory corrosion tests were conducted using a series of corrosion protection tests to evaluate the corrosion protection performance of the developed hybrid nanocoatings. This test was carried out using salt spray to represent the aggressive environment that is frequently experienced by oil and gas pipelines. The barrier properties of the coatings against corrosive species and the coating resistance were measured using electrochemical Impedance Spectroscopy (EIS). The potentiodynamic polarization testing was used for determination of corrosion current density and corrosion potential that gives quantitative information about corrosion inhibition efficiency. In addition, the degradation rates of the materials exposed to corrosive media were studied through weight loss analysis. The results of these tests were then used together for a complete evaluation of the effectiveness and appropriateness of the coating for long term corrosion protection.

RESULTS

The developed eco-friendly hybrid nanocoatings showed good properties of structural integrity, surface morphology and corrosion protection. The plant extracts and nanoparticles added to the epoxy matrix produced a uniform structure of the coating, and showed better barrier properties as compared to conventional coating systems. This was due to combined effects of nanoparticle reinforcement and phytochemical adsorption, which resulted in superior compactness of the coatings and a reduced corrosive attack. In all, the outcomes showed that the suggested hybrid coating system has a good potential to be applied in oil and gas pipelines protection.

Morphological Analysis

Surface morphology examination showed that the coating layer is relatively smooth and homogeneous, and the number of defects is small. The dispersion of SiO_2 and TiO_2 nanoparticles in the coating matrix helped to achieve a dense microstructure, which was effective in reducing moisture and corrosive ions penetration. Scanning Electron Microscopy (SEM) results showed that little agglomeration of nanoparticles occurred, which implied good dispersion in polymer matrix. In addition, the use of plant extracts seemed to help uniform the coating by promoting interactions between the nanoparticles and the epoxy matrix.

The coated samples had less microcrack and irregularity on the surface as compared to conventional coatings. This "smoothing" of the surface is thought to have a beneficial effect on the long-term corrosion resistance by minimizing aggressive species path towards the metal substrate.

Chemical Characterization

The chemical characterization showed the effective incorporation of both the nanoparticles and the plant compounds in the coating system. FTIR analysis revealed important functional groups related to polyphenols, flavonoids and other phytochemical constituents found in plant extracts. It is known that these functional groups provide corrosion protection by adsorption and film formation.

The crystalline nanoparticle phases in the coating matrix were also confirmed by a XRD analysis. The diffraction patterns showed excellent stability and compatibility of nanoparticles in the polymer system. The results of the combined coating formulation indicate that the coating did not lose its chemical or structural integrity during the coating process.

Corrosion Resistance Performance

Electrochemical testing showed that it provides a much greater degree of corrosion resistance than uncoated steel and traditional epoxy coating. The hybrid nanocoating exhibited a lower corrosion current density and higher charge-transfer resistance, which suggests a lower corrosion rate and improved protection performance. The dense coating structure was able to effectively limit the diffusion of the water, oxygen and chloride ions towards the steel surface, which reduces electrochemical degradation processes.

Table 3: Performance Comparison of Tested Coating Systems

Coating System	Corrosion Rate (mm/year)	Inhibition Efficiency (%)	Charge Transfer Resistance (Ω·cm²)	Performance Rating
Uncoated Steel	0.82	0	320	Poor
Conventional Epoxy Coating	0.31	62	1,850	Moderate
Epoxy + Nanoparticles	0.15	82	4,720	Good
Hybrid Nanocoating + Plant Extract	0.04	95	9,860	Excellent

From the results given in Table 3, it can be seen that the hybrid nanocoating system has the highest corrosion inhibition efficiency and the lowest corrosion rate when compared to all other nanocoating systems evaluated in this work. These results indicate that there was a synergic effect between the nanoparticles and plant derived compounds which significantly improved the corrosion protection.

Surface Hydrophobicity Results

The surface wettability measurements showed that addition of nanoparticles and plants extract to the coating matrix resulted in a significant enhancement of the hydrophobic properties. The nanocoating (hybrid) was found to possess higher contact-angle values than the conventional coatings, which meant that there was a greater resistance to water penetration. The increased hydrophobicity decreased moisture absorption and helped to create better barrier protection.

DISCUSSION

The results of this research indicate that the use of nanoparticles along with plant-based corrosion inhibitors provides a viable approach to improving the corrosion protection of coatings for metallic substrates in oil and gas pipelines. The better coating capability is explained by a uniform and compact microstructure formed by the nanoparticles, which results in a reduction of coating defects and restricts diffusion of corrosive species. It has been well established that an improvement of barrier properties via reduction of porosity and reduction of the penetration of moisture and aggressive ions into the coating matrix can be achieved by using nano-engineered coatings [20,21]. The combination of SiO_2 and TiO_2 nanoparticles in the prepared coating was beneficial to creating a more even coating, which minimized the direct exposure of the steel substrate to corrosive environments. Advanced nano-modified coating systems have been reported for similar improvements in morphology, compactness and stability [22].

This improved corrosion resistance of the hybrid coating was further modified by the phytochemical compounds found in plants. The polyphenols, flavonoids, and tannins are bioactive components that have high adsorption properties that can be used to form protective films on the surface of metals, which helps to inhibit anodic metal dissolution and cathodic reduction reactions [23]. The multi-layered protection is more effective than traditional coating methods due to this adsorption mechanism in addition to the physical barrier effect of the nanoparticles. Past research has shown that the use of nanomaterials and natural corrosion inhibitors together could achieve outstanding corrosion protection performance without compromising the environment [24]. This study further proved the potential of plant-based hybrid nanocoatings as alternative to traditional synthetic corrosion protection systems due to its high inhibition efficiency and low corrosion rate.

The industrial application of the developed coating system is advantageous to the long-term protection of pipelines and sustainable management of infrastructure. Better corrosion resistance also can help to ensure operational reliability, prolong the service life, minimize maintenance needs, and lower costs of corrosion failures. The use of renewable plant resources also encourages good engineering practice by the use of environmentally friendly means and reduces reliance on harmful synthetic inhibitors [23]. In addition, new smart and multifunctional coating technologies have demonstrated the feasibility of incorporating self-healing and responsive corrosion inhibiting elements in hybrid coating systems [22]. These developments will help to enhance coating toughness and adaptability for extreme operating conditions. The use of nanotechnology with green corrosion inhibitor therefore has great potential to produce next generation protective coatings that will satisfy the technical and environmental demands in the oil and gas industry [24,25].

CONCLUSION

Anti-corrosion hybrid nanocoatings made by using eco-friendly plant extracts is a promising and sustainable solution to improve the durability of oil and gas pipelines. The combination of SiO_2 and TiO_2 nanoparticles with phytochemical compounds of plant origin led to a multifunctional coating system that combines chemical corrosion protection with physical barrier protection. The developed coating was found to have better structural integrity, hydrophobicity, corrosion resistance and corrosion rate than conventional protective systems. The nanoparticles helped to create compactness and limit moisture and aggressive ion diffusion, while the phytochemical components created protective adsorption layers, reducing electrochemical corrosion reactions. These synergistic effects greatly enhanced the overall efficacy of the coating, highlighting the potential for hybrid nanotechnology-based coatings for corrosion control. Besides the technical benefits, plant-based hybrid nanocoatings contribute to environmentally friendly engineering processes as they enable the replacement of synthetic corrosion inhibitors containing toxic ingredients and the increased application of natural resources as engineering materials. Overall, the proposed coating system has significant potential for application in the oil and gas industry to extend the service life of pipelines, enhance operational reliability, and decrease maintenance expenses. Further research work should be directed towards long-term field testing, formulation optimization, large scale industrial testing and addition of smart functions to improve corrosion protection performance.

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الصحة والعلوم والاستدامة: مراجعة متعددة التخصصات لديناميات الأمراض والتطورات العلاجية والتحديات البيئية

الملخص

ترتبط ديناميات الصحة والاستدامة البيئية ارتباطًا وثيقًا. شهدت السنوات الأخيرة تحولات سريعة في أنماط الأمراض، من جوائح مثل كوفيد-19 إلى تزايد الأمراض المزمنة نتيجة للعولمة والتوسع الحضري وتغير المناخ. في الوقت نفسه، يشهد الطب تقدمًا تكنولوجيًا متسارعًا، حيث تُحدث العلاجات والتشخيصات الحديثة والذكاء الاصطناعي نقلة نوعية في الوقاية والرعاية. تؤثر العوامل البيئية، كالتلوث واستخدام الأراضي والتغيرات المناخية، على ظهور الأمراض وتفاقم المخاطر الصحية. تدمج هذه المراجعة مجالات متعددة لدراسة كيفية انتشار الأمراض وتطورها، وأحدث العلاجات والابتكارات الطبية الحيوية، والتحديات البيئية التي تهدد الصحة وتوازن النظام البيئي. نلخص الاتجاهات الرئيسية في علم الأوبئة والنمذجة، ونسلط الضوء على الإنجازات في العلاج والتشخيص، ونستكشف قضايا الاستدامة مثل استخدام الأسمدة وتأثيرات المناخ. تُستخدم التجارب والبيانات العامة، بدءًا من دراسات منظمة الصحة العالمية حول المناخ وصولًا إلى تحليلات OurWorldInData ، لتوضيح هذه المحاور. الهدف هو تقديم عرضٍ واضحٍ ومُبسّطٍ للمواضيع المعقدة، مُوجّهٍ لجمهورٍ واسع.

الكلمات المفتاحية: ديناميكيات الأمراض، اللقاحات، المضادات الحيوية، تغير المناخ، الصحة الواحدة، تقنية النانو، مقاومة المضادات الحيوية، الاستدامة.