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Economic influence of corrosion on mild steel in an industrial setup: An overview

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Abstract: Most manufacturing industries throughout the world are facing many corrosion problems. Contaminants such as CO_2 and H_2S which deteriorate pipe lines and machine components made from mild steel are the major challenge of these industries. Corrosion is a pervasive and financially detrimental process that significantly impacts industrial operations, with mild steel b eing particularly susceptible due to its widespread use and inherent reactivity. This paper examines the multifaceted economic influence of mild steel corrosion within an industrial setting, distinguishing between direct and indirect costs. The direct economic burden includes expenses related to frequent maintenance, repair, and premature replacement of corroded assets, as well as capital costs associated with overdesign and the implementation of corrosion control measures. Indirect costs, often more substantial and difficult to quantify, encompass losses from production downtime, decreased operational efficiency, product contamination, and environmental cleanup. By synthesizing data from various industrial sectors, this paper highlights that the total cost of corrosion represents a considerable percentage of a nation's Gross Domestic Product (GDP). Proactive corrosion management, including the strategic use of coatings, cathodic protection, and material selection, is identified as a critical factor in mitigating these financial losses and enhancing the longevity, safety, and profitability of industrial infrastructure.

Keywords : corrosion; economics; mild steel; maintenance and environment

1. Introduction

Corrosion occurs when materials, such as mild steel, interact with their environment and lose their qualities. Corrosion, according to Perez [1] is a process of slow metal deterioration caused by the chemical or electrochemical contact of metals with their surroundings. It was also mentioned that corrosion refers to the tendency of most metallic materials to revert to their chemically stable original oxidized state under natural settings. Most metals particularly mild steel is prone to corrosion [2], and practically all minerals in the earth's crust are susceptible to degradation. While metals corrode, polymeric materials age, and selective dissolution occurs in ceramics as stated by Frankel, et al. [3]. Răuţă, et al. [4] noted that corrosion of so many metals is inevitable, but it can be controlled with the possible surface-active technology. On the other side, dry corrosion occurs in extremely high-temperature media and also in some specific special processes. Corrosion is mostly electrochemical, which occurs in a highly electrolytic environment. This environment is a medium that contains ions that have been dissolved and can migrate in an electric field. As an electrochemical process, the corrosion process can be imagined to be similar to an electrolytic cell [5]. The primary cause of all corrosion is the fact that the Gibbs energy of all systems naturally reduces. Energy can be added to a system during metal production processes, the thermodynamic process leads to an increase of the driving force of these metals, making them return to their low energy, original state, which will eventually lead to corrosion. Some procedures can be used to slow down the thermo-dynamical process toward the state of equilibrium; these procedures are known as corrosion control techniques [6].

Proper attention must be given to the control and prevention of corrosion which is inevitably a significant scientific issue [7]. The need for metallic materials in all areas of technological development is substantively growing daily. Also, the need to utilize substances that are sustainable and environmentally friendly, such as natural resources, has increased. This is because many of the organic chemicals or synthetic inorganic materials that have been used in the past are toxic to their environment. One of the leading phenomena that are causing failures of parts in the saline environment is corrosion [8]. Ajayi, et al. [9] and Hussein-Farh, et al. [10] explained that corrosion tends to result from the failures of plants, machines, and infrastructures, though, their repairs are not only usually expensive, but such failures can lead to product contamination, environmental hazards, and even huge risks to human lives [11], [12]. Therefore, an accurate assessment of factors leading to corrosion has a high impact on the structures or components' integrity [13], [14]. The study of failures due to corrosion is then becoming very essential in scientific and engineering research. Hence, researchers need to provide adequate solutions to corrosion problems because it is one of the major challenges facing manufacturing and industrial communities [15]. Corrosion, particularly in metallic materials like mild steel, remains a critical issue in various industries, leading to significant structural failures, high maintenance costs, environmental contamination, and safety hazards [16]. Despite advancements in materials science, the occurrence of corrosion in different environments, such as saline or high-temperature settings, continues to pose a challenge to the integrity and longevity of metallic components [17], [18].

This review aims to address the problem of corrosion by examining the latest corrosion control techniques and the role of surface-active technologies in mitigating corrosion effects. It will also discuss innovative strategies for corrosion prevention and how these solutions can be integrated into modern manufacturing and industrial practices to enhance material sustainability and reduce environmental impact. The study further emphasizes the need for comprehensive research and development in this field to combat the ongoing challenges posed by corrosion and ensure the reliability of metallic materials in demanding environments.

2. Economic influence of corrosion

Corrosion has significant and comprehensive economic impacts on industrial setups [19], [20]. Some of the impacts outspread beyond simple repair costs and include a variety of direct and indirect expenses that can severely affect industry's bottom line and even a country's GDP. The global cost of corrosion is over 3% of the world's GDP as estimated [21]. Corrosion is generally belief to be a worldwide enemy that should be accepted as a procedure that is inevitable [22], [23]. Throughout the world, the consequences of corrosion failure are becoming more expensive day in day out. Besides, more than 10 percent of the total metal output in the world particularly mild steel is estimated to be lost in corrosion, this has a significant affect in the nation's economy and her assets [21]. Corrosion if it is not well managed can eat up infrastructures, transportation, utilities, nuclear and military facilities, and production and manufacturing plants of an industrialized nations [24]. The survey carried out far back in some two decades ago in the United States of America revealed that the US spent about thirteen (13) times the gross productivity of Nigeria, which was at about $41.9 billion to fight corrosion. The costs of corrosion are partially related to attempts to give an attractive look to engineering equipment, structures and designs [25]. Partly because of the direct replacement and maintenance costs and concurrent losses due to interruption to plant operation and additional costs associated with the use of expensive materials and other preventive measures [26]. Corrosion cost can be classified into direct cost and indirect cost [27]; direct costs are the most obvious economic impacts of corrosion and include expenses directly tied to addressing the physical damage like maintenance and repair, equipment replacement, overdesign, corrosion prevention measures [28]. Companies must invest in proactive measures like protective coatings, cathodic protection systems, and chemical inhibitors to slow down or prevent corrosion. These are ongoing costs for industrial facilities. Indirect costs are less visible but can be even more impactful than direct costs [29]. They represent the economic losses that stem from corrosion-related failures and disruptions. Production downtime, Loss of product, reduced efficiency, safety and environmental impacts are the major outcome of indirect cost. The economic impact of corrosion is felt across all sectors but is particularly acute in certain industries such as oil and gas [30], infrastructure and transportation due to the materials and environments involved [31].

3. Forms of corrosion and prevention methods

Corrosion can be classified into various forms based on its behavior and degradation effects [32], [33]. It is possible to identify these forms of corrosion by observing visually, but the use of microscopes for magnification of the corroded metals is sometimes required. These forms of corrosion are unique and interconnected. Overall attack corrosion, regional corrosion, galvanic corrosion, intragranular corrosion, de-alloying corrosion, fretting corrosion, high-temperature corrosion, erosion-corrosion, stress corrosion, cracking, and microbially induced corrosion are the types of corrosion discuss under this section.

3.1 Forms of corrosion

Corrosion manifests in several forms, each with distinct mechanisms and impacts on materials [34]. These forms include general attack corrosion, galvanic corrosion, pitting corrosion, crevice corrosion, intergranular corrosion, and stress corrosion cracking [35]. The type of corrosion that occurs largely depends on the material's environment and the specific conditions to which it is exposed. Each form of corrosion poses unique challenges to the integrity and longevity of materials, and understanding these mechanisms is crucial for developing effective prevention methods [36].

3.1.1 General attack corrosion

General attack corrosion also known as uniform attack corrosion or general corrosion, this usually occurs whenever a metal's surface is in contact with the surrounding air. Melchers [37] reported an assumption that an even metal surface loss is an attribute of general attack corrosion damage. There is a high tendency for the general attack to occur in situations where many elements of corrosion are acting simultaneously, and there is a constant change in place between the cathodes and anodes moving along the metal surface [38]. Measurements of general attack corrosion are relatively easy, as this is done using either the average surface penetration or simply weight loss [39]. They are mostly expressed in millimeters per year (i.e., mm/year). The atmospheric corrosion (or rusting) of most parts made of carbon steel is usually characterized by uniform corrosion, as illustrated in Figure 2 (a). The most common type of metal corrosion, known as general attack corrosion, is still regarded as one of the safest forms of corrosion because it is predictable, easy to manage, and often preventable.

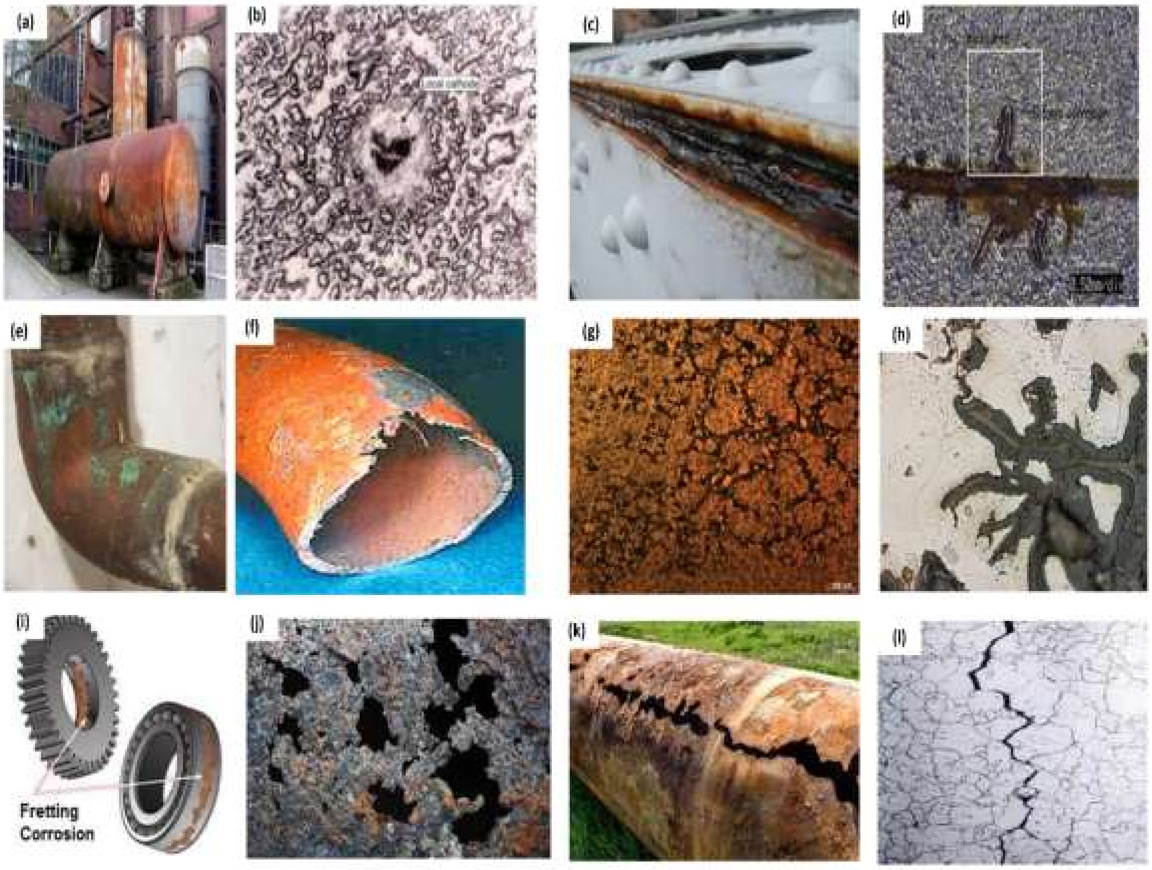

Figure 2. Forms of Corrosion (a) General attack corrosion (b) localized corrosion (c) Pitting corrosion (d) Crevice corrosion (e) Filiform corrosion (f) Dissimilar metal corrosion (g) Flow-assisted corrosion (h) Intergranular Corrosion (i) De-alloying Corrosion (j) Fretting Corrosion (k) High-temperature Corrosion (l) stress corrosion cracking

3.1.2 Localized corrosion

Unlike general attack corrosion, this type of corrosion will specifically target a portion of the metallic structure. Pitting, crevice and filiform corrosion are three different types of localised corrosion. When a small hole or hollow appears on the surface of a metal, this is known as pitting corrosion. It usually happens as a result of a tiny region being de-passivated. A localized galvanic reaction results from the passivated area becoming anodic and a piece of the remaining metal becoming cathodic. This little area's deterioration grows across the metal, finally causing catastrophe. Because this particular sort of corrosion is generally tiny and hidden by corrosion-producing substances, it is difficult to detect. As seen in Figure 2 (b). Pitting corrosion is defined by the creation of small voids in the metal, which are pits [40]. The depth and shape of the holes can vary widely, and they can be strewn across the surface with varying frequencies [41].

3.1.3 Pitting corrosion

Pitting is notoriously challenging to locate and monitor[41], [42]. The resulting openings might be rather small, and corrosion products might fully encase them [43], [44]. Pitting occasionally occurs suddenly [45]. On the surface, there can only be one, and it will be a through-the-pit, which will cause equipment failure. Cooney and Hoffman, [46] and Akpanyung and Loto [41] reported pitting corrosion as one of the most insidious and extremely destructive corrosion forms. This is because it leads to equipment failure due to perforation that only occurs with a little weight loss percentage out of an entire structure. Detection of pits is quite challenging majorly because they usually have small sizes and the pits are regularly covered with corrosion products, making them invisible [47], [48]. Additionally, its quantitative measurement and comparison of pitting extent are quite difficult, as the depths and number of pits occurring in similar conditions vary [49], [50]. Furthermore, it is difficult to predict pitting using test information from the laboratory [51], [52]. Occasionally, it takes pitting a very long time, spanning from months or years, to be visibly observed in actual service. Pitting is a localised and intense corrosion form, thus making it specifically vicious, and causes sudden failures most times [53], [54].

3.1.4 Crevice corrosion

Figure 2 (c) illustrates crevice corrosion, which resembles pitting corrosion except that it starts in a specific location. This type of corrosion is tied closely to a relatively stable macro-environment, such as the ones found under car gaskets and washers. Crevice corrosion will almost certainly occur in the presence of acidic circumstances or a loss of oxygen in the crevice [55]. Crevice corrosion is a kind of localized corrosion caused by a divergent aeration cell's operation [56]. This happens in small areas (gaps/crevices) between metals or between metal and non-metal materials. The electrolyte in the gap is typically static, and the oxygen level inside the gap is significantly lower than the outside [57]. As a result, the metal surface of the gap acts as an anode, while the metal surface on the outside acts as a cathode. When a crevice attack starts, it spreads quickly.

3.1.5 Filiform corrosion

Normal locations for filiform corrosion also known as underfilm corrosion are beneath painted, coated, or plated surfaces [58], [59]. Filiform corrosion will start at tiny surface flaws in the coated material when water penetrates the coating and spread to weaken the structural integrity of the entire metal formation [47](see Figure 2 (d)). Filiform corrosion characteristically initiates at a defect in the coating, inform of a scratch, a chip, or a poorly prepared surface. The corrosion process is an electrochemical reaction that requires moisture and oxygen [60], [61]. The head of the "filament" acts as a moist, oxygen-depleted anode, where the metal dissolves. The tail, which is made of dry, porous corrosion products, acts as a cathode, where oxygen is reduced. The difference in oxygen concentration between these two regions creates a corrosion cell that drives the propagation of the filament [61], [62]. This process is particularly accelerated in high-humidity environments, especially when chlorides (from salt) or other corrosive agents are present [63], [64].

3.1.6 Dissimilar metal corrosion

When two dissimilar metals are present in a corrosive electrotype, dissimilar metal corrosion, also known as galvanic corrosion or bimetallic corrosion, occurs [65]. In between two metals, a galvanic pair formed, with one metal acting as an anode (sacrificial metal) and the other as a cathode. The sacrificial metal will corrode, and decay more quickly than it would normally, whereas the cathode would depreciate more slowly. Before galvanic corrosion may occur, certain conditions must be met, including the presence of electrochemically distinct metals, electrical contact between the metals, and exposure to an electrolyte [66]. The potential difference between linked metal and the geometrical ratio of the metal are both important aspects of galvanic corrosion [67], [68]. The standard potentials of anodic reactions for interacting metals are determined thermodynamically [69]. Figure 2 (e) shows a dissimilar metal corrosion on a material.

3.1.7 Flow-assisted corrosion

Whenever winds or water dissolves or removes a protective layer of oxide from a metal's surface, it causes flow-accelerated corrosion, also known as FAC. The underlying metal is consequently exposed to additional degradation and corrosion (see Figure 2 (f)) [70]. Flow-assisted corrosion (FAC), also known as flow-accelerated corrosion, is a degradation mechanism where a protective oxide layer on a metal surface is removed by a fast-flowing fluid, causing the underlying metal to corrode at an accelerated rate [71]. This process is a combination of mass transfer and electrochemical corrosion, and it's particularly problematic in industrial systems like power plants. typically, magnetite (Fe3O4), forms on the surface of susceptible metals, like carbon steel, when exposed to water or steam. This layer acts as a barrier, slowing down further corrosion [72]. When the fluid is flowing rapidly, especially in turbulent areas such as bends, elbows, or valves, the protective oxide layer is dissolved and carried away by the flow. This dissolution is an electrochemical process enhanced by the fluid dynamics [73]. With the protective layer gone, the freshly exposed metal is no longer protected and begins to corrode to form a new oxide layer. The high-velocity fluid immediately dissolves and sweeps away this new oxide layer as it forms, repeating the cycle and leading to a continuous loss of metal. This results in wall thinning of the pipe or component, which can eventually lead to leaks or even catastrophic rupture [74].

3.1.8 Intergranular corrosion

When a chemical and an electrochemical attack occurs on the grain boundaries of metals, intergranular corrosion occurs [75], See Figure 2 (g). This is usually caused by impurities in the metal, which tend to be present in larger concentrations near grain boundaries. These areas may be more prone to corrosion than the rest of the metal. The consequences of grain boundary are minor or non-existent in most metal applications [76], [77]. A uniform attack is usually a result of corrosion in metals because the grain boundaries are typically more reactive than the matrix to some extent. Nevertheless, under some particular conditions, the interfaces of the grains are highly reactive, causing intergranular corrosion to occur, it is a localized attack corrosion that occurs adjacent to and at the grain boundaries, with the grains being corroded minimally [78]. The impurities that might occur at the grain boundaries, alloying element enrichment, and element depletion in the area of the grain boundary, influence the occurrence of intergranular corrosion [79], [80].

3.1.9 De-alloying corrosion

Intergranular corrosion is a result of both chemical and electrochemical attack on the grain boundaries of metals. Impurities in the metal, which are concentrated more heavily along grain boundaries, are typically to blame for this. These edges could corrode the metal more than the rest of it. In the vast majority of metal applications, the effects of the grain boundary are negligible or nonexistent [81]. Similar procedures are used in several other systems where de-alloying is used to remove cobalt, aluminum, iron, chromium, and some other elements Lim et al., [75] Figure 2 (h) depicts a case of de-alloying corrosion.

3.1.10 Fretting corrosion

Fretting corrosion occurs when repeated wearing, tearing and vibration take place where two different surfaces have an interface that brings them into quite a proximity that will result in rough surface corrosion [82]. Rotation and impact machinery, bearings, and bolted assemblies are all susceptible to fretting corrosion. Surfaces that are subjected to vibration during transport are not excluded [83]. An example of fretting corrosion is shown in Figure 2 (i).

3.1.11 High-temperature corrosion

Fuels containing vanadium or sulfates, which are used in gas turbines, diesel engines, and other machinery, can produce substances during combustion with a low melting point [84], [85]. These substances significantly damage metal alloys. High-temperature corrosion can be influenced by oxidation, hot temperatures, sulphidation, and carbonization. Figure 2 (j) shows a high-temperature corrosion illustration.

3.1.12 Erosion corrosion

Erosion Corrosion is described as an increment or speed in the rate of damage and breakdown on metal caused by relative movement between a material's surface and an environment that is corrosive [86] (see Figure 2 (k)). The movement is generally extremely quick and encompasses the consequences of abrasions or wear characteristics. In the form of dissolved ions, the metal can be removed from the surface. At times, the metal creates solid corrosion products that can be mechanically cleaned away from the surface of the metal. In the presence of localized attack under stagnant conditions, fluid (i.e., environment) mobility can sometimes reduce the pace of corrosion which is not an erosion-corrosion process because the damage will not increase. Erosion corrosion can be characterized by the way it appears in grooves, waves, valleys, rounded holes, and gullies [87], [88]. They typically display directional patterns. Severally, failures resulting from erosion-corrosion ensue rapidly, and these are surprising mostly due to the corrosion evaluation tests that were run under some static conditions, or because the effects of erosion were not put into consideration [89], [90].

3.1.13 Stress corrosion cracking

This type of corrosion is characterized by the development of fissures on the metal surface [91]; however, the process is not solely mechanical. Only metals that are sensitive to it are affected by Stress Corrosion Cracking (SCC), which happens when tensile stress and corrosive environments interact. only when these three circumstances are met is SCC feasible. Compressive loads do not contribute to SCC. Residual stresses can either directly or indirectly apply tensile tension [92]. Both are sometimes accurate. Operations employed in manufacturing and mechanical treatment (such as cold working, welding, heat treating, and machining) result in residual tensions [93]. It is nearly difficult to avoid the presence of tensile stresses in an engineering structure in practice. The time to failure and the tensile stress value have a linear connection; the higher the tensile stress, the faster the time to failure [94], [95]. Figure 2 (l) shows stress corrosion cracking in detail.

3.1.14 Microbiologically influenced corrosion

Microbiologically Influenced Corrosion (MIC), also referred to as "microbial corrosion," is a type of corrosion brought on by bacteria [96], [97]. The microbes (bacteria and fungi), which can initiate and support the formation of corrosive media, are involved in this type of corrosion. Although MIC doesn't take on a particular shape, it can cause a variety of corrosion processes, including pitting, crevice corrosion, under-deposit deterioration, and selective de-alloying. Additionally, galvanic and erosion-corrosion systems can be combined with it. These variables make it challenging to pinpoint corrosion that is microbially motivated. MIC could be viewed as the most divisive type of corrosion. The presence of corrosion-causing microorganisms in a specific medium does not imply that you have found

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the source of the corrosion, as these species can be found in the environment at any time [98]. Figure 3 shows images of microbiologically influenced corrosion.

Figure 3. Microbiologically influenced corrosion

3.2 Corrosion prevention

Corrosion can only be managed and prevented but stopping it completely in any metal is thermodynamically impossible because the process of corrosion is thermodynamic [99]. Metals generally will gain electrons during their respective extraction metallurgy processes, which leads to an increase in their Gibbs free energy or excitation level [100]. This results in the metals throwing away their extra e1ectros to retain their original low-level state, which later leads to corrosion, by forming sulphides, oxides, hydroxides, and carbonates on the surfaces of the metals. In the real sense, these corrosion products were the companion of the metals while in the ore state. Nevertheless, corrosion can be controlled and prevented.

One significant fact about corrosion management is to accurately identify the problem and find the right method for treatment [101]. Corrosion prevention requires proper and adequate planning [102], [103], as this is considered in the design phase of equipment and very early phases of the construction project. Strategies applied are generally aimed at corrosion prevention, which is basically to reduce the rates of corrosion to the nearest minimum [104]. With corrosion prevention, the automatic achievement of standard planned values is mostly the case. Proper plans and precautions are applied, such as the ways of performing some basic tests without leading to corrosion of the components used, which will be identified, highlighted, and applied as part of the standard operating procedures of the plant.

An important example is a topography in which pipelines are being laid, as fluid stagnation increases the likelihood of microbial corrosion, thus the design of pipeline laying should be done to avoid too many branches, which can initiate fluids being stagnated. According to Angst [105], correct design and intelligent selection of construction materials are clear needs, and achieving them can prevent corrosion while the project is still in the engineering stages. A thorough approach to these issues allows for the avoidance of a wide range of corrosion issues at a reasonable cost. Mistakes or disregard of these issues during the design phase might result in substantially greater costs, which will be necessary to avoid the repercussions of corrosion failures during operation. Corrosion can be controlled by applying known measures and principles, without necessarily significantly changing the process, which can affect the overall process in service [106]. Corrosion control methods include the use of inhibition, protection using coatings, and materials selection [5], [102], [107]. These strategies seemly suit existing equipment and assets. With corrosion control, corrosion rates achieved are usually lower than the key performance indicators that have been set by the regulations and standards [27], [108]. Prevention of corrosion can be taken based on the form of corrosion. However, some more general methods include but are not limited to our selection of materials, alteration of the environment, chemical treatment such as the use of inhibitors, thin-film application (Coatings), anodic protection (AP) methods, and cathodic protection (CP) methods which are discussed below.

3.2.1 Materials selection

Some materials such as titanium and stainless steel are known for their excellent corrosion-resistant properties to a certain extent [109]. This is a result of their mechanical and chemical properties; however, their costs are on the high side, making them non-feasible for use in service for many applications, as the cost factor cannot be underestimated. The selection of a wrong combination of metals can lead to disastrous effects originating from galvanic corrosion [46], [110]. Moreover, many corrosion failures have happened in service due to wrong materials selection, especially when materials were selected majorly because of their high cost. Hence, applications, properties, and cost are the major factors to put in mind in selecting suitable materials for use in industries.

3.2.2 Cathodic protection

Thermodynamically, metals in their fabricated forms spontaneously lose electrons when exposed and used in service, which originates to corrosion [1], [111]. Nevertheless, it is possible to get the lost electrons fed back to their ions, this allows them to become atoms, and thus, reduce the rate of corrosion significantly. This forms the basis of cathodic protection against corrosion. This is illustrated in Figure 4. The external sources of the electrons which are used for the electron replacement, are by inducing current from an external source and by scarifying another metal which is known as the "sacrificial anode".

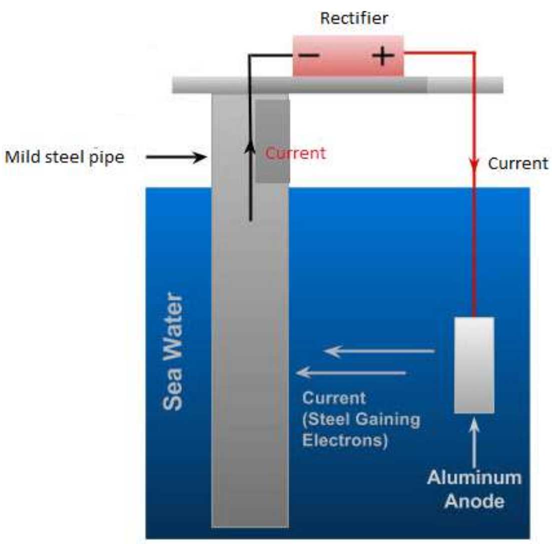

Figure 4. Cathodic protection against corrosion [22]

3.2.3 Application of inhibitors

Inhibitors are chemical treatment processes that are being considered globally. Other chemical methods being used for corrosion control include the use of biocides that can be natural, green, and biological, which can kill organisms such as bacteria, thus controlling the severity of corrosion normally caused by a microorganism. Other chemical treatments include the use of oxygen venger. Corrosion

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inhibitors affect either both the anodic and cathodic reactions in a way that a significant reduction in the overall corrosion rate is achieved [112], [113].

3.2.4 Thin film application (protective coatings)

Coatings protect metals from having direct contact with the electrolytes, thus controlling the rate of corrosion. An effective coating is expected to be free from cracks and pits, as corrosion can be initiated and enhanced from the defect location. It is important to mention an assertion of that the accumulation of bacterial cells, which is also known as biofilm tends to act as a damaged coating and thus, accelerating the rate of corrosion [114]. Manu et al., [115]and Sakthinathan et al., [116] reported that the mechanical, optical, electrical, tribological chemical, and some other properties of several substrate materials can be greatly enhanced by thin film deposition.

These thin-film depositions are generally accomplished using either the chemical vapor deposition (CVD) or the physical vapor deposition (PVD) processes, which are summarized in Figure 5. The methods of preparing the films primarily have evident effects on the thin films' physical properties. Figure 5 shows that there are several ways thin films can be produced. For instance, Binder [117] asserted that artificial polymer thin film development is a process, which occurs by chemically connecting numerous 100 -1000 monomer molecules, resulting in macromolecule formation. The most significant processes of thin-film formation are established on liquid-phase chemical methods, gases phase chemical techniques, glow discharge techniques, and evaporation methods.

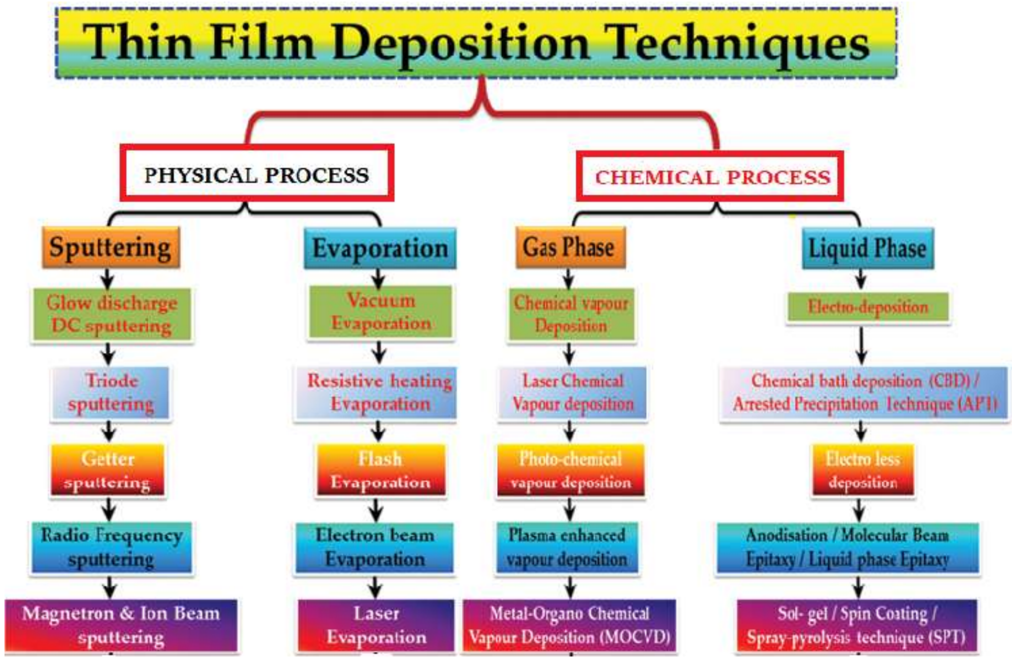

Figure 5. Flowchart illustrates the physical and chemical deposition process of widespread thin film techniques [82]

Primarily, Physical Vapour Deposition (PVD) is a vaporization and plating method, which involves the process of Rz-face deposition that is involved in decorations, protection of tools, and other equipment [118]. The basic mechanism is transferring the atoms of material from the solidified form to the vaporized form and then back to the solidified form. A thin film is, therefore, aggressively built on the substrate's surface. The most widely utilized physical vapor deposition processes are evaporation and sputtering.

Typically, PVD techniques are being used in a range of film deposition thicknesses between very few nanometers (nm) to massive nanometers (nm). It is also possible to use physical vapor deposition approaches in forming multi-layered deposit coatings. The substrate size in PVD processes can range from very small to very large. The shape of the substrates can also be flexible, ranging from flat geometries, the simple and complex shapes [119], [120]. In general, the deposition rates of physical vapor deposition methods are usually between 1-10 nm per second. It is possible to use reactive deposition processes along with PVD when elements, alloys, and compounds films deposition is being done. In the reactive deposition processes, the compounds are generally made by the reaction between the atmospheric pressure gas environment and the depositing materials. An example of the atmospheric pressure gas used is nitrogen, as in the case of titanium nitride.

Chemical vapor deposition (CVD) is used to synthesize thin film, as reactions occur within the vapor-phase constituents to deposit coatings on the substrates' surfaces. These reactions make CVD techniques unique, and it is, therefore, vital to perfectly understand the reactants' reaction and the usual process variables [121]. Examples of the chemical reactions CVD employs in forming thin films are synthetic chemical transport reaction, pyrolysis, reduction, and oxidation. In chemical vapor deposition, the gaseous chemical reactant is transported to the reaction chamber, thermally stimulated, reacts with one another, and forms a solid deposit on the surface of the materials [122].

The resulting deposits from CVD on both simple and complex-shaped substrates, and possess low porosity and uniform thickness. The most important methods for film growth at low temperature due to their flexibility in the deposition of a large number of elements and compounds are the chemical deposition procedure. These chemical deposition processes are highly economically effective and useful; they have been industrially used on large scale. CVD methods are widely used industrially, due to their flexibility in depositing huge diversity of compounds and elements which covers a broad range between amorphous deposits towards epitaxial layers and with a great degree of purity plus perfection [123].

3.3 Challenges, impact, applications, and future directions

3.3.1 Impact of corrosion

Corrosion presents a significant global challenge, impacting industries, economies, and infrastructure. It leads to the degradation of materials, which results in costly repairs, replacements, and maintenance [124]. The economic implications are considerable, with corrosion costing nations billions of dollars annually. Beyond the direct financial losses, corrosion has serious safety and environmental impacts, including structural failures that can jeopardize human lives and cause significant environmental damage, particularly in sectors like oil and gas, transportation, and manufacturing [125]. The impact of corrosion extends beyond just financial concerns; it also affects the efficiency and performance of industrial processes, leading to increased downtime, loss of productivity, and disruption in service delivery. In critical infrastructure such as bridges, pipelines, and power plants, corrosion can compromise structural integrity, leading to catastrophic failures and the loss of service continuity [126].

3.3.2 Challenges in mitigating corrosion

One of the primary challenges in corrosion mitigation is the complexity of its nature [127]. Corrosion processes are influenced by a range of factors, including environmental conditions (humidity, temperature, presence of corrosive agents), material composition, and mechanical stresses. The inability to predict the onset and progression of corrosion in certain environments makes it challenging to design universally applicable prevention methods [128]. Present corrosion control methods often have limitations in terms of effectiveness, cost, and environmental sustainability. Conventional techniques, such as coating and galvanization, are commonly used to protect metals from corrosion, but these methods can wear off over time, requiring frequent maintenance. The use of chemical inhibitors is another option, though many of these compounds are hazardous to both health and the environment. Thus, there is a strong demand for innovative, eco-friendly corrosion prevention technologies [129].

3.3.3 Applications and latest trends

Corrosion prevention is vital across a range of industries, from construction and transportation to energy and manufacturing. As the need for more durable and sustainable materials grows, the development of advanced coatings, self-healing materials, and corrosion-resistant alloys has become a major focus of research [130], [131]. Self-healing coatings, for instance, are designed to autonomously repair small damages to the material's surface, greatly extending its lifespan and reducing maintenance costs [132], [133]. Another emerging trend is the use of nanotechnology in corrosion control. Nanomaterials, with their enhanced mechanical and chemical properties, are being incorporated into coatings to provide better protection against corrosion [134]. In addition, the integration of corrosion monitoring systems, such as sensors and smart coatings, allows for real-time detection of corrosion, providing early warnings and reducing the need for invasive inspections. The incorporation of machine learning and artificial intelligence into corrosion monitoring holds promise for predictive maintenance, allowing industries to anticipate and mitigate corrosion issues before they result in significant damage [135].

3.3.4 Future directions

The future of corrosion management lies in the development of more sustainable, effective, and cost-efficient solutions. There is an increasing focus on creating environmentally friendly corrosion inhibitors and coatings that do not compromise material performance or contribute to environmental pollution. Additionally, research into alternative materials, such as corrosion-resistant composites and bio-inspired materials, holds promise for reducing the reliance on traditional metals prone to corrosion. Avancements in corrosion detection and monitoring technologies, such as the integration of artificial intelligence and machine learning, will likely revolutionize corrosion management. These technologies can predict corrosion-related failures, enabling timely interventions and minimizing the risk of catastrophic damage.

4. Conclusion

This paper identified and reviewed the impact, causes and types of corrosion in an industrial setup. Some various methods of combating corrosion were also abridged. Corrosion was discovered to have direct and indirect influence on the nation and world economy. Estimate of the avoidable costs of corrosion ranges between 10-40%. Although most studies have focused on the direct costs of corrosion, it is agreed that the indirect impact of corrosion is much more significantly greater. The neglect of indirect costs is because of the inherent difficulty in its estimate.

Author's declaration

Author contribution

Samuel A. Ajayi: Conceptualization, Methodology, Funding, Methodology, Supervision, Validation, data curation, original draft; **Olufemi Ajide and Christian O. Osueke:** Supervision, Editing, Analysis, Editing and Validation; **Ejiroghene Onokpite and Agberegha Larry Orobome:** Review and Editing; **Abideen T. Oyewo**: Validation, Review and Editing.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Conflict of interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Ethical clearance

Not applicable

AI statements

This article is the original work of the author without using AI tools for writing sentences and/or creating/editing table and figures in this manuscript.

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