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A Review of Up-To-Date Research Knowledge on the Corrosion Inhibiting Capability of Garlic (Allicin Sativum) for Steel Materials

T.N. Guma, Jacob O. Aremo

Department of Mechanical Engineering, Faculty of Engineering and Technology, Nigerian Defence Academy, Kaduna, Nigeria

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ABSTRACT

Corrosion is a monumental economic and technological problem worldwide. Despite the poor corrosion resistance of steel material, contributing to about 90% of all corrosion problems worldwide, it remains the most versatile and critical structural material in the construction of automobiles, ships, aircraft, rail transport systems, engine systems, pipeline systems, bridges, buildings, petroleum refineries, etc. Corrosion inhibitors are effective alternatives for protecting steel against corrosion in aqueous environments. Synthetic corrosion inhibitors pose serious problems to global environmental issues and health risks in usage to reduce corrosion of large amounts of steel goods, so natural plant extracts have been under study for replacing synthetic inhibitors in various environments due to their excellent environmental properties, handling safety, and good corrosion inhibition capabilities. This paper aims to present up-to-date research knowledge on the corrosion inhibition capability of garlic for steel materials, covering its requirements as a potential corrosion inhibitor and various research studies on its steel corrosion inhibition capability in various aqueous environments as integrated knowledge for application. The review shows that garlic is a very effective corrosion inhibitor of steel corrosion. It is also a safe-for-handling, biodegradable, and eco-friendly plant that is sustainably available around the world. Its extracts can be dependably prepared in sufficient quantity around the world for corrosion inhibition of steel materials and some other purposes. However, little is seen to have been done with the existing research findings for practical protection of steel materials in various aqueous environments. The review information is therefore posited for standardization and commercialization consideration of garlic extracts as corrosion inhibitors for practical corrosion inhibition of steel materials or further research requirements.

-Key words: Steel material, Corrosion problems, Most important, Better inhibitors, Garlic extracts, Research knowledge, Application level, Further research

I. INTRODUCTION

Corrosion is any natural process, especially an electrochemical process, by which a material component, especially metal, is gradually attacked by interaction with its environment, resulting in the destruction or reduction of its useful properties and values [1]. Different types of engineering materials are subject to corrosion in different types of macro- and micro-environmental conditions in their service applications, but the critical concern is for structural materials such as steel, concrete, wood, and aluminum, which are more susceptible to hazardous failure under deterioration processes. Out of these materials, steel is the most versatile and most used in various structural applications because of its outstanding engineering properties and wider availability at relatively cheaper rates, coupled with its sustainable production in the foreseeable future. However, the corrosion of steel accounts for about 90% of all global corrosion problems [1,2, 3]. The corrosion resistance of steel decreases with a decrease in its carbon content or alloy elements. Plain carbon steel is essentially an iron-carbon alloy material with up to 0.7% carbon content by weight and no or negligible amounts of other elements to affect its properties. Mild steel is a type of plain carbon steel with a carbon content of only up to 0.3% and negligible alloy elements. Stainless steels and alloy steels are iron-carbon metal alloys that contain one or more alloying elements, such as chromium, nickel, molybdenum, tungsten, vanadium, sulfur, etc., in significant amounts by weight that modify their characteristics to varying degrees. Mild steel makes up about 90% of all applied steels, and 90% of corrosion issues with all steels globally are due to the usage of mild steel in various engineering applications [1, 3, 4,]. Mild steel has exceptionally good fabrication properties, such as formability, bendability, forgeability, weldability, braze-ability, and machinability, coupled with its easy accessibility and affordability, good hardness, and high tensile, impact, and fatigue strengths that are maintained without breaking easily. It is also widely available at relatively cheaper rates with sustainable production in the foreseeable future[1, 2]. Steel, especially mild steel as the most versatile and widely used structural material, finds applications in all areas of engineering technology, from mere household and farm parts to large industrial structures such as road bridges, railways, storage tanks, aircraft, automobiles, and ocean liners. A lot of money amounting to several billion American dollars is spent annually globally on research on the science and methods of negating steel corrosion at the lowest cost, yet the up-to-date efforts and technological sophistication on the subject are still far from utopian achievements [1, 2, 3].

Various corrosion control methods are needed to avert corrosion of steel under various environmental conditions. One of the most versatile, economical, and widely used method is by the use of corrosion inhibitors. A corrosion inhibitor is any substance that, when introduced in small quantities into a corrosive medium in gaseous, liquid, or solid coating state, can restrain the corrosion of a material component or system in the medium to an appreciable level, even up to 100% [4, 5]. The effectiveness of a corrosion inhibitor in an environment depends on the material component it should protect. Various corrosion inhibitor types are employed for various materials in various industrial environment types, but all of them have at least an issue with regards to cost, availability, performance level, safety in usage, dependability level, environmental limitations, ineffectiveness for some materials, effective time limitations, etc., so there has been continued search to date for better corrosion inhibitors for steel material types in various environments. The use of corrosion inhibitors is one of the most feasible, economical, and effective methods of protecting steel components used in many industrial settings, such as petroleum extraction and processing, gas production, chemical and petrochemical manufacturing, heavy industrial manufacturing, water treatment, water and other fluid storing containers, engine cooling systems, ferrous metal cleaners, automatic fluid transmission systems, automotive components manufacturing, machining, etc., from corrosion [4, 5, 6]. Effective corrosion inhibitors are expected to perform under a wide range of conditions; hence, special attention must be paid to selecting inhibitors for various practical applications. Despite the great number of studies devoted to corrosion inhibitors, most of what is known is the result of trial and error, both in the laboratory and in the field. Historically, the development of corrosion inhibitors is always basically determined by their effectiveness, sustainable availability, costs, handling and environmental safety levels, and handling safety, environmental corrosivity level [5]. The continued development and use of toxic corrosion inhibitors that contain heavy metals that pollute water and soil, and eventually plants and animals, by accumulating and not biodegrading in them, so entering the food chain and having permanent negative impacts on human health, is of critical concern. The biotoxicity of synthetic and widely used inorganic corrosion inhibitors, such as chromate, dichromate, nitrite, nitrate, etc., for steels and other alloys or metals in several environmental conditions, is well documented, as are their non-environmentally friendly characteristics, which limit their application and handling levels [5-9]. Heterocyclic corrosion inhibitors containing polar groups and π-electrons, as well as organic products with one or more polar functionalities, have been found to be effective alternative corrosion inhibitors in reducing the impact of metallic corrosion.This is due to their ability to easily displace water molecules and get adsorbed and bonded on the metal surface, with the bonding efficiency enhanced by the presence of polar functions with S, O, or N atoms in the molecule, heterocyclic compounds, and π-electrons, so they act as a tight barrier layer and prevent or reduce the ingress of corrosive agents or species [5, 10, 11].

Plant extracts have been under study for replacing synthetic inhibitors in various environments due to their excellent environmental properties, handling safety, and good corrosion inhibition abilities of many of them. Research interest in the use of extracts from garlic as an easily accessible, biodegradable, and harmless herb, grown around the world and which has been used fornatural medicine, food, pesticidal, bactericidal, antiviral, etc.purposes, since the dawn of civilization for protecting steel from corrosion in various aqueous environments, has reached a highly advanced stage nowto have a clear overview of what has been achieved. Garlic is capable of performing its various usage functions due to the effects of a variety of its functional groups such sulfur-containing compounds with strong biological activity[5-10].

The aim of this paper is to present a review report of up-to-date research knowledge on the corrosion-inhibiting capability of garlic for steel materials, covering its availability, handling, and environmental safety levels in usage; chemical composition; extract types and extraction methods; and research advances on corrosion inhibition of steel materials in various aqueous environments as integrated knowledge for the overall appreciation of the level attained on the subject for practical application or further research requirements.

II. THE REVIEW REPORT

The review information was sourced from various relevant books, theses, journal articles, and other reputable literary sources that were published from 2014 to 2024, which are available in hardcopy forms in institutional libraries or softcopy form on the INTERNET, integrated, fine-tuned, analyzed, and presented in a more readable and understandable form to showcase the significance of the work.

2.1 Garlic Production and Availability

An essential requirement for garlic extracts to be used as dependable corrosion inhibitors that the raw garlic from which the extracts are derived must be sustainably available from time to time. The total world production of garlic is currently about29,149,438 metric tons. It is agriculturally produced in significant quantitiesin mostcontinents andcountries of the world. China, with an annual garlic production of 20,058,388 metric tons, stands as the largest garlic producing country in the world as of September 2024 with a 76.28% share, followed by India at 9.28% share. Bangladesh, South Korea, Egypt, and Myanmar trailed with 1.66%, 1.14%, 1.05%, and 0.7% values respectively. Significant producers in Europe include Spain (0.92%), Uzbekistan (0.8%), Russian Federation, and Ukraine. In Africa, the main garlic producer countries in decreasing orderincludeAlgeria, Ethiopia, Sudan, Mali, Morocco, Niger, Tanzania, Libya, Kenya, Madagascar, andNigeria with average annual production quantities that range from about 195,976 to 2,183.1 metric tons.On the continents of America, garlic is produced mainly in the USA, Brazil, Argentina, Peru, Mexico, Guatemala, Canada and Chile. On the other hand, many countries including Spain, Argentina, Netherlands, Mexico, France Egypt, Afghanistan, Peru, India, Malaysia,United States. Chile, and Myanmar are exporters of large quantities of garlic to other countries including those that do not produce garlic. These indicate that garlic will be sustainably available globally for its juice extractions and preparations in sufficient in appreciable quantity for corrosion inhibition and other purposes around the world at a low cost [12, 13, 14].

2.2 Safety indices of Garlic as a Corrosion Inhibitor

Garlic has been used as a condiment and medicine since prehistoric times, as evidenced by ancient writings from China, Egypt, Greece, and India. It has been used in many cultures for thousands of years in funerals and religious ceremonies to mummify bodies. Participating athletes in the Olympic Games chewed garlic to improve their strength, stamina, and endurance. During the Roman times, soldiers and workers chewed garlic before battle, and Slavs chewed it to protect them from snakebite. In Africa, fishermen used to paint their bodies with garlic extract to ward off crocodiles. In Europe, garlic was used by some people to ward off vampires, evil spirits, and demons. The use of garlic is even referred to in the Bible. Garlic has been used in Egypt, Greece, Rome, India, and China, and many ancient civilizations to treat a variety of illnesses, such as poisoning, stomach and respiratory conditions, abnormal growth, headaches, insomnia, and depression. An ancient Greek physician, Hippocrates (c. 460–370 BC), the "father of western medicine," recommended garlic for treating weariness, indigestion, parasites, and respiratory issues. Garlic is a powerful remedy for a variety of illnesses, including viral ones. In China, patients with cryptococcal meningitis have also been treated by ingesting fresh garlic or by administering extracts of it intravenously. Garlic was used to treat colds, fevers, coughs, asthma, and wounds in Asia and Europe. Traditional African medicine, especially in Ethiopia and Nigeria, has utilized garlic to heal wounds, tuberculosis, respiratory tract infections, and sexually transmitted infections. Garlic has been used historically to cure intestinal worms, rheumatism,

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diabetes, bronchitis, tuberculosis, liver problems, flatulence, and fever throughout the Middle East, East Asia, and Nepal. All these and other various uses of garlic indicate that it is very friendly to the human body, even curing the body in diseased or perilous conditions, so it will be very safe for personnel handling in its usage as a corrosion inhibitor [15, 16].

Garlic is also biodegradable and poses minimal bad effects to plants, animals, and the soil [3, 4, 6]. A whole head of unpeeled garlic will last for about six months only if properly stored. One unpeeled clove lasts for roughly three weeks. But garlic begins to deteriorate more rapidly after the skin is removed. When stored in the refrigerator, individual peeled garlic cloves can survive up to a week, while chopped garlic can only last a day unless it is smeared with olive oil, which extends its shelf life to two or even three days. Garlic should be kept out of direct sunlight and closer to room temperature to reduce its deterioration time. These are just to further illustrate the biodegradability indices of garlic extracts in usage as a corrosion inhibitor.

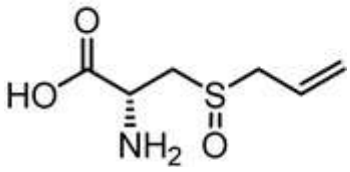
2.3 Chemical Composition and Physical Properties of Garlic Extract

The chemical composition and physical properties of any substance greatly determines its corrosion inhibition capability. It has been documented that an undamaged fresh garlic contains approximately 200 chemical compounds.It contains sulfur-containing compounds, volatile oils, enzymes, carbohydrates, minerals, amino acids, and vitamins [4, 5, 6, 17]. The average garlic bulb contains 65% water, 28% carbohydrates, 2.3% OSC, 2% proteins, 1.2% free amino acids, 1.5% fiber, and minerals including potassium (93.4–401 mg/100 g), sulfur (183.4 mg/100 g), aluminum (0.47 mg/100 g), iron (1.7–3.11 mg/100 g), sodium (8.93–17 mg/100 g), magnesium (15.4-25 mg/100 g), zinc (1.53 mg/100 g), copper (1.6 mg/100 g), calcium (181 mg/100 g), phosphorous (153 mg/100 g), selenium (14.2 μg/g), manganese (1.672 mg/100 g), and vitamins including thiamine (0.2 mg/100 g), riboflavin (0.11 mg/100 g), pantothenic acid (0.596 mg/100 g), vitamin B6 (1.235 mg/100 g), folate (3 μg/100 g), and vitamin C (31.2 mg/100 g) [15]. Garlic oil contains 60% Diallyl disulfide; 2.62% Alliin; 0.15-0.66 Allicin, 0.09-0.68%. γ-glutamyl-S- (E, Spropenyl) cysteine, and the remainder is composed of various non-protein amino acids and lipids. Garlic has an unusually high proportion ofsulfur-containing chemicals (13%)of which some types with theirnames, formulae, and compositions are shown in Table 1. The main components of garlic that contain sulfur are however g-glutamyl cysteines and S-alkyl-L-cysteine sulfides (ACSOs), which include allicin.The processing steps have been confirmed to impact the final bioactive potency directly, and slight differences in the level of active ingredients may also cause profound [18, 19].

At the physical state of 25°C and one atmosphere of pressure; garlic powder is solid, garlic oil is liquid,garlic power is white to yellowish-white in color, garlic oil is clear yellow to red-orange in color. Garlic is distinct pungent garlic in odor and the density/specific gravity of its oil ranges from 1.050 to1.095. The melting point of garlic oil is-59.48°C while its boiling point is 136.32°C. Garlic oil is soluble in most fixed oils, and mineral oils. The oil is incompletely soluble in alcohol, and insoluble in glycerin, and propylene glycol. The vapor pressure of garlic oil is 10 mm at 20°C, and its pH ranges from 5.5 to 6.0. Garlic oil has aviscosity(η) of 9.2 mPa/s ±0.4,and unreported miscibility value. Garlic oil is stable in storage but highly flammable. The oil is a corrosion inhibitor of steel. The oil has an air half-life of 2.81 hrs., soil half-life of 720 hrs., water half-life of 360 hrs., and persistence of 244 hrs. [18, 19].

From the foregoing it is apparent that the chemical composition of garlic is highly complex, and the composition also includes severalpolar functions with S, O, or N atoms in the molecule, heterocyclic compounds, and π-electrons which known to be components ofbest-known organic corrosion inhibitors [5, 10].

Table 1: List and structures of some of the sulfur-containing compounds isolated from Allium sativum[18, 19].

Compounds	Molecular formula	Structure
Alliin	$C_6H_{11}NO_3S$	

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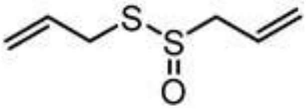
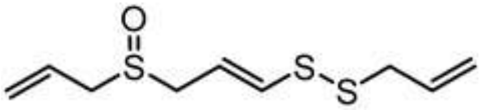
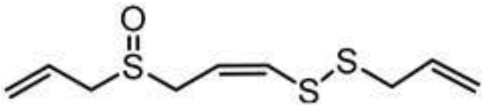
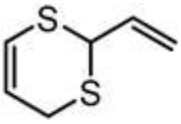
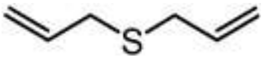
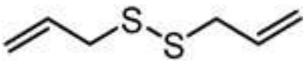
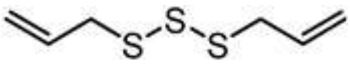
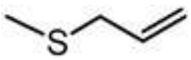
Compounds	Molecular formula	Structure
Allicin	$C_6H_{10}OS_2$	
E-Ajoene	$C_9H_{14}OS_3$	
Z-Ajoene	$C_9H_{14}OS_3$	
2-Vinyl-4H-1,3-dithiin	$C_6H_8S_2$	
Diallyl sulfide (DAS)	$C_6H_{10}S$	
Diallyl disulfide (DADS)	$C_6H_{10}S_2$	
Diallyl trisulfide (DATS)	$C_6H_{10}S_3$	
Allyl methyl sulfide (AMS)	C_4H_8S	

2.4 Garlic Extractsand Extraction Methods

Garlicextractsare derived from the garlic bulb.A number of different methods including manual methods have been in use for extracting garlic but the significant methods used forhigher productivity, and efficiency atlower extraction time are the Soxhlet extraction, ultrasonic-assisted extraction, steam distillation. pressurized liquid extraction, supercritical-fluid extraction, and microwave extraction [20, 21].Thetypes ofgarlic extractthat are commercially available in the market worldwidewhich can be used for corrosion inhibition of metallic surfacesaregarlic oil,prebiotic polysaccharide, aged garlic,black garlic, and garlic powder, The popular methods of extracting garlic oil are by hydro distillation,steam distillation, solvent extraction,supercritical CO_2extraction,microwave extraction.On the other hand, the frequently used methods of extractingprebiotic polysaccharideare by solvent extraction,pressured liquid extraction, enzyme-assisted, microwave-assisted,pulse electric field, and ultrasound-assisted extractions technologies.The aged garlic extract is produced by extracting sliced garlic inaqueous or ethanol and aging it naturally for up to 20 months, afterwhich the unpleasant and irritating components in garlic arenaturally transformed into more stable and more efficient compounds. The black garlic is extracted using thermo-hydrostatchamber,rice cooker, thermohygrostatic chamber, and microwave heating. Garlic powder is produced by dehydration garlic cloves by varieties of methods such as thermal hot air drying, infrared drying, microwave drying, solar, and vacuum drying as well as non-thermal (freeze-drying) technologies followed by grinding into powder[20, 21]

2.5 Review of someResearch on the Use of Garlic for Steel Corrosion Inhibition

Ikumapayi, et al. [11] contended that corrosion is one of the great challenges faced in the industries today, as it accounts for a lot of setbacks and losses. The use of corrosion inhibitors in solving corrosion problems has special advantages in terms of the ease of their application and effectiveness in performance. Among various inhibitors, organic inhibitors are mostly used due to their eco-friendliness and availability. Their research focused on the inhibitory properties of garlic extract in 0.5M HCl. They investigated the inhibitive effect of garlic (Allium sativum) on the corrosion of mild steel in 0.5M HCl using weight loss measurement and electrochemical methods. The garlic extracts were characterized using atomic absorption spectroscopy (AAS) and Fourier transform infrared spectroscopy (FTIR). Their results from the electrochemical and weight loss techniques demonstrated that mild steel corrosion rates in 0.5M HCl decrease with increasing garlic extract content. The concentration of 8 v/v% garlic extract produced the lowest corrosion rates and weight loss, at 0.53 mm/yr and 0.22 g, respectively. Using the electrochemical approach, the corrosion rate dropped from 1.66 mm/yr to 0.53 mm/yr, and the cumulative weight loss decreased from 1.71 g to 0.22 g. As the content of garlic extract grew, so did the efficiency of corrosion inhibition. The extract's maximum inhibitory efficiency of 68% was reached at a concentration of 8 v/v%. Fourier Transform Infrared Spectroscopy (FTIR) revealed the existence of an aromatic and phenolic functional group, which was responsible for the garlic extract's good inhibitory qualities. Atomic absorption spectroscopy was used to verify the garlic extract's environmental friendliness.

Yang et al. [22] examined garlic extract as a corrosion inhibitor for mild steel in acidic media. According to the extract's IR spectrum analysis, the primary component is amino acids. The optimal extracting conditions are 30°C, 50 mL, 10% H_2SO_4, and 20 g of peeled garlic. These conditions cause the extract to react for 120.0 hours, yielding a composite amino acid concentration of 19.0 mg/L. The outcome of corrosion inhibition performance utilizing static weight loss demonstrates that corrosion inhibition is significantly impacted by extract dosage, temperature, and acidic medium concentration. At 4.0% (V/V) and 6.0% (V/V) of garlic extract, respectively, the corrosion-inhibitive efficiency of A3 steel is 93.26% in 5% hydrochloric acid and 79.2% in 5% mud acid. According to the extract's electrochemical performance results, the corrosion potential of A3 steel shifts negatively in both mud acid and hydrochloric acid, indicating that the extract inhibits cathodic corrosion. Additionally, the circular-arc radius of alternating-current impedance spectroscopy increases noticeably in acidic media, demonstrating the extract's remarkable corrosion inhibition effect. As a result, extracting inhibitors from garlic is possible.

Afia et al. [23] studied steel corrosion inhibition by acid garlic essential oil as a green corrosion inhibitor and sorption behavior. The study used weight loss, electrochemical impedance spectroscopy (EIS), and potentiodynamic polarization techniques to examine the inhibitory effect of acid garlic essential oil (GO oil) on carbon steel corrosion in a 1M HCl solution at varying temperatures. In a hydrochloric acid environment, GO oil effectively prevents carbon steel from corroding. The creation of an adsorbed coating of inhibitor on the metal surface, which prevents corrosion, is thought to be the cause of the inhibition process. The outcome shows that when inhibitor concentration rises, so does inhibition efficiency. GO oil's %IE varies with concentration, reaching about 95.8% for 2.5 g/L at 298K. It was also investigated how temperature affected the way carbon steel corroded in 1 M HCl with essential oil added. The Langmuir adsorption isotherm was followed by the essential oil's adsorption on the carbon steel surface. The inhibitory efficiency values determined by electrochemical impedance spectroscopy, potentiodynamic polarization, and weight loss accord well. Polarization curves demonstrated the mixed-type inhibitory behavior of GO oil. In addition to other thermodynamic characteristics for the inhibition process, the activation energy was computed and analyzed. According to the results, carbon steel corrosion in hydrochloric acid solutions may be effectively inhibited by the acid garlic essential oil.

Barreto et al. [24] studied the corrosion inhibition efficiency of peel garlic extract (Allium sativum. L.) for possible replacement of benzotriazole (BTAH) for corrosion inhibition of ASTM 1020 carbon steel (CS-1020) in 0.5 mol/L hydrochloric acid media. Weight loss measurements, anodic and cathodic potentiodynamic curves, and electrochemical impedance (EIS) experiments were carried out. Fourier transform infrared spectroscopy (FTIR) was carried out to evaluate the chemical compounds. The morphological characterization was obtained to observe the inhibitory effect of the corrosion products on the substrate surface. The results showed that the addition of both inhibitors effectively hindered the corrosion process and indicated their adsorption on the electrode surface. The inhibiting efficiency of the peel garlic extract was only slightly inferior to BTAH, showing that the former inhibitor can be an environmentally friendly alternative to toxic inhibitors. The FTIR analysis showed the presence of chemical compounds that possess antioxidant properties.

Miralrio and Vazquez [25] contended that "natural extracts have been widely used to protect metal materials from corrosion. The efficiency of these extracts as corrosion inhibitors is commonly evaluated through electrochemical tests, which include techniques such as potentiodynamic polarization, electrochemical impedance spectroscopy, and weight loss measurement. The inhibition efficiency of different extract concentrations is a valuable indicator to obtain a clear outlook to choose an extract for a particular purpose. A complementary vision of the effectiveness of green extracts to inhibit the corrosion of metals is obtained by means of surface characterizations; atomic force microscopy, scanning electron microscopy, and X-ray photoelectron spectroscopy analysis are experimental techniques widely used for this purpose. Moreover, theoretical studies are usually addressed to elucidate the nature of the corrosion inhibitor-metal surface interactions. In addition, calculations have been employed to predict how other organic substances behave on metal surfaces and to provide experimental work with fresh proposals.'' Their research work reported a broad overview of the current state of the art research on the study of new extracts as corrosion inhibitors on metal surfaces in corrosive media. Most constituents obtained from plant extracts are adsorbed on the metal, following the Langmuir adsorption model. Electron-rich regions and heteroatoms have been found to be responsible for chemisorption on the metal surface, whereas physisorption is due to the polar regions of the inhibitor molecules. The plant extracts compiled in this work obtained corrosion inhibition efficiencies above 60%, most of them around 80–90%. The effect of concentration, extraction solvent, temperature, and immersion time were studied as well. Additional studies regarding plant extracts as corrosion inhibitors on metals are needed to produce solutions for industrial purposes.

Karthigaet al. [26] evaluated the inhibition efficiency of allium sativum extract (garlic extract) in controlling corrosion of mild steel immersed in well water using the weight loss method. The study revealed that the formulation consisting of 10 mL of garlic extract and 90 mL of well water has a 90% corrosion inhibition efficiency for the steel. The mechanistic aspects of the corrosion inhibition were evaluated by polarization studies and AC impedance spectra. FTIR spectra revealed that the protective film consisted of a Fe2+-allicin complex. This was further confirmed by UV-visible absorption spectra.

Barreto et al [27] investigated the use of garlic peel extract (Allium sativum) and cacao peel (Theobroma L.), as well as their synergy as a corrosion inhibitor for carbon steel in a 0.5 mol/L hydrochloric acid solution. The comparative study was performed on 1.11 g/L of the extract. The investigation was carried out using gravimetric techniques, Fourier transform infrared spectroscopy (FTIR), electrochemical impedance spectroscopy (EIS), and scanning electron microscopy techniques. Gravimetric test results showed a reduction in the corrosion rate of the extracts, with 90.7% efficiency for garlic extract and 89% for cacao extract. The mixture of the compounds presented an inhibition superior to 98%, showing the great synergism between the studied species. The EIS results showed a higher impedance module value for cacao extract compared to garlic extract. The chemical analysis of extracts of garlic and cacao obtained by FTIR showed the presence of compounds based on Sulphur and nitrogen, which are responsible for the corrosion-inhibiting effect. The SEM images obtained showed the formation of a film, which reduces the evaluation of the corrosive process. Then, it is possible to conclude that the carbon steel surface immersed in a 0.5 mol/L HCl solution with garlic peel extracts, cacao peel extracts, or both presents a corrosion-inhibiting effect.

Rajam et al. [28] evaluated the inhibition efficiency (IE) of an aqueous extract of garlic in controlling corrosion of carbon steel in well water in the absence and presence of Zn2+. using the mass-loss method. The formulation consisting of 2 mL of garlic extract and 25 ppm Zn2+ offered 70% inhibition efficiency to carbon steel immersed in well water. The polarization study revealed that this formulation controls the anodic reaction predominantly. FTIR spectra reveal that the protective film consists of the Fe2+-allicin complex and Zn (OH)2.

Belkaid et al. [29]contended that "the high toxicity of industrial metal corrosion inhibitors raises various environmental and health problems, so the study of metal and alloy corrosion inhibition in acidic media by eco-compatible organic compounds has become a very attractive research field.'' In their research, the inhibition efficiency (IE) of garlic extract (GE) against API X60 carbon steel (CS) and 316L stainless steel (SS) corrosion in a 1 M sulfuric acid (H2SO4) solution was investigated using electrochemical techniques, including potentiodynamic polarization (PPD) and electrochemical impedance spectroscopy (EIS). The experimental results showed the remarkable corrosion-inhibitive performance of garlic extract (GE). The corrosion IE, which depends on the inhibitor concentration, increased up to 90% for SS and 67% for CS, as shown from the PPD tests. EIS analysis showed that the corrosion resistance (CRST) was increased in the medium with GE, indicating the improvement of the properties of the passive films formed on surfaces of the steels.

Joycee et al. [30] investigated the inhibiting effect of garlicextracts (Allium sativum) in controlling corrosion of mild steel in simulated oil well water (SOWW) in the absence and presence of Zn^{2+} using different techniques such as weight loss method, potentiodynamic polarization, and electrochemical impedance spectroscopy for different concentrations of the plant extract. The corrosion inhibition efficiency increased with increasing garlic extract concentrations, and the aqueous formulation consisting of 100,000-ppmgarlic extract and 50-ppm Zn^{2+} provided 87% inhibition efficiency. The inhibitor system was found to be a cathodic inhibitor with an optimum inhibition concentration of 10 mL of Allium sativum and 50 ppm of Zn^{2+} in a potentiodynamic polarization study. The corrosion potential was observed to shift from -777 mV vs. SCE to -880 mV vs. SCE. The linear polarization resistance (LPR) value increased from 482 Ohm·cm^2 to 1831 Ohm·cm^2. The corrosion current decreased from 1.034×10^{-4} A/cm^2 to 0.1515×10^{-4} A/cm^2. These factors confirmed that allium sativum extracts control the corrosion of mild steel in SOWW. The AC impedance spectra confirmed that the protective coating was very stable, as revealed by the fact that in the presence of an inhibitor on mild steel, the charge transfer resistance increased and impedance increased, whereas double layer capacitance decreased to a great extent. Surface analysis was carried out to find out the surface morphology of the mild steel in the presence and absence of the inhibitor. The obtained results show that the Allium sativum extract acts as a good inhibitor for the corrosion of mild steel in SOWW.

Yaro et al. [31] investigated the corrosion inhibition of mild steel in H_3PO_4 solution by garlic powderusing weight loss and polarization techniques. The adsorption of garlic powder was found to obey the Langmuir adsorption isotherm. Maximum inhibition efficiency was 75% at 50 ^oC and 250 ppm inhibitor concentration. The values of heat of adsorption were negative, indicating a spontaneous adsorption process. Quantum chemical calculations were used successfully to evaluate the theoretical inhibitor efficiency. Mathematical and statistical analyses were also used to represent the corrosion rate data with high correlation coefficients. Polarization measurements showed that garlic powder was a mixed-type inhibitor.

Wei-Min and Dao-Yong [32] carried out a study on the use of garlic juice as a corrosion inhibitor of carbon steel in hydrochloric acid and oil field water media with or without CO_2 or H_2S using the weight loss method, and the corrosion inhibiting mechanism was proposed by the use of SEM and electrochemical methods. The results show that garlic can obviously slow down the corrosion rate of steel in hydrochloric acid, and the inhibitor efficiency reaches 95.4% in 15% HCl at 80 °C. The inhibitory efficiency decreases with an increase in the concentration of hydrochloric acid. Garlic juice can also slow down the corrosion rate of steel in oil field water, and the inhibitor efficiency ranges from 42% to 64%. One kind of thin film can form on the steel surface, and studies reveal that the film is of the absorbed type.

Fouda et al. [33] conducted a study on the use of allium sativum (garlic) as a green inhibitor of low-carbon steel corrosion in 1M HCl using weight loss measurements, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and electrochemical frequency modulation (EFM) techniques. Results showed that allium sativum extract is a good inhibitor of steel corrosion in the acid by reducing the corrosion rate due to the formation of an external layer formed by the Sulphur-containing film present in the extract, which was adsorbed physically on the metal surface. Allium sativum acts as a mixed-type inhibitor. The inhibition efficiency increases with increasing the inhibitor concentration but decreases with raising the temperature. The adsorption of allium sativum on the metal surface follows Temkin's adsorption isotherm from EFM. The causality factors are very close to theoretical values, which indicate that the measured data are of good quality, and Nyquist plots showed a single capacitive loop in uninhibited and inhibited solutions.

Parthipan et al. [34] estimated the effectiveness of garlic extracts to inhibit the biocorrosion of carbon steel API 5LX (CS) and stainless steel 316 (SS) in the presence of Bacillus subtilis A1 and Streptomyces parvus B7. Weight loss and electrochemical studies, including linear polarization and AC impedance, along with surface analysis, were used to examine the antibacterial corrosion inhibition efficiency (IE) for both metals in the presence of GAE. Test results and analyses identified 100 ppm of the GAE as the minimal inhibitory concentration for bacterial growth. The strains A1, B7, and their mixed consortium caused severe corrosion in both metals. In the presence of GAE, the IE for abiotic systems was about 81 ± 3% and 75 ± 3%, while in the presence of the mixed consortium, the IE was 72 ± 3% and 69 ± 3% for CS and SS, respectively. Gas chromatography mass spectrum analysis of GAE indicated that GAE contains a sulfur-rich compound, which plays a key role in the inhibition of both bacterial development and corrosion. This was the first time garlic extract was proposed as a green corrosion inhibitor with biocidal activity to control biocorrosion in a hypersaline, corrosive environment containing microorganisms.

Rodriguez-Clemente et al. [35] used potentiodynamic polarization curves, electrochemical impedance spectroscopy, and weight loss measurements to investigate the applicability of Allium sativum (garlic) as a corrosion inhibitor for carbon steel corrosion in 0.5 M H2SO4 at 25, 40, and 600 °C, with inhibitor concentrations of 0, 100, 200, 400, 600, and 800 ppm. They demonstrated that Allium sativum is a potent inhibitor of steel corrosion, with an effectiveness of 96% at 400 ppm concentration. The S-containing film in the extract, which was physically adsorbed on the steel surface, created an exterior layer that was responsible for the decrease in the rate of corrosion. Allium sativum functioned as an inhibitor of mixed types.

Elwaleed [36] aimed to evaluate the efficacy of garlic extract (GAE) as a biocide and investigate the biocorrosion of an ancient knife found in burial dirt. They swabbed the knife to find bacteria, and the organisms were cultivated for 24 hours at 37 degrees Celsius in tryptic soy broth. Scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) was used to examine the knife; X-ray diffraction was used to examine the corrosion products; and gas chromatography-mass spectrometry (GCMS) and Fourier transform infrared spectroscopy (FT-IR) were used to examine the garlic extract. To investigate the behavior of microbial corrosion, coupons made of synthetic materials with the same chemical composition as the knife under investigation were produced and subsequently exposed to isolated species of bacteria. Utilizing scanning electron microscopy, the biofilm that had developed on the coupons' surfaces was investigated. The findings showed that six different kinds of fungi and five different species of bacteria were present, along with the appearance of a carbon steel blade on the knife. It was found that the bacteria were made up of one type of acid-producing bacteria (APB) and four different species of iron-oxidizing bacteria (IOB). To assess the bacterial growth on the surface of the agar plate, sessile IOB was measured in units of CFU. Using GCMS, a sulfur-rich molecule found in GAE was identified as potentially inhibiting the growth of bacteria. Allicin is the active component of garlic that gives it antibacterial qualities against both Gram-positive and Gram-negative bacteria. In conclusion, they asserted that GAE may be sold as a natural biocide in order to substitute for more dangerous commercial biocides.

According to Patil and Zaware [37], reinforced concrete is one of the most affordable and adaptable building materials in use today. Concrete uses steel as a reinforcing material to impart tensile strength to its fragile nature. When exposed to harsh environmental conditions, one of the key factors affecting these steels' strength and endurance is corrosion. The passivity of reinforcing steel bars will be destroyed, and corrosion will result from concrete with a PH of less than 10. As part of their research, they conducted an experimental investigation on how to use the natural inhibitor allium sativum to prevent steel corrosion in concrete. They employed different amounts of HCL and water, ranging from 30% to 50% of the solution's total weight, to accelerate their corrosion process. Epoxy resin with an artificial inhibitor was utilized to compare results. They obtained an inhibitory efficacy of 90% to 95% from analyses of the results of electrical resistance and weight loss tests and concluded that Allium sativum is a good inhibitor.

According to Maestro et al. [38], mild steels' primary shortcoming is their resistance to corrosion, according to AISI 1020. In order to slow down the deterioration of steel, corrosion inhibitors are used; lately, green inhibitors have become more popular because of their little environmental impact. The use of inhibitors in acidic media is the primary emphasis of the literature, despite substantial research on the subject. The purpose of their study was to evaluate garlic peel's ability to inhibit corrosion of mild steel at different pH levels by examining its effectiveness as a green inhibitor in three different aqueous solutions: acid (with HCl), neutral (with NaCl), and basic (with NaOH). Tests on mass loss and electrochemical corrosion showed effectiveness in all evaluated situations. After the mass loss tests, SEM/EDS analysis was done to examine how the corrosion products changed and decreased. The efficacy of the inhibitor declined over time in an acidic medium, reaching a maximum of 24 hours. On the other hand, the inhibition efficiency rose for up to 24 hours in neutral and basic media. This rise was greater in the basic solution containing NaOH. These results were corroborated by quantum modelling, which showed that the garlic chemicals alliin and allicin produce more active specimens under simple circumstances. This realization contributes to the explanation of the NaOH solution's better performance.

Ojha [39] studied the effect of garlic extracts on mild steel in 1 M HCl as an eco-friendly corrosion inhibitor. Through weight loss and scanning electron microscopy (SEM) examination, the study examined the impact of garlic extract on mild steel in order to demonstrate corrosion behavior in an acidic medium (1 M HCl). This test was conducted to determine the corrosion rate at three different temperatures: 298K, 313K, and 323K. As the inhibitor concentration increased, the inhibition performance increased as well. With 4 g/l of extract present, the best inhibitory performance (76.47%) was attained at 298K. These results are further corroborated by mild steel's resilience to corrosion in this medium. According to the corrosion rate of 31.62 mm/yr, corrosion in this medium decreased as the austenitic temperature rose. The test findings had a correlation coefficient (R2) of 0.999 and followed the Langmuir adsorption isotherm.

Da Silvaa et al. [40] used commercial (glutaraldehyde) and natural (garlic oil) biocides to control the microbiologically-influenced corrosion (MIC) of AISI 1020 carbon steel by sulphate-reducing bacteria (SRB) in artificial seawater. These bacteria infected artificial saltwater. The most probable number (MPN) approach was utilized to quantify the sessile SRB in order to assess the proliferation of microorganisms on the steel surface. Potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) were used to investigate the role of biocides in the biocorrosion process. Using scanning electron microscopy (SEM), the biofilm formation and corrosion products on the steel surface were observed. The findings indicated that garlic oil may be used as a natural biocide in these circumstances since it reduced the corrosion process more than glutaraldehyde did, even if it was unable to entirely stop the growth of sessile SRB.

Ojha et al. [41] carried out an investigation on the effect of garlic extract on the corrosion behavior of mild steel in hydrochloric acid (1 M) medium by weight loss and SEM analyses. In order to determine the corrosion rate, tests were conducted at three different temperatures, 298, 313, and 323 K. It was found that as the inhibitor concentration increased, the efficiency of inhibition increased as well. With 4 g/L of the extract present, the maximum inhibitory efficiency of 76.47% was attained at 298 K. These results were further corroborated by the corrosion rate of 31.62 mm/yr, which shows that mild steel's resistance to corrosion in this medium declined as the austenitic temperature rose. Test results were found to obey the Langmuir adsorption isotherm with a correlation coefficient (R2) of 0.999. Quantum chemical parameters calculated by density functional theory (DFT) were correlated with the experimental results.

Asfia et al. [42] conducted electrochemical and theoretical studies on corrosion prevention of AISI 304 stainless steel in hydrochloric acid medium using garlic extract as a green corrosion inhibitor. They observed that garlic extract is a good option for preventing AISI 304 stainless steel from corrosion in acidic electrolytes because its primary molecules include a variety of functional groups. The study used weight loss measurement, potentiodynamic polarization, electrochemical noise analysis, and computational simulation, including density functional theory (DFT), Monte Carlo (MC), and molecular dynamics (MD), to examine the corrosion of AISI 304 stainless steel in 0.5M HCl with garlic extract present. Garlic extract slows down the corrosion of stainless steel in HCl solution by up to 88%, according to electrochemical tests and weight loss. By preventing both cathodic and anodic processes on the surface, the extract functions as a mixed-type corrosion inhibitor. Subsequent analysis revealed that the inhibitor adheres to the Langmuir adsorption isotherm throughout the adsorption phase. Furthermore, the computational results from DFT modelling and molecular simulations based on MC and MD provide additional insight into the garlic extract's surface adsorption characteristics.

Lu et al. [43] studied the corrosion and adhesion of a phytic acid-based conversion coating post-treated with garlic extract on Q235 steel. Before applying the natural garlic extract as a post-treatment for the conversion coating, a green phytic acid layer was created on the steel surface. In order to determine the elemental composition and micro-morphology of various samples, a scanning electron microscope (SEM) fitted with an X-ray energy dispersive spectrum (EDS) was used. The produced coating's adhesion qualities were evaluated using contact angle measurement and atomic force microscopy (AFM). Finally, polarization curves in a 3.5 weight percent NaCl solution and electrochemical impedance spectroscopy (EIS) were used to analyze the electrochemical properties of the coating on the Q235 steel. According to SEM and AFM analyses, the steel surface was covered with a uniform, flake-like layer that had fewer cracks. In particular, EIS experiments demonstrated a significant improvement in the anti-corrosion performance of the coating treated with garlic extract and a concurrent increase in the adhesive characteristic with the successive covering.

Acosta et al [44] evaluated the effectiveness of an aqueous extract of garlic, or Allium sativum, in preventing carbon steel from corroding in an acidic environment. In order to determine whether total phenols were present in the decomposing garlic extracts made with ethanol at a maximum concentration of 86.05 mg/100 mL, the first step in their study was to obtain and describe the extracts made in ethanol and water using phytochemical tests. Weight loss experiments were then conducted to measure the corrosion rate using varying extract concentrations in order to confirm the inhibitory efficiency. Higher concentrations of garlic extract demonstrated superior corrosion inhibition efficiencies, according to the data, with the decomposing garlic extracts made in ethanol exhibiting the maximum efficiency of 82.70% at a 10% extract concentration.

III. CONCLUSION

A review report of up-to-date research knowledge on the corrosion-inhibiting capability of garlic for steel materials covering its availability, handling and environmental safety levels, chemical composition, extract types and extraction methods, and corrosion inhibition research with steel materials in various aqueous environments has been presented. The review shows that:

i. The corrosion of steel material presents a significant challenge to the durability and safety of critical infrastructures worldwide, with profound economic, safety, and technological consequences.
ii. The use of corrosion inhibitors is one of the most versatile and important methods of controlling steel corrosion, and there has been an ongoing search for years for more effective, cheaper, sustainably available, environmentally friendly, and safe-for-handling corrosion inhibitors for the steel material in its service environments.
iii. Garlic is cheap, sustainably available, and has a complex chemical structure that contains active functional groups such as nitrogen, oxygen, and sulfur-containing groups, which are well known to play significant roles in the effectiveness of organic corrosion inhibitors.
iv. Various types of pure garlic extracts, such as garlic oil, prebiotic polysaccharide, aged garlic, black garlic, and garlic powder, are commercially available in the market worldwide, which can be used for corrosion inhibition of steel surfaces, and there are many extraction methods that can be used to cheaply produce the extract types in large quantities.
v. From several previous research findings, pure garlic extracts have very high corrosion inhibition of steel material in various types of aqueous media with inhibition efficiencies that can be up to 100% depending on the concentrations of the extracts used in the media for the corrosion inhibition.

The review information is intended to provide integrated knowledge of the level attained on the use of garlic for corrosion inhibition of steel materials for the standardization and commercialization consideration of garlic extracts as corrosion inhibitors for practical corrosion protection of steel materials in aqueous environments or further research requirements.

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