

(Green) Corrosion Inhibitors: An Overview of Recent Research

Sanjay K. Sharma ¹, Ackmez Mudhoo ^{2,a}, Gargi Jain ¹

¹ Computational & Green Chemistry Research Laboratory, Department of Chemistry and Environmental Engineering, Institute of Engineering and Technology, Alwar, India.
(drsanjay1973@gmail.com)

² Consultant Chemical Engineer, China International Water & Electric Corp., Mauritius Branch Office, Mauritius. (ackmezchem@yahoo.co.uk)

Abstract

Corrosion is more than just an inevitable natural process. It is also a serious engineering problem in this modern age of technological advancement and which accounts for economic losses and irreversible structural damage. Several efforts have been made to restrain the onset and thereafter destructive effects of corrosion using several preventive measures. Green Chemistry which has emerged as a new branch of environmental chemistry provides environmental friendly corrosion inhibitors specifically termed as 'Green inhibitors'. Green inhibitors are non-toxic, biodegradable and eco-friendly, and have proven effective in controlling the corrosion of steel, stainless steel, mild steel, iron, aluminium, copper, 2024-T3 aluminium alloy, steel in concrete structures, carbon steel, AA5083 Al-Mg alloy, nickel, magnesium and zinc. This paper reviews and discusses the use of and research on corrosion inhibitors and green inhibitors recently reported in corrosion literature.

Keywords: *corrosion, green inhibitors, biodegradable, steel, aluminium alloys.*

1. Introduction

Corrosion is the destruction of material resulting from exposure and interaction with the environment. It is a major problem that must be confronted for safety, environment and economic reasons (Thompson [1]). Safety concerns are of utmost importance in every society and in all situations. Environmental concerns include corrosion caused pollution, depletion of resources such as those needed for replacement of the corroded structures

^a **Corresponding Author:** Consultant Chemical Engineer, China International Water & Electric Corp., Mauritius Branch Office, Mauritius. (ackmezchem@yahoo.co.uk)

and disposal of the corroded structures. To combine the technological progress with environmental safety is one of the key challenges of the millennium. Cleaner technology is new dimension that is emerging rapidly at both national and international level. Cleaner production has been identified as a key method for reconciling environment and economic development. The basic idea of cleaner production is to increase production efficiency while at the same time eliminate, or at least, minimize wastes generation and emissions at their source rather than treat them at the end of pipe only after they have been generated. The concept of cleaner production, pollution prevention or waste reduction is still relatively young, although the concepts involved are much older. Both cleaner production and sustainability came into focus with the publication of 'Our Common Future'. This report provided a focused definition for the concept of sustainable development: "A process of change in which the exploitation of resources, the direction of investment, the orientation of the technological development and instituted change are all in harmony and enhance both current and future potential to meet human need and aspiration". According to the World Commission on Environment and Development, Brundtland Commission on Environment and Development, Brundtland Commission 1987, sustainable development is "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable development (Hutzinger [2], Desimone and Popoff [3]) demands change, requires doing more with lesser resource input and less waste generation. Instead of end-of-pipe technology, it requires pollution prevention philosophy, which is: "First and foremost, reduce waste at the origin-through improved housekeeping and maintenance, and modification in product design, processing and raw material selection. Finally, if there is no prevention option possible, treat and safely dispose off the waste."

In the efforts to move towards 'Sustainable Development', chemistry nowadays is at the forefront of the development of clean production processes and products. Chemistry is no doubt determining to understand and protect our environments as the world's future is strongly dependently on the chemical processes adopted. Chemistry plays an integral part of our lives and is all around us in the clothes we wear, the food, air and buildings etc. Sustainability, eco-efficiency and green chemistry are new principles that are guiding the development of next generation of products and processes (Sanghi [4]). Green Chemistry is considered an essential piece of a comprehensive program and also an alternating research Methodology which is more eco- as well as economy friendly (Sharma et al. [5]). In its essence Green Chemistry (Anastas and Farris [6], Tundo and Selva [7], Collins [8], Wilkinson

[9], Anastas [10]) is a science based, not regulatory and economically driven approach to achieving the goals of environmental protection and sustainable development.

In order to be eco-friendly, or *green*, organic synthesis (Grieco [11], Faber [12], Jessop and Leitner [13], Sanghi [14]) must meet, if not all, at least some of the following requirements: avoid waste, be atom efficient, avoid use and production of toxic and dangerous chemicals, produce compounds which perform better or equal to the existing ones and are bio-degradable, avoid auxiliary substances, reduce energy requirements, use renewable materials, use catalysts rather than stoichiometric reagents. These requirements can be easily met by the concept of green chemistry. Safety and environmental concerns tend to be very difficult to translate and quantify in terms of monetary value. However, economic concerns tend to sensibly affect the cost estimates. According to a recently completed study sponsored by the Federal Highway Administration (FHWA), corrosion of metals costs the United States in excess of \$276 billion per year. This loss to the economy is more than the entire gross national product of many countries around the world. This loss for 1975 was estimated at \$82 billion or 4.9% of the gross National Product. However, corrosion not only affects the economy but it can also present a threat to life through the collapse of a structure or to the environment through the leakage of toxic chemicals.

Several efforts have been made using corrosion preventive practices and the use of corrosion inhibitors is one of them. *Green Chemistry* provides many environmental friendly corrosion inhibitors, called "*Green inhibitors*". The use of inhibitors for the control of corrosion of metals (Valdez et al. [15]) and alloys which are in contact with aggressive environment is an accepted practice (Taylor and Chambers [16], Khaled [17]). Large numbers of organic compounds have been studied and are being studied to investigate their corrosion inhibition potential. All these studies have revealed that organic compounds especially those with N, S and O show significant inhibition efficiency. However, most of these compounds are not only expensive but also toxic to living beings (Bothi Raja and Sethuraman [18]). It is needless to point out the importance of cheap, safe inhibitors of corrosion. Plant extracts and organic species have therefore become important as an environmentally acceptable, readily available and renewable source for wide range of inhibitors (Rajendran et al. [19], Mathiyarasu et al. [20], Mesbah et al. [21], Okafor et al. [22], Lebrini et al. [23], Radojcic et al. [24], Refaey et al. [25]). They are the rich sources of ingredients which have very high inhibition efficiency (Little et al. [26], Bothi Raja and Sethuraman [18]) and are hence termed '*Green Inhibitors*' (Lebrini et al. [23]). These green inhibitors are non-hazardous and eco-friendly. This paper reviews and discusses the use

of and research on corrosion inhibitors and, in particular, green inhibitors recently reported in corrosion literature.

2. Corrosion Control and Role of Inhibitors

By analyzing the corrosion cell, it can be seen that corrosion can be controlled or eliminated through several methods (Khramov et al. [27], Ramesh et al. [28], Hamdy [29], Poon et al. [30], Hamdy and Butt [31], Quitmeyer [32]) including decreasing the voltage differences between anode and cathode to zero, which in turn eliminates the current flow between the anode and the cathode; thereby discontinuing the electric path between the anode and the cathode; and increasing the resistance to current flow in the circuit (Shim et al. [33], Soares et al. [34], Liu et al. [35]). But practically, it becomes impractical and an expensive affair to completely eliminate corrosion; and in most examples it suffices to reduce corrosion rates to acceptable levels (Qian et al. [36]). Corrosion control can be achieved with proper material selection and designing, environmental modifications, coating, use of green inhibitors (Yee et al. [37]) or cathode protection. For better designing, computer aided techniques are very helpful for a corrosion engineer (Ignatova et al. [38], Kiselev et al. [39], Najjaran et al. [40], Tumbull et al. [41], Xie et al. [42], Guessasma et al. [43], Holme and Lunder [44], Pidaparti et al. [45]).

There are several types of inhibitors available including, volatile inhibitors, passivating (anodic) inhibitors, precipitation inhibitors, cathodic inhibitors, organic inhibitors, inorganic inhibitors, mixed inhibitors and green inhibitors (Wiston [46]). The effectiveness of an corrosion inhibitors depends on the specific ability to react with the surface of a metal (or any other material) to form a protective film or coating (Ravichandran et al. [47], Elayyachy et al. [48], El-Etre et al. [49], Khramov et al. [50], Palanivel et al. [51], Paliwoda-Porebska et al. [52], Sawada et al. [53], Zheludkevich et al. [54], Ann et al. [55], Fuchs-Godec [56], Gu and Liu [57], Muller and Fischer [58], Oguzie et al. [59], Sherif and Park [60], Yurt et al. [61], Fouda et al. [62], Lamaka et al. [63], Mishra and Balasubramaniam, [64,65], Antonijevic and Petrovic [66], El-Ashry et al. [67], Barouni et al. [68], Elewady et al. [69], Senthilkumar and Sethuraman [70]); thereby reducing or providing protection against corrosion. It has been known from years that certain substances have the capacity to reduce and stop attack by acids or other chemicals on metals; this effect is called *inhibition*. Several compounds are capable to inhibit corrosion in metals, but they show variations in their mode of action and in their effectiveness in different media (or electrolytes) (Yasakau et al. [71]). According to Davis et al. [72] it is the nature of the chemisorbed layer on the metal formed by the

inhibitors, rather than its thickness that governs effectiveness of an inhibitor to corrosion. Among the methods for the corrosion control and prevention, certain types of chemicals may be added to the environment to reduce the aggressiveness of the environment or to slow down the corrosion reaction. Inhibitors work by the adsorption of ions or molecules onto the metal surface (Bentiss et al. [73], Popova et al. [74], Abiola [75], Na and Pyun [76]). They reduce the corrosion rate by increasing or decreasing the anodic and/or cathodic reaction, decreasing the electrical resistance of the metal surface and decreasing the diffusion rate for reactants to the surface of the metal.

Non-specific adsorption of ions (Ristic et al. [77], de Queiroz Baddini et al. [78], Ye et al. [79]), or molecules that can form ions, depend upon the surface charge of the metal. At the point of zero charge, both ions and molecules can be adsorbed. When they are adsorbed, the zero point charge (ZPC) shifts to being slightly more negative. For inhibition by anions, the metal must be held positive to its ZPC, and the metal positively charged. Such a positive charge normally prevents the corrosion of metals in even acidic environment (Refaey et al. [25]). In neutral and basic medium, an additional agent such as oxygen is generally required to maintain the metal corrosion potential (E_{corr}) positive to the ZPC.

Inhibitors are often easy to use and offer the advantage of *in-situ* application without causing any significant disruption to the process (Ravichandran et al. [47], Luo et al. [80], Soylev and Richardson [81]). The central importance is in the fact that inhibitor must be present in the medium to which the metal is exposed, or it must be capable of being leached from a suitable carrier. However, there are several considerations when choosing a corrosion inhibitor. These are cost of the inhibitor which can be sometimes very high, toxicity of the inhibitor (Scendo [82], Gomez and Callao [83], Mu et al. [84]) which may cause jeopardizing effects on living beings hence causing the use of *green inhibitors* (Leite et al. [85], Umoren et al. [86]) to increase for the same reason, and the availability of inhibitor material and molecular species to the corrosion protection process. The succeeding sections make a modest, but reasonably representative, compilation and discussion of only a few findings in corrosion inhibition research, the adsorption mechanisms and corrosion inhibitor loaded hybrid coatings.

2.1 Observed Adsorption Mechanisms in Corrosion Inhibition

Elayyachy et al. [48] synthesized and tested two new telechelic compounds as inhibitors for the corrosion of steel in 1 M HCl solution. Weight loss measurements, potentiodynamic

polarisation and impedance spectroscopy (EIS) methods were used. Elayyachy et al. [48] found that the inhibiting action increased with the concentration of methyl 4-{2-[(2-hydroxyethyl)thio]ethyl}benzoate (T2) and 11-[(2-hydroxyethyl)thio]undecan-1-ol (T3) to attain 92% at 10^{-3} M and 90% at 10^{-4} M, respectively. The investigated adsorption of T3 on the steel surface was found to obey to the Langmuir adsorption model. Elewady et al. [69] studied the role of some surfactants in the corrosion of Al in 1 M HCl using weight loss and galvanostatic polarization techniques. The results of Elewady et al. [69] showed that the inhibition occurred through adsorption of the inhibitor molecules on the metal surface. The inhibition efficiency was found to increase with increasing inhibitor concentration and decreased with increasing temperature which is due to the fact, that the rate of corrosion of Al is higher than the rate of adsorption. The latter observation was contrary to that observed by Elayyachy et al. [48] whereby the study of the effect of temperature studied between 35 and 80°C showed that inhibition efficiency to have remained almost constant. Elewady et al. [69] also deduced, in contrary to many other researchers that the adsorption of these compounds on the metal surface was found to obey Freundlich adsorption isotherm. Further research by Elewady et al. [69] showed that the inhibiting action of these compounds are considerably enhanced by the addition of KI, due to the increase of the surface coverage and therefore indicating the joint adsorption of these compounds and iodide ions. The thermodynamic parameters for adsorption and activation processes were determined, and the subsequent galvanostatic polarization data indicated that these compounds acted as mixed-type inhibitors.

On the other hand, Fuchs-Godec [56] came to a different conclusion in the study of mixed-type inhibitors. Fuchs-Godec [56] performed electrochemical measurements to investigate the effectiveness of cationic surfactants of the *N*-alkyl quaternary ammonium salt type, i.e. myristyltrimethylammonium chloride (MTACl), cetyldimethylbenzylammonium chloride (CDBACl), and trioctylmethylammonium chloride (TOMACl), as corrosion inhibitors for type X4Cr13 ferritic stainless steel in 2 M H₂SO₄ solution. The potentiodynamic polarization measurements made by Fuchs-Godec [56] showed that these surfactants hindered both anodic and cathodic processes, i.e. they acted as mixed-type inhibitors. It was found that the adsorption of the *N*-alkyl ammonium ion in 2 M H₂SO₄ solution followed the Langmuir adsorption isotherm as observed by other researchers in their study (Elayyachy et al. [48], Quraishi and Khan [87], Yurt et al. [61], Lebrini et al [23]). The calculated values of the free energy of adsorption ΔG_{ads} by Fuchs-Godec [56] were, in cases when the charge on the metal surface was negative with respect to the point of zero charge (PZC), relatively high what is characteristically for the chemisorption. On the other hand, for positive metal surfaces Fuchs-Godec [56] assumed that SO₄²⁻ anions were adsorbed first, so the cationic

species would be limited by the surface concentration of anions. Accordingly ΔG_{ads} values were lower in this case and the adsorption was attributed due to merely electrostatic attraction, which was characteristically of physisorption.

In their study, Lebrini et al. [23] studied corrosion inhibition of mild steel in molar perchloric acid by 3,5-bis(*n*-pyridyl)-4-amino-1,2,4-triazoles (*n*-PAT, *n* = 2, 3 and 4) at 30 °C using gravimetric and electrochemical impedance spectroscopy techniques. Protection efficiencies of 95% and 92% were obtained with 12×10^{-4} M of 3-PAT and 4-PAT, respectively; while 2-PAT reached only 65%. The inhibiting properties of *n*-PAT were found to depend on the concentration and the order of increasing inhibition efficiency was correlated with the modification of the position of the nitrogen atom in the pyridinium substituent. It was shown by Lebrini et al. [23] that adsorption of 4-aminotriazole derivatives on the steel surface was consistent with the Langmuir adsorption isotherm and the obtained standard free energy of adsorption values indicated that the corrosion inhibition of the mild steel in 1 M HClO₄ is depends on both physic-and chemisorption, as opposed to the conclusions of sole physisorption from Fuchs-Godec [56]. Still with respect to research on the adsorption mechanism of corrosion inhibition, Yurt et al. [61] investigated the effect of newly synthesised three Schiff bases—2-[2-aza-2-(5-methyl(2-pyridyl))vinyl]phenol, 2-[2-aza-2-(5-methyl(2-pyridyl))vinyl]-4-bromophenol, 2-[2-aza-2-(5-methyl(2-pyridyl))vinyl]-4-chlorophenol—on the corrosion behaviour of aluminium in 0.1 M HCl using potentiodynamic polarisation, electrochemical impedance spectroscopy and linear polarisation methods. Polarisation curves obtained by Yurt et al. [61] indicated that all studied Schiff bases were acting as mixed-type inhibitors (Fuchs-Godec [56]). All measurements made by Yurt et al. (2006) showed that inhibition efficiencies increased with increase in inhibitor concentration (Amin [88], Quraishi and Khan [87], Fouda et al. [62]). This revealed that inhibitive actions of inhibitors were mainly due to adsorption on the aluminium surface. Adsorption of these inhibitors followed the Langmuir adsorption isotherms and the thermodynamic parameters of adsorption (K_{ads} , ΔG_{ads}) of studied Schiff bases were calculated using the Langmuir adsorption isotherm. However, in the study of corrosion inhibition of copper in aerated non-stirred 3% NaCl solutions in the temperature range 15–65°C using sodium oleate as an anionic surfactant inhibitor, Amin [88] found that the sigmoidal shape of the adsorption isotherm confirmed the applicability of Frumkin's equation to describe the adsorption process rather than the much observed Langmuir isotherms.

The variation in inhibition efficiency values were found to depend on the type of functional groups substituted on benzene ring. It was also found by Yurt et al. [56] that the presence

of bromine and chlorine atoms in the molecular structure of studied Schiff bases facilitate the adsorption of molecule on aluminium surface, thus partially agreeing with the observations made by and Fouda et al. [69] and Elewady et al. [69] whereby the latter showed that the inhibiting action of telechelic compounds would be considerably enhanced by the addition of KI (iodide species). Yurt et al. [61] also studied the correlation between the inhibition efficiencies of studied Schiff bases and their molecular structure using quantum chemical parameters obtained by MNDO semi-empirical SCF-MO methods. Their results indicated that adsorption of studied Schiff bases depended on the charge density of the adsorption centres and their dipole moments. On the same line of discussion, El-Ashry et al. [67] also recently studied correlation of the quantum chemical SCF calculations of some parameters of benzimidazoles with their inhibition efficiency in case of steel in aqueous acidic medium. Geometric structures, total negative charge on the molecule (TNC), highest occupied molecular orbital (E_{HOMO}), lowest unoccupied molecular orbital (E_{LUMO}), dipole moment (μ) and linear solvation energy terms, molecular volume (V) and dipolar-polarization (π^*) were all found to be correlated to the corrosion inhibition efficiency. The correlation between quantum parameters obtained by AM1 calculation and experimental inhibition efficiency were validated by single point calculations for the semi-empirical AM1 structure using B3LYP/6-31G* as a higher level of theory and equations (with high R^2 values) were successfully proposed using linear regression analysis to calculate corrosion inhibition efficiency. It was ultimately established by El-Ashry et al. [67] that the increase of the orbital energies E_{HOMO} favoured the inhibition efficiency toward steel corrosion.

Yasakau et al. [89] have carried out an extensive and very interesting study of the mechanism of corrosion protection of the widely used 2024-T3 aluminium alloy by cerium and lanthanum inhibitors in chloride media. Yasakau et al. [89] investigated the corrosion process by means of scanning Kelvin probe force microscopy (SKPFM), *in situ* atomic force microscopy, and scanning electron microscopy coupled with energy dispersive spectroscopy. These high resolution and in-situ techniques as employed by Yasakau et al. [89] provided a deep understanding of the details of the physical chemistry and mechanisms of the corrosion processes. All the more, the applicability of the SKPFM for mechanistic analysis of the effect of different corrosion was demonstrated for the first time in corrosion analysis. Yasakau et al. [89] found that the inhibitors under study showed sufficient hindering of the localized corrosion processes especially in the case of pitting formation located around the intermetallic S-phase particles. The main role of Ce^{3+} and La^{3+} in the corrosion protection was the formation of hydroxide deposits on the S-phase inclusions thereby buffering the local increase of pH, which was attributed by Yasakau et al. [89] to the acceleration of the intermetallics dealloying. The formed hydroxide precipitates

could also act as a diffusion barrier hindering the corrosion processes in active zones. Yasakau et al. [89] concluded that cerium nitrate exhibited higher inhibition efficiency in comparison with lanthanum nitrate. An account of the mechanism of the corrosion in chloride media explained by Yasakau et al. [89] based on thermodynamic analysis is illustrated and briefly revisited in Figure 1.

Mechanism of corrosion in chloride media explained by Yasakau et al. [89]: The 2024 aluminium alloy as well as any aluminium-based substrate is covered by a native oxide film. However, the intermetallics have a thinner and more defective oxide film due to the presence of different elements in an intermetallic phase. Immediately after contact of the alloy with a chloride-containing environment the chloride ions interact with the native oxide film (Figure 1A) leading to its breakdown especially in the weak places that originated from the S-phase intermetallic precipitates. Water then comes in contact with the intermetallic surface after failure of the barrier oxide layer causing the chemical reaction of active aluminium and magnesium with water (Figure 1B) as per equations 1 and 2, the chemical dealloying of the S phase occurs due to these processes leading to the formation of a copper-rich surface and local nonuniformities of the intermetallics composition. The most likely cathodic process is the reaction of oxygen reduction due to very high overpotential of the electrochemical hydrogen evolution on copper-rich cathodes. Thus the hydrogen evolution evidently proves the occurrence of reactions 1 and 2. However, simultaneously, the electrochemical dissolution can take place at this stage as well causing faster dealloying. The local increase of pH around the S-phase particles as well as enrichment of their surface with copper lead to shifting the dissolution processes from chemical to electrochemical. The hydrogen bubbles are removed from the alloy surface, and an electrochemical dissolution is starting. The cathodic reaction occurs on copper-rich remnants by the following equation 3. Simultaneously the oxidation of magnesium and aluminium occurs at the anodic parts of the S phase (equations 4 and 5). Dissolution of aluminium and magnesium leads to deeper dealloying of the S phase forming the porous copper remnants. An additional increase of the pH occurs due to cathodic

reaction 3 at the intermetallic surface. This leads to formation of a sufficient gradient of OH^- ions between the bulk solution and the surface of the intermetallic particle. The aluminium and magnesium cations can immediately react with hydroxyl ions forming insoluble hydroxide sediments or soluble hydroxyl complexes (Figure 1D) depending on pH values (equations 6–11). The aluminium cations originated from anodic dissolution of the S-phase, interact with the hydroxyl anions generated at the cathodic zones, and form $\text{Al}(\text{OH})_4^-$ complex ions, which diffuse to the bulk solution. On reaching the zones of the solution with lower pH (about 8), the complex anions are transformed into the insoluble $\text{Al}(\text{OH})_3$, which is a thermodynamically preferable state in such conditions. Thus, aluminium hydroxide forms an insoluble deposit at a certain distance from the active intermetallic (Figure 1D). The electrochemical dissolution of magnesium and aluminium from the S-phase leads to the formation of a very porous structure with the copper particles connected to the copper remnants. When the neck between a copper nanosized particle and a remnant is broken, the particle loses the electrical contact with the alloy. Then the chemical reaction of copper oxidation by dissolved oxygen is thermodynamically possible as per equation 12: The nanosize confers even an enhanced reactivity to the copper particles. Partial dissolution of the copper hydroxide occurs due to formation of hydroxo complexes. The complex ions then are electrochemically reduced again to metallic copper when contact with the surface of the aluminium alloy or with the copper remnants formed after dealloying as schematically shown in Figure 1E.

2.2 Hybrid Coatings and Corrosion Inhibitors

Another field of extensive research on corrosion inhibition is the application of hybrid coatings preloaded with the inhibitors, and especially sol-gel derived organic-inorganic hybrid coatings (Pathak et al. [90]). Back in 2004, Pepe et al. [91] reported that chromates are among the most common substances used as corrosion inhibitors. However, these compounds are highly toxic, and an intense effort is being required (and is being undertaken) to replace them. According to Pepe et al. [91] cerium compounds seemed to fulfill the basic requirements for consideration as alternative corrosion inhibitors. The aim of the work of Pepe et al. [91] was therefore to study the effect of the incorporation of cerium ions in silica sol-gel coatings on aluminium alloys as potential replacement of chromate treatments. The main idea was to combine the ‘barrier’ effect of silica coatings with the ‘corrosion inhibitor’ effect of the cerium inside the coatings. Thin (below 1 μm for a single layer) and transparent cerium doped silica sol-gel coatings were prepared by

dipping 3005 aluminium alloys in sol-gel solutions. Ultra-violet-visible spectra (UV-vis) showed that cerium ions, Ce^{3+} and Ce^{4+} , always were present in the coatings, independently of the cerium salt or firing atmosphere used. Active protection with single and two layer coatings prepared with Ce(IV) salt seemed to improve corrosion protection of the coated aluminium while coatings prepared with Ce(III) salt only entailed a protection when applied as a two layer, possibly due to sealing of pre-existent defects in the first layer. The improvement of active protection with immersion time would imply that corrosion is inhibited by cerium ions that migrate through the coating to the site of the attack (a defect in the coatings) and then react to passivate the site.

The results of Pepe et al. [91] were initiated a boost for research on the hybridization of corrosion inhibitors in sol-gel coatings. Thereafter, Khramov et al. [50] have developed sol-gel derived organo-silicate hybrid coatings preloaded with organic corrosion inhibitors in order to provide active corrosion protection when integrity of the coating is compromised. The incorporation of organic corrosion inhibitors into hybrid coatings has been achieved as a result of physical entrapment of the inhibitor within the coating material at the stage of film formation and cross-linking. Entrapped corrosion inhibitor become active in corrosive electrolyte and can then slowly diffuse out of the host material. To ensure continuing delivery of the inhibitor to corrosion sites and long-term corrosion protection, a sustained release of the inhibitor is achieved by a reversible chemical equilibrium of either ion-exchange of the inhibitor with the coating material or through cyclodextrin-assisted molecular encapsulation. Several organic compounds, such as mercaptobenzothiazole, mercaptobenzimidazole, mercaptobenzimidazolesulfonate, and thiosalicylic acid, have been selected and tested by Khramov et al. [50] to evaluate the effectiveness of these two approaches. Still, Lamaka et al. [63] studied the active corrosion protection of AA2024-T3 alloy provided by an environmental-friendly, well adhering pre-treatment system consisting of an inhibitor-loaded titanium oxide porous layer and a sol-gel based thin hybrid film. As a matter of fact, Lamaka et al. [63] proposed a novel approach aimed at developing a nanoporous reservoir for storing of corrosion inhibitors on the metal/coating interface. The nanostructured porous TiO_2 interlayer was prepared on the aluminium alloy surface by controllable hydrolysis of titanium alkoxide in the presence of template agent. The morphology and the structure of the TiO_2 film were characterized with TEM, EDS, SEM, and AFM techniques. Lamaka et al. [63] found that, in contrast to direct embedding of the inhibitors into the sol-gel matrix, the use of the porous reservoir eliminated the negative effect of the inhibitor on the stability of the hybrid sol-gel matrix. Hence, TiO_2 /inhibitor/sol-gel systems showed enhanced corrosion protection and self-healing ability confirmed by EIS and scanning vibrating electrode technique measurements.

Zheludkevich et al. [92] presented a new contribution to the development of a new protective system with self-healing ability composed of hybrid sol-gel films doped with nanocontainers that released entrapped corrosion inhibitor in response to pH changes caused by the corrosion process. A silica-zirconia based hybrid film was used in this work as an anticorrosion coating deposited on 2024 aluminium alloy. Silica nanoparticles covered layer-by-layer with polyelectrolyte layers and layers of inhibitor (benzotriazole) were randomly introduced into the hybrid films. The hybrid film with the nanocontainers revealed significantly enhanced long-term corrosion protection in comparison with the undoped hybrid film. The SVET also showed an effective self-healing ability of the defects. This effect was obtained due to regulated release of the corrosion inhibitor triggered and self-controlled by the pH feedback by the corrosion processes started in the cavities. This concept of feedback was further studied by Shchukin and Möhwald [93] wherein nanocontainers with the ability to release encapsulated active materials in a controlled way could be employed to develop a new family of self-repairing multifunctional coatings, which would possess not only passive functionality but also rapid feedback activity in response to changes in local environment. Several approaches to fabricate self-repairing coatings on plastic and metal substrates were surveyed by Shchukin and Möhwald [93]. The release of the active materials was established to occur only when triggered by specific properties of the corrosion process, which prevented leakage of the active component out of the coating and increased coating durability.

Further research was conducted by Moutarlier et al. [94] to improve the self-repair properties of sol-gel films on aluminium alloy was carried out. Moutarlier et al. [94] studied chromium(III), molybdate, permanganate and cerium (III) by polarisation resistance (R_p) in chloride medium and compared to the standard corrosion inhibitor, i.e. hexavalent chromium (Pepe et al. [91]). The evolution of the composition of sol-gel coatings, during the corrosion test, was examined by glow discharge optical emission spectroscopy (GDOES). Moutarlier et al. [94] have come with a fresh explanation in respect as to they showed that the morphology of sol-gel and the solubility of the additive played a determinant role in the effectiveness of corrosion protection for a long term. Additives such as molybdate and permanganate ions decreased the sol-gel network stability and were too soluble (they were rapidly lost from the sol-gel films, in an aggressive medium), decreasing the power to prevent corrosion. Incorporation of Ce(III) was not efficient for a long time, as opposed to the findings of Pepe et al. [91] due to its high solubility.

Sol-gel films containing Cr(VI) and Cr(III) seemed to provide adequate corrosion protection, due to the sol-gel stability and their low solubility. Still maintaining that the chromium (III)

and (IV) species were less suited for inhibition, Poznyak et al. [95] developed Titania-containing organic-inorganic hybrid sol-gel films as an alternative to chromate-based coatings for surface pretreatment of aluminium alloys. Stable hybrid sols were prepared by hydrolysis of 3-glycidoxypyltrimethoxysilane and different titanium organic compounds in 2-propanol solution in the presence of small amounts of acidified water. Different diketones were used as complexing agents in this synthesis for controllable hydrolysis of titanium organics. The properties of the obtained coatings were compared with those of zirconia-containing films. Electrochemical impedance spectroscopy (EIS) measurements and standard salt spray tests have been performed by Poznyak et al. [95] to investigate the corrosion protection performance of the hybrid coatings. It was revealed that their protective properties depended significantly on the nature of metalorganic precursors and complexing agents used in the process of sol preparation. The best anticorrosive protection of AA2024 in chloride solutions was provided by the titania-containing sol-gel films prepared with titanium(IV) tetrapropoxide and acetylacetone as starting materials. In the case of zirconia-containing films, better protective properties were found when applying ethylacetoacetate as a complexing agent. Equally for AA2024, Yasakau et al. [96] worked a certain number of corrosion inhibitors for AA2024 as additives to the hybrid sol-gel formulations in order to confer active corrosion protection without damaging the coating. 8-hydroxyquinoline, benzotriazole and cerium nitrate were added at different stages of the synthesis process to understand the role of possible interaction of the inhibitor with components of the sol-gel system. SVET and Electrochemical Impedance Spectroscopy were employed as two main techniques to characterize the corrosion protection performance of the hybrid sol-gel films doped with inhibitors and to understand the mechanisms of corrosion protection. Yasakau et al. [96] have demonstrated that 8-hydroxyquinoline and cerium nitrate do not affect the stability of sol-gel films but would confer additional active corrosion protection effect. In contrast to this, benzotriazole lead to the deterioration of the corrosion protection properties of hybrid sol-gel films.

2.3 Corrosion Research and Mathematical Modelling

The value of mathematical and computer-aided models to organize data, to consider interactions in complex systems in a rational way, to correct the conventional wisdom, and to understand essential qualitative, and at times quantitative, features of biological, electrochemical, nuclear, physical, physicochemical, mathematical and microscopic systems

have been reasonably clearly documented in prior research for each of the latter field of science and engineering.

The impact of modelling research specific to corrosion inhibition (Papavinasam et al. [97], Zieliński and Sobieszczyk [98]) analysis discovery has so far been however moderate, but this will change in the future if we are adept in recognizing emerging opportunities and in integrating new concepts and tools into our research methodology. Mathematical structures and methods, allied with extraordinary contemporary computing power, are essential to the emerging field of metallurgical behaviour prediction and analysis. Important in this quest is thence a hierarchy of powerful modelling, analysis, and computational tools which can capture essential quantitative features of available experimental data and use these effectively for analysis and design of corrosion resistant structures. The few applications of computer modelling in corrosion inhibition discussed immediately below attempt at providing an overview of the level of complexity involved in the corrosion process to a point to justifiably warrant the use of powerful modelling techniques.

Isgor and Razaqpur [99] developed a robust and comprehensive finite element model for predicting the rate of steel corrosion in concrete structures. The model of Isgor and Razaqpur [99] consisted of initiation and propagation stages which were cast in the same time and space domains, that is, processes which commenced in the initiation stage, such as temperature, moisture, chloride ion, and oxygen transport within the concrete, maintained continuity into the propagation stage while active corrosion occurred contemporaneously. The model of Isgor and Razaqpur [99] was much innovative in the sense that it allowed the model to include the effects of changes in exposure conditions during the propagation stage on corrosion and the effects of the corrosion reactions on the properties of concrete. All the more, as a novel approach to corrosion inhibition analysis, Isgor and Razaqpur [99] calculated the corrosion rates on steel surface by solving the much intricate Laplace's equation for electrochemical potential with appropriate boundary conditions. These boundary conditions included the relationship between overpotential and current density for the anodic and cathodic regions. Due to the non-linear nature of these boundary conditions, a non-linear solution algorithm was used. According to Isgor and Razaqpur [99], their model being reasonably robust shall successfully enable designers to carry out comprehensive sensitivity analyses and to gauge the significance of variations in the values of certain parameters on the rate of corrosion in concrete structure, so that ultimately better corrosion resistant concrete structures be developed and cast for building and structural applications.

Kubo et al. [100] developed a mathematical model for the simulation of the changes in the pore solution phase chemistry of carbonated hardened cement paste when aqueous solutions of organic base corrosion inhibitors are applied to the surface of the material and constant current densities in the range of 1–5 A/m² are passed between anodes placed within the inhibitor solutions and steel mesh cathodes embedded within the paste. The model which was derived from the much used Nernst–Planck equation, was used to predict the concentration profiles of electrochemically injected inhibitors and the major ionic species present within the pore electrolyte as the corrosion reactions proceeded. For their part of scientific contribution in the mathematical modelling of corrosion inhibition, Colorado–Garrido et al. [101] presented a predictive model for corrosion polarization curves using artificial neural network (ANN). This proposed model obtained predictions of current in base of a corrosion inhibitor concentration and potential. The model of Colorado–Garrido et al. [101] was significantly different from other models developed to study corrosion inhibition in that the model took into account the variations of inhibitor concentration over steel by thermo mechanical processing to decrease corrosion rate. For the ANN, the Levenberg–Marquardt learning algorithm, the hyperbolic tangent sigmoid transfer–function and the linear transfer–function were dexterously used by Colorado–Garrido et al. [101]. The best fitting training data set was obtained with five neurons in the hidden layer, which made it possible to predict efficiency with accuracy at least as good as that of the theoretical error, over the whole theoretical range. On the validation data set, simulations and theoretical data test were in very good positive agreement with an $R > 0.985$. Hence, the robustness of the model of Colorado–Garrido et al. [101] resided in its accurate predictive capacity of the current in short simulation times. On still a different scenario of corrosion inhibition, Jingjun et al. [102] recently studied the flow–induced corrosion mechanisms for carbon steel in high–velocity flowing seawater and attempted to explain the corrosive phenomena. The design methodology of Jingjun et al. [102] comprised the derivation of an overall mathematical model for flow–induced corrosion of carbon steel in high–velocity flow seawater in a rotating disk apparatus using both extensive numerical computer simulation and test methods. By studying the impact of turbulent flow using the kinetic energy of a turbulent approach and the effects of the computational near–wall hydrodynamic parameters on corrosion rates, the corrosion behaviour and mechanism were satisfactorily explored and explained by Jingjun et al. [102]. Jingjun et al. [102] held that their overall modelling and simulation approach could enable to understand afresh and in depth the synergistic effect mechanism of flow–induced corrosion. Jingjun et al. [102] also maintained for a first time that it was indeed scientific and reasonable to investigate carbon steel corrosion through correlation of the near–wall hydrodynamic parameters, which could accurately describe the influence of fluid flow on

corrosion. The subsequent computational corrosion rates obtained by the model of Jingjun et al. [102] were in good agreement with actual measured corrosion data. Jingjun et al. [102] also succeeded in showing that serious flow-induced corrosion is caused by the synergistic effect between the corrosion electrochemical factor and the hydrodynamic factor, while the corrosion electrochemical factor plays a dominant role in flow-induced corrosion.

3. Green Inhibitors

All synthetic processes or engineering methods involve the use of different chemicals and materials which may cause corrosion to metals during the specific process. Some of them are very hazardous and environmentally problematic in nature. To control corrosion with conventional 'toxic' corrosion inhibitors, they pose significant adverse effects on the environment and at the end of the chain, to mankind. Such corrosion inhibitors are called "Grey inhibitors" as have been discussed in the earlier sections. However, Green Chemistry provides many environmental friendly corrosion inhibitors, called "*Green Inhibitors*" which are non-hazardous and eco-friendly (Davo et al. [103], Bendahou et al. [104], Craddock et al. [105], Deacon et al. [106], Taha [107], Little et al. [26], Scendo [108], Bothi Raja and Sethuraman [18]).

3.1 Natural Derivatives for Green Corrosion Inhibitors

The safety and environmental issues of corrosion inhibitors arisen in industries have always been a global challenge. Chromates for example are used in the pretreatment of aluminium alloys (Hinton et al. [109]). Since chromates are both toxic as well as carcinogenic, many alternative corrosion inhibitors are being developed to reduce the jeopardizing effects on humans, animals and environment. *Green Inhibitors* are environment friendly corrosion inhibitors and range from rare earth elements (Kilbourn [110], Bethencourt et al. [111], Virtanen et al. [112], Bethencourt et al. [113], Powell et al. [114], Arenas et al. [115], Hughes et al. [116]) to organic compounds (Choi et al. [117], Davis et al. [72], Cano et al. [118]). Research has been conducted using some rare earth metals such as lanthanide compounds (Bethencourt et al. [11]). Aballe et al. [119] have conducted experiments using lanthanum, cerium chloride and their binary mixtures as corrosion inhibitors of AA5083 Al-Mg alloy in aerated 3.5% sodium chloride (aq.) solution. There is good evidence that cerium is effective for corrosion protection of metals and alloys. The effect of pyrazolo-containing compounds on the corrosion of carbon steel in 1M sulphuric acids has been investigated using polarization methods (El-Maksoud [120]). The adsorption behaviour of pyrazolo was

found to obey orthophosphate corrosion inhibition for copper pipe in soft water. Amines and its complexes and barbiturates equally find their applications in green corrosion inhibition (Choi et al. [117], Cano et al. [118], Karda and Solmaz [121]). In an attempt to find suitable replacements to the conventional benzotriazole (BTA) inhibitors, Moretti et al. [122] examined the inhibition of tryptamine (TA), a derivative of tryptophan, on the corrosion behaviour of ARMCO iron in 0.5M deaerated sulphuric acids by means of potentiodynamic curves and electrochemical impedance spectroscopy. Subsequent evidence showed that chitin/chitosan derivatives can exhibit inhibiting effects for both corrosion protection and water treatment purposes (El-Sawy et al. [123]). Other chemicals such as fast green, fuchsin basic and fuchsin acid have also been studied as green corrosion inhibitors of copper in citric acid solution (Cano et al. [118]). A study conducted by Khamis and Al-Andis [124] has proven that the use of herbs as new type of green inhibitors acting on acidic corrosion of steel. The investigated compounds were namely thyme, coriander, hibiscus, anis, black cumin and garden cress. On the other hand, Davis et al. [72] performed experiments using tobacco extracts.

3.2 Research on Green Corrosion Inhibitors

The following digest of only some of the umpteen researches being carried out on the development and testing of green corrosion inhibitors exemplify potential for the very wide array of green derivatives that can be synthesized and extracted for the said purpose. Many of the reported researches (over 3000) in literature may be broadly classified in the following categories of green derivatives for corrosion inhibitors: organic, amino acids, plant extracts and rare earth elements based.

3.2.1 Organic-Based Green Inhibitors

Khaled [17] synthesized a new safe corrosion inhibitor namely N-(5,6-diphenyl-4,5-dihydro-[1,2,4]triazin-3-yl)-guanidine (NTG) and its inhibitive performance towards the corrosion of mild steel in 1M hydrochloric acid and 0.5 M sulphuric acid has been investigated. Corrosion inhibition was studied by chemical method (weight loss) and electrochemical techniques included the Tafel extrapolation method and electrochemical impedance spectroscopy. These studies of Khaled [17] have shown that NTG was a very good inhibitor in acid media and the inhibition efficiency could be reached as high as up to

99% and 96% in 1M HCl and 0.5M H₂SO₄, respectively. Khaled [17] intensified the research and made polarization measurements reveal that the investigated inhibitor is cathodic in 1M HCl and mixed-type in 0.5M H₂SO₄. The activation energies of the corrosion process in the absence and presence of NTG were obtained by measuring the temperature dependence of the corrosion current density. Khaled (2008) successfully demonstrated that the adsorption of the NTG inhibitor on the metal surface in the acid solution was found to obey the Langmuir's adsorption isotherm as has been observed with many of the conventional, but toxic, corrosion inhibitors (Elayyachy et al. [48], Quraishi and Khan [87], Yurt et al. [61], Lebrini et al [23]). Gao and Liang [125] tested β -amino alcohols compounds in the series of 1,3-bis-dialkyl (C_nH_{2n+1}) aminopropan-2-ols as volatile corrosion inhibitors for brass in simulated atmospheric water using potentiodynamic, potentiostatic current transient, electrochemical impedance spectroscopy, gravimetric, and volatile inhibition ability measurements. The evolution of the inhibition effect of the investigated compounds has been monitored by Gao and Liang [125] according to the length of alkyl chain. The results obtained by Gao and Liang [125] indicated that the inhibition efficiency increased with increasing the alkyl chain length and also inhibitor concentration. Polarization curves deduced by Gao and Liang [125] clearly supported that these compounds acted as good anodic inhibitors in simulated atmospheric water. Gao and Liang [125] discussed the inhibition mechanism in light of the chemical structure of undertaken inhibitors and came to the same, but widely validated, conclusion that the adsorption of the alcohol-based inhibitors on the brass surface followed the Langmuir adsorption isotherm model.

3.2.2 Amino Acids-Based Green Inhibitors

Barouni et al. [68] studied the inhibition effect of five amino acids on the corrosion of copper in molar nitric solution by using weight loss and electrochemical polarization measurements. Valine (Val) and Glycine (Gly) were found to accelerate the corrosion process; but Arginine (Arg), Lysine (Lys) and Cysteine (Cys) inhibited the corrosion phenomenon, with cysteine being the best among the three inhibitors. Its efficiency increased with the concentration to attain 61% at 10⁻³ M. Ismail [126] further investigated the efficiency of cysteine as a non-toxic corrosion inhibitor for copper metal in 0.6 M NaCl and 1.0 M HCl by electrochemical studies. Potentiodynamic polarization measurements and electrochemical impedance spectroscopy were equally employed by Ismail [126] to study the effect of cysteine on the corrosion inhibition of copper. Ismail [126] observed that a higher inhibition efficiency of about 84% could be achieved in the chloride solutions. The

potentiodynamic polarization measurements made by Ismail [126] showed that the presence of cysteine in acidic and neutral chloride solutions affected mainly the cathodic process and decreased the corrosion current to a great extent and then shifted the corrosion potential towards more negative values. The experimental impedance data obtained by Ismail [126] were analyzed according to a proposed equivalent circuit model for the electrode/electrolyte interface. The results obtained from potentiodynamic polarization and impedance measurements by Ismail [126] were in good agreement, and the adsorption of cysteine on the surface of Cu, in neutral and acidic chloride solutions, followed the Langmuir adsorption isotherm very well with an adsorption free energy of cysteine on Cu of 25KJ/mol revealing a strong physical adsorption of the organic-based inhibitor on the metal surface.

3.2.3 Plant Extracts–Based Green Inhibitors

Bendahou et al. [104] evaluated the effect of natural rosemary oil as non toxic inhibitor on the corrosion of steel in H_3PO_4 media at various temperatures. The oil was initially hydro-distilled and used as inhibitor in various corrosion tests with gravimetric and electrochemical techniques being used to characterise the corrosion mechanisms. Chromatographic analysis by Gas Chromatography showed that the oil was rich in 1,8-cineole. Bendahou et al. [104] demonstrated good agreement between the various methods explored for corrosion inhibition analysis. The polarisation measurements showed that rosemary oil acted essentially as a cathodic inhibitor. The efficiency of the oil increased with the concentration (to attain 73% at 10g/L) but decreased with the rise of temperature in the 25–75°C range. According to novel results of Bendahou et al. [104], the natural oil could thus be used in chemical cleaning and pickling processes, thereby validating the originality of their work in finding of a safe and cheap inhibitor from natural plants. In Bothi Raja and Sethuraman [18], the corrosion inhibitive effect of the extract of black pepper on mild steel (MS) in 1 M H_2SO_4 media was evaluated by conventional weight loss studies (33–50°C), electrochemical studies viz., Tafel polarization, ac impedance and scanning electron microscope (SEM) studies. Results of weight loss study reveal that black pepper extract acts as a good inhibitor even at high temperatures also. The inhibition is through adsorption which is found to follow Temkin adsorption isotherm. Tafel polarization method revealed the mixed mode inhibition of black pepper extract. Analysis of impedance data has been made with equivalent circuit with constant phase angle element for calculation of double layer capacitance value. SEM studies provide the confirmatory evidence for the protection of MS by the green inhibitor.

El-Etre et al. [49] tested the aqueous extract of the leaves of henna (lawsonia) as a corrosion inhibitor of C-steel, nickel and zinc in acidic, neutral and alkaline solutions, using the polarization technique. El-Etre et al. [49] found that the extract acted as a very good corrosion inhibitor for the three tested electrodes in all tested media. The inhibition efficiency increased as expected with the concentration of extract when increased. El-Etre et al. [49] postulated that the degree of inhibition depended on the nature of the metal and the type of the medium. For C-steel and nickel, the inhibition efficiency increased in the order: alkaline < neutral < acid, while in the case of zinc it increased in the order: acid < alkaline < neutral, thereby reconciling with the much observed concept of the lawsonia extract being a mixed inhibitor as has been the case with umpteen grey inhibitors. The inhibitive action of the extract was discussed in view of adsorption of the complex lawsonia molecules onto the metal surface. El-Etre et al. [49] found that this adsorption followed Langmuir adsorption isotherm in all tested systems. El-Etre et al. [49] proposed, as a fresh explanation, that the formation of a complex between the metal cations and lawsone was an additional inhibition mechanism of C-steel and nickel corrosion. In their research with plant extracts for corrosion inhibition, Oguzie et al. [127] appraised the inhibiting effect of *Ocimum basilicum* extract on aluminium corrosion in 2M HCl and 2M KOH solutions, respectively, at 30 and 60°C. The corrosion rates were determined using the gas–volumetric technique and the values obtained in absence and presence of the extract was used in the calculation of the inhibition efficiency by Oguzie et al. [127]. Oguzie et al. [127] estimated the mechanism of inhibition from the trend of inhibition efficiency with temperature. According to Oguzie et al. [127] the *Ocimum basilicum* extract was believed to inhibit aluminium corrosion in both the acidic and alkaline environments. Inhibition efficiency increased with extract concentration but decreased with rise in temperature, again suggesting physical adsorption of the organic matter on the metal surface. These results were corroborated by kinetic and activation parameters for corrosion and adsorption processes evaluated from the experimental data at the temperatures studied by Oguzie et al. [127]. On further testing, Oguzie et al. [127] found that halide additives synergistically improved the inhibition efficiency of the extract. Hence, the research of Oguzie et al. [127] provided new information on the possible application of *Ocimum basilicum* extract as an environmentally friendly corrosion inhibitor. Oguzie et al. [127] maintained that the mixed extract – iodide formulation provided an effective means for retarding aluminium corrosion even in highly aggressive alkaline environments. Yet a ‘sweeter’ research was undertaken by Radojcic et al. [24] in their study of the influence of natural honey (chestnut and acacia) and natural honey with black radish juice, on the corrosion of tin in aqueous and sodium chloride solutions using weight loss and polarization techniques. Radojcic et al. [24] observed that the inhibition efficiency of acacia honey was lower than that of chestnut

honey, while the addition of black radish juice increased the inhibition efficiency of both honey varieties. The mechanism of corrosion inhibition was explained from a new perspective by Radojcic et al. [24] in that the process of inhibition was attributed to the formation of a multilayer adsorbed film on the tin surface, still following the established Langmuir adsorption isotherm.

Sethuraman and Bothi Raja [128] on their side have evaluated the corrosion inhibition potential of *Datura metel* in acid medium on mild steel (MS) with a view to develop new green corrosion inhibitors. The methodology of Sethuraman and Bothi Raja [128] consisted in studying an acid extract of the *D. metel* for its corrosion inhibitive effect by electrochemical and weight loss methods. Using weight loss measurement data, an attempt was made by Sethuraman and Bothi Raja [128] to probe the mechanism of inhibitive action by fitting the different established adsorption isotherms. Sethuraman and Bothi Raja [128] were much convincing in showing significant corrosion inhibitive effect in acid medium on MS. Sethuraman and Bothi Raja [128] explained based on their findings that inhibition was through adsorption of the phytoconstituents on MS following both the Temppkin and Langmuir adsorption isotherms. According to Sethuraman and Bothi Raja [128], the *Datura metel* plant was being investigated for the first time by them for its corrosion inhibitive and their developed green inhibitor could possibly find use in the inhibition of corrosion in industries where MS is used as a material of choice for the fabrication of machinery.

3.2.4 Rare Earth Elements–Based Green Inhibitors

Considerable research efforts have been made to develop non-toxic and equally performing green corrosion inhibitors base don rare earth elements. In principle, the rare earth element is selected from cerium, terbium, praseodymium, or a combination thereof, and at least one rare earth element should be in the tetravalent oxidation state. An inorganic or organic material is then used to stabilize the tetravalent rare earth ion to form a compound that is sparingly soluble in water. Specific stabilizers are chosen to control the release rate of tetravalent cerium, terbium, or praseodymium during exposure to water and to tailor the compatibility of the powder when used as a pigment in a chosen binder system. Stabilizers may also modify the processing and handling characteristics of the formed powders. Many rare earth–valence stabilizer combinations have been shown to equal the performance of conventional hexavalent chromium systems. A modest couple of these prospective researches are discussed here.

Blin et al. [129] investigated the corrosion inhibition mechanisms of new cerium and lanthanum cinnamate based compounds through the surface characterisation of the steel exposed to NaCl solution of neutral pH. Blin et al. [129] used Attenuated Total Reflectance–Fourier Transform Infrared (ATR–FTIR) spectroscopy to identify the nature of the deposits on the metal surface and confidently demonstrated that after accelerated tests the corrosion product commonly observed on steel (which is lepidocrocite, γ -FeOOH) is absent. The cinnamate species were clearly present on the steel surface upon exposure to NaCl solution for short periods and appeared to coordinate through the iron. At longer times the Rare Earth Metal (REM) oxyhydroxide species were proposed by Blin et al. [129] to have formed as identified through the bands in the 1400–1500 cm^{-1} regions. According to Blin et al. [129], the protection mechanism appeared to involve the adsorption of the REM–cinnamate complex followed by the hydrolysis of the REM to form a barrier oxide on the steel surface, this being a novel mechanism involved and observed in corrosion inhibition. Blin et al. [130] further intensified their research on rare earth elements by demonstrating through a combination of linear polarisation resistance (LPR) and cyclic potentiodynamic polarisation (CPP) measurements that the lanthanum–4 hydroxy cinnamate compound could inhibit both the cathodic and anodic corrosion reactions on mild steel surfaces exposed to 0.01 M NaCl solutions. However, the dominating response was shown to vary with inhibitor concentration. At the concentrations for which the highest level of protection was achieved, both REM–4 hydroxy cinnamate (REM being lanthanum and mischmetal) displayed a strong anodic behaviour for mild steel and their inhibition performance, including their resistance against localised attack, improved with time.

4. Concluding Remarks

The diverse set of research summarized and discussed advocate that intense research efforts are being deployed to tackle the much problematic phenomenon of corrosion. Although it is realized that the preceding discussions are modest, the essence remains that a wide variety of chemical, biological, physical, mechanical, electrical, metallurgical, nuclear, electrochemical and computational techniques are being employed to make progress the current research to shift from grey corrosion inhibitors to green corrosion inhibitors. Green corrosion inhibitors are being more and more synthesized from organic, amino acids and plant extracts and tested in their inhibition efficiencies, while modelling research is attempting to address and elucidate the mechanism of the femtochemical reactions involved in the corrosion process and in corrosion inhibition with the use of modelling techniques like finite element modelling and artificial neural network. Grey corrosion inhibitions unanimously adhere to the Langmuir adsorption model while several

findings of research on equally performing and inhibitive green inhibitors have supported additional adsorption mechanisms captured rightly by the Frumkin's equation, Freundlich and Temkin adsorption isotherms. Latest corrosion protection techniques involve the use of nanomaterials but the use of green inhibitors remains a much safer and environmentally secure way of protection against corrosion. It is not only environment friendly but also a cost effective method with the added advantage of waste minimization. Therefore, it may be inferred that the applications of green inhibitors have a wide scope of research and development yet to be fully explored.

Acknowledgements

The authors are very grateful to Dr. V.K. Agarwal (Chairman) of the Institute of Engineering and Technology (IET) Group of Institutions, Alwar, India, for providing us the opportunity to establish a well-equipped Computational and Green Chemistry Research Laboratory at IET whereat burgeoned the idea to carry out the present review. The authors also sincerely acknowledge the use of chemical equations and illustrations from Yasakau et al. [89].

References

- [1] N.G. Thompson, M.Yunovich and D. Dunmire, *Corrosion Reviews*, **25**, 3/4, pp247–262, 2007.
- [2] O. Hutzinger, *Environmental Science and Pollution Research*, **6**, pp123, 1999.
- [3] L. Desimone, and F. Popoff, "Eco-efficiency: The business link to sustainable development, MIT Press, 2000, Cambridge MA, USA.
- [4] R. Sanghi, *Current Science*, **79**, pp 1662, 2000a.
- [5] S.K. Sharma, A. Chaudhary, and R.V. Singh, *RASAYAN Journal of Chemistry*, **1**, 1, pp68–92, 2008.
- [6] P.T. Anastas, and C.A. Farris (Eds.), "Benign by Design: Alternative Synthetic Design for Pollution prevention", A.C.S. Symposium. Ser N557, 1994, Washington DC, USA.
- [7] P. Tundo, and M. Selva, "Green Chemistry: Designing Chemistry for the Environment", Williamson Eds. ACS Sym Series, **626**, pp81, 1996.
- [8] T.J. Collins, "Green Chemistry", Macmillan, Encyclopedia of Chemistry, New York,, 1997.
- [9] S.L. Wilkinson, *Chemical Engineering News*, **75**, pp35, 1997.
- [10] P.T. Anastas, *Critical Reviews on Analytical Chemistry*, **29**, pp167, 1999.
- [11] P.A. Grieco, "Organic Synthesis in water", Ed. Blackie, 1988, London, UK.

- [12] K. Faber, "Bio transformations in Organic Chemistry: Text book", 3rd completely rev. ed; Springer Verlag, Berlin, 1997.
- [13] P.G. Jessop, and W. Leitner (Eds), "Chemical Synthesis in Supercritical Fluids", Wiley – VCH, 1999, Weinheim.
- [14] R. Sanghi, *Resonance*, **5**, 3, pp77, 2000b.
- [15] B. Valdez, J. Cheng, F. Flores, M. Schorr and L. Veleza, *Corrosion Reviews*, **21**(5–6) (2003), 445–458.
- [16] S.R.Taylor and B.D. Chambers, *Corrosion Reviews*, **25**, 5/6, pp571–590, 2007.
- [17] K.F. Khaled, *Int. J. Electrochemical Science*, **3**, pp462–475, 2008.
- [18] P. Bothi Raja and M.G. Sethuraman, *Materials Letters*, **62**, **1**, pp113–116, 2008.
- [19] S. Rajendran, A.J. Amalraj, M.J. Joice, N. Anthony, D.C. Trivedi and M. Sundaravadivelu, *Corrosion Reviews*, **22**, 3, pp233–248, 2004.
- [20] J. Mathiyarasu, S.S. Pathak and V. Yegnaraman, *Corrosion Reviews*, **24**, 5/6, pp307–322, 2006.
- [21] A. Mesbah, C. Juers, F. Lacouture, S. Mathieu, E. Rocca, M. François and J. Steinmetz, *Solid State Sciences*, **9**, 3/4, pp322–328, 2007.
- [22] P.C. Okafor, V.I. Osabor, and E.E. Ebenso, *Pigment and Resin Technology*, **36**, 5, pp299–305, 2007.
- [23] M. Lebrini, M. Traisnel, M. Lagrenée, B. Mernari and F. Bentiss, *Corrosion Science*, **50**, 2, pp473–479, 2008.
- [24] I. Radojčić, K. Berković, S. Kovač, and J. Vorkapić–Furač, *Corrosion Science*, **50**, 5, pp1498–504, 2008.
- [25] S.A.M. Refaey, A.M. Abd El Malak, F.Taha1 and H.T.M. Abdel–Fatah, *Int. J. Electrochemical Science*, **3**, pp167–176, 2008.
- [26] B.J. Little, J.S. Lee and R.I. Ray, *Biofouling*, **23**, 2, pp87–97, 2007.
- [27] A.N. Khramov, N. N. Voevodin, V.N. Balbyshev and M.S. Donley, *Thin Solid Films*, **447–448**, pp549–557, 2004.
- [28] S. Ramesh, S. Rajeswari and S. Maruthamuthu, *Applied Surface Science*, **229**, 1/4, pp214–225, 2004.
- [29] S. Hamdy, *Surface and Coatings Technology*, **200**, 12/13, pp3786–3792, 2006.
- [30] R.W.Y. Poon, J.P.Y. Ho, C.M.Y. Luk, X. Liu, J.C.Y. Chung, P.K. Chu, K.W.K. Yeung, W.W. Lu and K.M.C. Cheung, *Nuclear Instruments and Methods in Physics Research*, **242**, 1/2, pp20–274, 2006.
- [31] S. Hamdy and D.P. Butt, *J. of Materials and Processing Technology*, **181**, 1–3, pp76–80, 2007.

- [32] J.-A. Quitmeyer, *Metals Finishing*, **106**, 3, pp33–39, 2008.
- [33] H.-M. Shim, K.-T. Oh, J.-Y. Woo, C.-J. Hwang, and K.-N. Kim, *J. of Biomedical Materials Research*, **73B**, 2, pp252 – 259, 2005.
- [34] M.E. Soares, C.A.C. Souza, and S.E. Kuri, *Surface and Coating Technology*, **201**, 6, pp2953–2959, 2006.
- [35] C. Liu, P.L.K. Chu, G. Lin, and D. Yang, *Corrosion Science*, **49**, 10, pp3783–3796, 2007.
- [36] S. Qian, D. Cusson, N. Chagnon, and Bruce Baldock, *Journal of Materials in Civil Engineering*, **20**, 10, pp29–36, 2008.
- [37] Y.J. Yee, “Green inhibitors for corrosion Control: A study on the inhibitive effects of extracts of honey and rosmarinus officinalis L. (rosemary),” M.Sc. Thesis, University of Manchester, Institute of Science and Technology, United Kingdom, May 2004.
- [38] V. Ignatova, D. Karpuzov, I. Chakarov, and I. Katardjiev, *Progress in Surface Science*, **81**, 6–7, pp247–335, 2006.
- [39] V.D. Kiselev, S.M. Ukhlovtssev, A.N. Podobae, and I.I. Reformatzskaya, *Protection of Metals*, **42**, 5, pp452–458, 2006.
- [40] H. Najjaran, R. Sadiq, and B. Rajani, *Computer-Aided Civil and Infrastructural Engineering*, **21**, 1, pp67–77, 2006.
- [41] Turnbull, L.N. McCartney, and S. Zhou, *Corrosion Science*, **48**, 80, pp2084–2105, 2006.
- [42] Y. Xie, D. Zhang, Z. Feng, and B. Sun, *Key Engineering Materials Vols.*, **324–325**, pp165–168, 2006.
- [43] S. Guessasma, O. Elkedim, Ph. Nardin, R. Hamzaoui, and T. Grosdidier, *Corrosion Science*, **49**, 7, pp2880–2904, 2007.
- [44] B. Holme, and O. Lunder, *Corrosion Science*, **49**, 2, pp391–401, 2007.
- [45] R.M. Pidaparti, L. Fang, and M.J. Palakal, *Comput. Mater. Sci.*, **41**, 3, 255–265, 2008.
- [46] R., Wiston, in *Uhlig’s Corrosion Handbook*, 2nd ed., John Wiley and Sons Inc., pp1093, 2001.
- [47] K. Ravichandran, N.M. Kumar, K. Subash, T.S.N. Narayanan, *Corrosion Reviews*, **19**, 1, 29–42, 2001.
- [48] M. Elayyachy, B. Hammouti, and A. El Idrissi, *Applied Surface Science*, **249**, 1–4, pp176–182, 2005.
- [49] A.Y. El-Etre, M. Abdallah, and Z.E. El-Tantawy, *Corrosion Science*, **47**, 2, pp385–395, 2005.

- [50] A.N. Khramov, N.N. Voevodin, V.N. Balbyshev, and R.A. Mantz, *Thin Solid Films*, **483**, 1–2, pp191–196, 2005.
- [51] V. Palanivel, Y. Huang, and W.J. van Ooij, *Progress in Organic Coatings*, **53**, 2, pp153–168, 2005.
- [52] G. Paliwoda-Porebska, M. Stratmann, M. Rohwerder, K. Potje-Kamloth, Y. Lu, A.Z. Pich, and H.-J. Adler, *Corrosion Science*, **47**, 12, pp3216–3233, 2005.
- [53] S. Sawada, C.L. Page, and M.M. Page, *Corrosion Science*, **47**, 8, pp2063–2078, 2005.
- [54] M.L. Zheludkevich, K.A. Yasakau, S.K. Poznyak, and M.G.S. Ferreira, *Corrosion Science*, **47**, 12, pp3368–3383, 2005.
- [55] K.Y. Ann, H.S. Jung, H.S. Kim, S.S. Kim, and H.Y. Moon, *Cement and Concrete Research*, **36**, 3, pp530–535, 2006.
- [56] R. Fuchs-Godec, *Colloids and Surfaces*, **280**, 1–3, pp130–139, 2006.
- [57] B. Gu, and J. Liu, *J. of Rare Earths*, **24**, 1, pp89–96, 2006.
- [58] B. Müller, and S. Fischer, *Corrosion Science*, **48**, 9, pp2406–2416, 2006.
- [59] E.E. Oguzie, A.I. Onuchukwu, P.C. Okafor, and E.E. Ebenso, *Pigment and Resin Technology*, **35**, 2, pp63–70, 2006.
- [60] E.M. Sherif, and S.-M. Park, *Corrosion Science*, **48**, 12, pp4065–4079, 2006.
- [61] A. Yurt, S. Ulutas, and H. Dal, *Applied Surface Science*, **253**, 2, pp919–925, 2006.
- [62] A.S. Fouda, H. A. Mostafa, S. E. Ghazy, and S. A. El-Farah, *Int. J. Electrochemical Science*, **2**, pp182–194., 2007
- [63] S.V. Lamaka, M.L. Zheludkevich, K.A. Yasakau, R. Serra, S.K. Poznyak, and M.G.S. Ferreira, *Progress in Organic Coatings*, **58**, 2–3, pp127–135, 2007.
- [64] A.K. Mishra, and R. Balasubramaniam, *Corrosion Science*, **49**, 3, pp1027–1044, 2007a.
- [65] A.K. Mishra, and R. Balasubramaniam, *Materials Chemistry and Physics*, **103**, 2–3, pp385–393, 2007b.
- [66] M.M. Antonijevic, and M.B. Petrovic, *Int. J. Electrochemical Science*, **3**, pp1–28, 2008.
- [67] E.S.H. El-Ashry, A.El Nemr, S.A. Essawy, and S. Ragab, *Progress in Organic Coatings*, **61**, 1, pp11–20, 2008.
- [68] K. Barouni, L. Bazzi, R. Salghi, M. Mihit, B. Hammouti, A. Albourine, and S. El Issami, *Mater. Lett.*, **62**, 19, pp3325–3327, 2008.
- [69] G.Y. Elewady, I.A.El-Said, and A.S.Fouda, *Int. J. Electrochemical Science*, **3**, pp177–190, 2008.
- [70] A.N. Senthilkumar and M.G. Sethuraman, *Corrosion Reviews*, **26**, 1, pp23–38, 2008.

- [71] K.A. Yasakau, M.L. Zheludkevich, and M.G.S. Ferreira, *J. Electrochemical Society*, **155**, 5, pp169–177, 2008.
- [72] G.D. Davis, A. von Fraunhofer, A. Krebs Lorrie, and C.M. Dacres, Paper 01558, Presented at Conference CORROSION 2001, Government work published by NACE International, 2001.
- [73] F. Bentiss, M. Bouanis, B. Mernari, M. Traisnel, and M. Lagrenee, *J. of Appl. Electrochem.*, **32**, 6, pp671–678, 2002.
- [74] Popova, M. Christov, S. Raicheva, and E. Sokolova, *Corrosion Science*, **46**, 6, pp1333–1350, 2004.
- [75] O.K. Abiola, *Corrosion Science*, **48**, 10, pp3078–3090, 2006.
- [76] K.-H. Na, and S.-I. Pyun, *J. of Electroanalytical Chemistry*, **596**, 1, pp7–12, 2006.
- [77] M. Ristić, S. Musić, and M. Godec, *J. of Alloys and Compounds*, **417**, 1–2, pp292–299, 2006.
- [78] A.L. de Queiroz Baddini, S.P. Cardoso, E. Hollauer, and J.A. da Cunha Ponciano Gomes, *Electrochimica Acta*, **53**, 2, pp434–446, 2007.
- [79] Y. Ye, L. Chen, and U.J. Krull, *Analytical Letters*, **41**, 2, pp289–301, 2008.
- [80] L. Luo, G. Ye, G. de Schutter, *Construction Materials*, **161**, 2, pp73–84, 2008.
- [81] T.A. Söylev and M.G. Richardson, *Construction Building and Materials*, **22**, 4, pp609–622, 2008.
- [82] M. Scendo, *Corros. Sci.*, **47**, 7, pp1738–1749, 2005.
- [83] V. Gómez, and M.P. Callao, *Trends in Analytical Chemistry*, **25**, 10, pp1006–1015, 2006.
- [84] G. Mu, X. Li, Q. Qu, and J. Zhou, *Corrosion Science*, **48**, 2, pp445–459, 2006.
- [85] A.O.S. Leite, W.S. Araújo, I.C.P. Margarit, A.N. Correia, and P. de Lima-Neto, *J. Brazilian Chemical Society*, **16**, 4, pp756–762, 2005.
- [86] S.A. Umoren, I.B. Obot, L.E. Akpabio, and S.E. Etuk, *Pigment and Resin Technology*, **37**, 2, pp98–105, 2008.
- [87] M.A. Quraishi, and S. Khan, *J. of Applied Electrochemistry*, **36**, 5, pp539–544, 2006.
- [88] M.A. Amin, *J. of Applied Electrochemistry*, **36**, 2, pp215–226, 2006.
- [89] K.A. Yasakau, M.L. Zheludkevich, S.V. Lamaka, and M.G.S. Ferreira, *J. Physical Chemistry*, **110**, pp5515–5528, 2006.
- [90] S.S. Pathak, A.S. Khanna and T.J.M. Sinha, *Corrosion Reviews*, **24**, 5–6, pp281–306, 2006.
- [91] A. Pepe, M. Aparicio, S. Ceré, and A. Durán, *J. of Non-Crystalline Solids*, **348**, pp162–171, 2004.

- [92] M.L. Zheludkevich, D.G. Shchukin, K.A. Yasakau, H. Möhwald, and M.G.S. Ferreira, *Chemical Materials*, **19**, 3, pp402–411, 2007.
- [93] D.G. Shchukin, and H. Möhwald, *Small*, **3**, 6, pp926–943, 2007.
- [94] V. Moutarlier, B. Neveu, and M.P. Gigandet, *Surface and Coatings Technology*, **202**, 10, pp2052–2058, 2008.
- [95] S.K. Poznyak, M.L. Zheludkevich, D. Raps, F. Gammel, K.A. Yasakau, and M.G.S. Ferreira, *Progress in Organic Coatings*, **62**, 2, 226–235, 2008.
- [96] K.A. Yasakau, M.L. Zheludkevich, O.V. Karavai, and M.G.S. Ferreira, *Progress in Organic Coatings*, Article in Press.
- [97] S. Papavinasam, R.W. Revie, W.I. Friesen, A. Doiron and T. Panneerselvan, *Corrosion Reviews*, **24**, 3–4, pp173–230, 2006.
- [98] A. Zieliński and S. Sobieszczyk, *Corrosion Reviews*, **26**, 1, pp1–22, 2008.
- [99] O.B. Isgor, and A.G. Razaqpur, *Materials and Structures*, **39**, 3, pp291–302, 2006.
- [100] J. Kubo, S. Sawada, C.L. Page, and M.M. Page, *Corrosion Science*, **49**, 3, pp1205–1227, 2007.
- [101] D. Colorado-Garrido, D.M. Ortega-Toledo, J.A. Hernandez, and J.G. Gonzalez-Rodriguez in Proc. of the Electronics, Robotics and Automotive Mechanics Conference – CERMA, pp213–218, 2007.
- [102] L. Jingjun, L. Yuzhen, and L. Xiaoyu, *Anti-Corrosion Methods and Materials*, **55**, 2, pp66, 2008–72.
- [103] B. Davó, A. Conde, and J.J. de Damborenea, *Corrosion Science*, **47**, 5, pp1227–1237, 2005.
- [104] M. Bendahou, M. Benabdellah, B. Hammouti, *Pigment & Resin Technology*, **35**, 2, pp95–100, 2006.
- [105] H.A. Craddock, S. Caird, H. Wilkinson, and M. Guzmán, *J. of Pet. Technology*, **58**, 12, pp50–52, 2006.
- [106] G.B. Deacon, M. Forsyth, P.C. Junk, S.G. Leary, and G.J. Moxey, *Polyhedron*, **25**, 2, pp379–386, 2006.
- [107] A.A. Taha, The 10th Annual Green Chemistry and Engineering Conference, 2006.
- [108] M. Scendo, *Corrosion Science*, **49**, 7, pp2985–3000, 2007.
- [109] B.R.W. Hinton, D.R. Arnott, and N.E. Ryan, *Met. Forum*, **9**, 3, pp162–173, 1986.
- [110] B.T. Kilbourn, *Cer. Eng. Sci. Proc.*, **6**, 9–10, pp1331, 1985.
- [111] M. Bethencourt, F.J. Botana, M. Cauqui, M. Marcos, and M. Rodriguez, *J. of Alloys and Compounds*, **250**, pp455–460, 1997.

- [112] S. Virtanen, M.B. Ives, G.I. Sproule, P. Schmuki, and M.J. Graham, *Corrosion Science*, **39**, 10–11, pp1897, 1997.
- [113] M. Bethencourt, F.J. Botana, F.J., J.J. Calvino, and M. Marcos, *Corrosion Science*, **40**, 11, pp1803–1819, 1998.
- [114] S.M. Powell, H.N. McMurray, and D.A. Worsley, *Corrosion*, **55**, 11, pp1040, 1999.
- [115] M.A. Arenas, A. Conde, and J. de Damborenea, *Corrosion Science*, **44**, pp511–520, 2002.
- [116] A.E. Hughes, D. Ho, M.Forsyth, B.R.W.Hinton, *Corrosion Reviews*, **25**, 5–6, pp591–606, 2007.
- [117] D.-J.Choi, Y.-W. Kim, and J.-G. Kim, *Materials and Corrosion*, **52**, pp697–704, 2001.
- [118] E. Cano, P. Pinilla, J.L. Polo, and J.M. Bastidas, *Materials and Corrosion* **54**, pp222–228, 2003.
- [119] L. Aballe, M. Bethencourt, F.J. Botana, and M. Marcos, *J. of Alloys and Compounds*, **323/324**, pp855–858, 2001.
- [120] A.S.A El-Maksoud, *Materials and Corrosion*, **54**, pp106–112, 2003.
- [121] G. Karda and R. Solmaz, *Corrosion Reviews*, **24**, 3–4, pp151–172, 2006.
- [122] G. Moretti, F. Guidi, and G. Grion, *Corrosion Science*, **46**, 2, pp387–403, 2004.
- [123] S.M. El-Sawy, Y.M. Abu-Ayana, A. Mohdy and A. Fikry, *Anti-Corrosion Methods and Materials*, **48**, 4, pp227–234, 2001.
- [124] E. Khamis, and N. Al-Andis, *Mat. -Wiss.u. Werkstofftech*, **33**, pp550–554, 2002.
- [125] Gao, and C. Liang, *J. Electrochemical Society*, **154**, 2, pp144–151, 2007.
- [126] K.M. Ismail, *Electrochimica Acta*, **52**, 28, pp7811–7819, 2007.
- [127] E.E. Oguzie, A.I. Onuchukwu, P.C. Okafor, and E.E. Ebenso, *Pigment and Resin Technology*, **35**, 2, pp63–70, 2006.
- [128] M.G. Sethuraman, and P. Bothi Raja, *Pigment and Resin Technology*, **34**, 6, pp327–331, 2005.
- [129] F. Blin, S.G. Leary, G.B. Deacon, P.C. Junk, and M. Forsyth, *Corrosion Science*, **48**, 2, pp404–419, 2006.
- [130] F. Blin, P. Koutsoukos, P. Klepetsianis, and M. Forsyth, *Electrochimica Acta*, **52**, 21, pp6212–6220, 2007.