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A Review On: Biocidal Activity of Some Chemical Structures and Their Role in Mitigation of Microbial Corrosion

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Abstract

Microbial corrosion has developed a foremost problematic in the oil and gas industrial field. This problem is by reason of the continual usage of water swamping in promoting oil recovery. This water moistens the walls of oil pipelines. Microbial corrosion is also present in other industries such as nuclear power reactors and in most hydropower applications. Increased corporate infrastructure also leads to increased microbial corrosion. Sulfate Reducing Bacteria (SRB) is considered as the main kind of bacterial which cause of pipeline corrosion. Because of microbial deterioration is not understood, until recently, there is no clear mechanism to explain why and how microbial corrosion occurs because of the complexity of this area. The new theory of bio-catalytic cathodic sulfate reduction is bio-electrochemistry based. In this theory, the bioenergetics can explain why microbial corrosion occurs, while the extracellular electron transference theory is capable of explain how microbial corrosion happens. The microbial corrosion can be caused by nitrate reducing bacteria, which led to an analogous biocatalytic cathodic nitrate reduction theory. The electron mediator assessment intended to validate the extracellular electron transference progression which anticipated in biocatalytic cathodic sulphate reduction. The electron mediators like riboflavin and flavin adenine dinucleotide were accomplished of hastening the microbial corrosion by indorsing electron transport flanked by an iron surface and a biofilm. In case of deficient in organic carbon, the elemental iron substituted the organic carbons as an energy source/electron donor for SRB to get their conservation energy. Under unembellished undernourishment of organic carbon, the largest pit depth was accomplished, which was consistent with the estimate of biocatalytic cathodic sulphate reduction. The developing request and crucial necessity in oil and gas industry is to find an effectual method to avoid and/or mitigate microbial corrosion at a rational cost.

Keywords: Microbiological corrosion; Sulphate-reducing bacteria; Biocides enhancer.

1. Introduction

Generally, microorganisms tend to create biofilms on a widespread variety of metallic and non-metallic structures by using extracellular polymeric matters to entrench sessile cells [1-5]. The biofilms afford surroundings encouraging to the manifestation of microbial corrosion in several production sectors [6-8]. Microbial corrosion comprises corrosion initiated by microorganisms in addition to corrosion by another pre-existing corrosion agent that is accelerated by microorganisms. Several kinds of mechanisms which connected with diversity of the microbial strains and kinds of metabolites [9-12]. Many defence mechanisms for the microorganisms to protect them against ecological risks [13-15]. It well known that the anaerobic bacteria in the formed biofilms have much more resistance to treatment equated with aerobic cells. Biocides have been applied to treat biofilms in connection with the physical cleaning. Many techniques have been industrialized to enhance the efficiency of biocide [16-20]. Current strategies and novel developing technologies as bacterial phage, quorum sensing inhibitors, and distinct compounds to improve biocides have been anticipated in recent years [21-25]. This review appraises these diverse treatment approaches and many procedures accustomed ration biocidal activity including microbiology, molecular biology, corrosion testing and electrochemical methods [26, 27]. The microbially influenced corrosion may be fixed for the tenacities of this assessment as, the deterioration of metallic structures encouraged by the actions of microorganisms. Therefore, by this description the inquiries in this sector necessitate a consideration of the arena of microbiology along with corrosion knowledge [28-

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30]. Subsequently, for many years, the numeral of research in the world has endured relatively small. Additionally, the interference has been an overall deficiency of consciousness of the denotation of the problem [31-33]. The microorganisms mostly concerned and principally considered in relation to microbial deterioration are the SRB. This bacterium, furthermore, to being stringent anaerobes has been difficult to grow, isolate, and count. SRB has been an extra barricade to those who would even be involved in working in the arena of microbially induced corrosion [34-37]. Correspondingly, the research papers in this arena have been approximately distributed entirely over the world in numerous incomprehensible journals. Through the former many years, the condition seems to be altering. Many research groups working on this field and the conferences are held to discuss this phenomenon [38-40]. Irregular papers on microbiological deterioration have been existed at the international symposia on biodeterioration and at the international congresses on metallic deterioration. Then, two groups, one in England and the other in the USA, continue to be energetic in microbiocidal corrosion research. Several researches are accepted to discuss this kind of corrosion have recently appeared in several countries. General reviews of microbial-based corrosion especially devoted to deterioration by SRB and sulphur-oxidizing bacteria have been described [41-44]. Undoubtedly the first conveyed recommendation that microorganisms might be elaborated in metallic deterioration. He ascribed the decomposition of lead cable to the accomplishment of bacteriological metabolites [45]. The bacteria iron and sulphur were elaborated in the deterioration of the internal and the external of water pipelines by representing the occurrence of strangely great quantities of sulphur. In iron depositing microorganisms such as Cadobacter and Gallionella, were described as presented and related to the deposits in pipelines. Even if research of underground decomposition in the absenteeism of stray currents sustained to gather, it was not until 1934 [46-50]. This theory was recognized to introduce more explanation for the anaerobic deterioration of carbon steel pipelines. The anticipated results are proved that the SRB is responsible for this type of corrosion. Suggestion for this bacterially accompanying corrosion continual to gather from everywhere the world and was reported. Subsequently, these premature revisions, are growing which give an indication that, extra organisms, in addition to SRB, have been elaborated in the weathering of iron pipes. A part of microorganisms in aerobic corrosion was hypothesized as being due in part to the creation of tubercles in aggregation with microbial colonies, which inductee's oxygen concentration cells [51-53]. Numerous microorganisms were described to be contemporary in noteworthy numbers in the sludge of fuel tank. Current research appears to indicate that, the organic acids, gained by microorganisms specially fungi, were principally intricated in this kind of corrosion. Several corrosion failures in the chemical process industries are occurred in the 1970s which, have been accredited to the actions of microorganisms [54-56]. Correspondingly, stern complications by reason of the actions of SRB have ascended in offshore oil operations. Two extra problems have ascended owing to bacteriological development in the legs and storage tanks of offshore structures besides the already exist corrosion problems. These are the creation of H_2S, since it is a serious hazard of personnel safety, and the creation of bacteriological metabolites that give growth to the weakening of concrete. Biological internal and/or external corrosion of extensive, great capacity, subsea pipelines, which are the current process of broadcasting to shore of oil and gas from offshore production fields, also give the impression to remain a foremost problematic effect [57-60]. Microbial corrosion, mainly due to SRB, is a noteworthy reason of the underground deterioration of constructions, especially pipelines. Several researches were estimated that, about 50% of all failures in pipeline of oil and gas industry in Great Britain were outstanding to the actions of SRB [61-63]. It is also extremely possible that an equal or superior percentage of failures occur in USA, though bacterial corrosion failures are not familiar in many pipeline workers. It has been recognized that, approximately one-half of the corrosion of steel culvert pipe in Wisconsin is owing to the actions of SRB [64]**.** In 1952, SRB interrelated to the deterioration of 70% of entirely the extremely rusted water mains inspected in the Great Britain [65]. The equipment's, and gas storage tanks may be extremely rusted by means of action of SRB [66]. An earlier statement designated that 77% of the corrosion happening in one group of producing wells was existed as a result of SRB [67]. The weathering of airplane fuel chambers has been stated ships and maritime buildings have been described to be susceptible to biological corrosion which, includes ship hulls and engines [68]. The holds and fuel tanks, offshore oil recovery platforms and ocean thermal energy conversion heat exchangers [69]. Furthermore, recovery of the gas, oil, and water supply, and the marine industries, the power generation and chemical industries and extra procedure of petroleum productions, all of these are now reported that, the microbiological deterioration is of significant meaning in cooling water systems and as well as heat exchangers [70]. Although the entire definite fees of metallic bio-deterioration are of problematic to determine, some current approximations of microbiological deterioration have been established. In USA, the national costs of metallic decomposition of such as spare, anticipation, and conservation are assessed to be 167 billion bucks in 1985 the microbial corrosion account for 16-17 billion out of the 167 billion dollars. This cost does not comprise the charge of demolition, disturbance, and deaths due to equipment failures such as gas pipeline ruptures. In the Great Britain, the researchers are specified possible microbial corrosion participation in 10% of cases responding to its corrosion investigations [71]. Corrosion of metals, especially iron, is common to most people as a "rust" process. Rust is simply a term referring to the product of rust of iron or its alloys, which are largely composed of aqueous ferric oxides. Corrosion of non-ferrous metals is frequently convoyed by the development of their oxides, which vary from blue green or red in case of copper metal to white in case of zinc compounds [72]. The basic source of decomposition is the ordinary uncertainty of metals in their sophisticated forms. Metals tend to reversion to their natural states through the procedure of corrosion since of the free energy change. The corrosion products may form loose films or very thin, tightly adhesive, defensive as well as pitting type which diminution the rate of corrosion. The deterioration procedure is fundamentally an electrochemical process and this assumption was first gotten by Whitney [73]. This process involves, a flow of electricity between convinced zones of a metallic outward through a solution which can comportment an electric current [74]. generally, when a metal is immersed in aqueous solution, the metal dissolves at positive sites (anodic sites), departure overdue a surplus of electrons as described in eq. (1):

$$M = M^{z+} + ze \qquad (1)$$

This reaction is shifted to the right, by removing of the released electrons which increasing the metal dissolution. The cathodic reactions, in which the electrons are detached, involve oxygen in neutral or alkaline solutions and protons under acidic conditions as mentioned in eq. (2,3):

$$\frac{1}{2} O_2 + H_2O + 2e = 2OH^- \qquad (2)$$

$$2H^+ + 2e = 2H = H_2 \qquad (3)$$

Areas on the surface of metal, where these electron utilization reactions occur are called cathodic sites and in circumstance of carbon steel and in the attendance of supplementary oxygen, the ferrous hydroxide is rehabilitated to ferric hydroxide see eq (4,5):

$$Fe^{2+} + 2(OH)^- = Fe(OH)_2 \qquad (4)$$

$$Fe(OH)_2 + \frac{1}{2} H_2O + \frac{1}{2} O_2 = Fe(OH)_3 \qquad (5)$$

Which precipitates as hydrous ferric oxide [$Fe_2O_3.H_2O$], a formula of rust. Electrons also can be removed by dissimilar metal coupling or by connection to the positive terminal of a battery. The corrosion in neutral environments is generally originated through the development of electrolytic cells. These may be recognized by variances in the electrical potential of dissimilar metals which exist in electrical interaction or variances in potential from spot to spot on the same metal surface i.e., if iron and copper are in contact in electrolyte the Cu^{2+} act as electron acceptors in the iron corrosion see the following eqs. (6,7):

$$Fe = Fe^{2+} + 2e \qquad (6)$$

$$2e + Cu^{2+} = Cu \qquad (7)$$

In case of protected metal surface by formation of a deposit, the metal exterior the deposit will be nearby to oxygen while that below the deposit will be shielded from it and foremost to localized corrosion which is call pit formation. The cathodic reaction can be achieved by movement of the liberating electrons to the outside metal surface from the rust layer to diminish oxygen by creating hydroxyl anions. This type of cell is mentioned to as an oxygen concentration cell and is principally elaborated in microbial corrosion. Another corrosion type is evolved like pitting corrosion is crevice corrosion which happens inside cracks or further protected zones anywhere a motionless electrolyte is existing. Whereas pitting is usually taking apartment on a plane metallic superficial, because of development of bio-layered of bacteria on the surface of metallic structures. These categories of decomposition cells which may be attributable to the actions of bacteriological deposits are produces innumerable chemical concentration cells [75]. The microbial corrosion not only affect steel and its alloys but also affect many other metals and its alloys see Table 1.

1.1. Microorganisms Involved in Corrosion

The microorganisms which have been accompanying with decay of metallic structures comprise many types and species. They may be divided into three groups: bacteria, fungi and algae. These microorganisms have been recognized as partaking roles in the microbiological decomposition. As a result of laboratory tests and field trials, where further types have purely been isolated from distrusted corrosion cases.

1.1.1. Bacteria

The greatest significant bacteria which play a significant character in the microbiological deterioration progression are those intertwined in the sulfur cycle [76]. These kinds of bacteria which intricated in the oxidation reduction reaction of sulfur. The SRB strain is the furthermost significant microorganisms which originated in microbially deterioration developments.

1.1.1.1. Sulfate-Reducing Bacteria

Fig. 1 shows that, the SRB strains are a collection of severe anaerobic bacteria which are taxonomy assorted nonetheless ecologically and physiologically comparable since these bacteria can survive for an extended time in the existence of oxygen. They are famous by their capability to comportment dis-simulant sulphate reduction, using sulphate as electron acceptor and reducing it to sulphide see Fig. 5. Some newly discovered species, such as Desulfuromonas Acetoxidans, use sulphur instead of sulphate as the electron acceptor [77]. The biochemistry of sulfate reduction and physiology of SRB have been revised [78]. These microorganisms in the species Desulfovibrio, which comprises seven classes, are non-spore creating microbes which are spirals shape or curved rods [79]. Laboratory and field isolation studies proved that; these strains have related to anaerobic microbial deterioration possibly further than any supplementary genus of SRB**.** Seven extra new species of SRB have now been documented and these kinds include: Desulfuromonas, Desulfomonas, Desulfobacter, Desulfobulbus, Desulfococcus, Desulfosarcina, and Desulfonema [80]. These new strains, separately from their morphological differences, is the widespread choices of carbon sources which they can use. Serviceable carbon sources for Desulfovibrio and Desulfotomaculum are principally limited to lactate, pyruvate, and malate, while with the new genera, CO_2 and fatty acids, from acetate to stearate, may be utilized.

1.1.1.2. Sulfur Oxidizing Bacteria

To emphasize the reputation of anaerobic corrosion by SRB, corrosive effects of produced acids by microorganisms may be overlooked but in case of sulphur-oxidizing bacteria the furthermost noteworthy and effective acid formed by this strain is sulfuric acid H_2SO_4 since, these microorganisms are acidophilic, aerobic chemolithoautotrophs in the species of Thiobacillus [81]. By using r-RNA molecular identification technology, the SRB can be categorized to seven groups phylogenetically. Fig. 1 shows five groups belonged to the bacteria, while the other two groups were archaea [82]. Various organic carbons such as ethanol, formate, lactate, pyruvate, malate and succinate can be digested for SRB growth and are capable of oxidizing fatty acids and aromatic compounds like benzoate and phenol. Some SRB partly oxidize these organic compounds to acetate, while others completely degrade the organic substrate to carbon dioxide. Various substrates can attend SRB as electron donors including sugars, amino acids, and one carbon compounds like methanol and carbon monoxide [83].

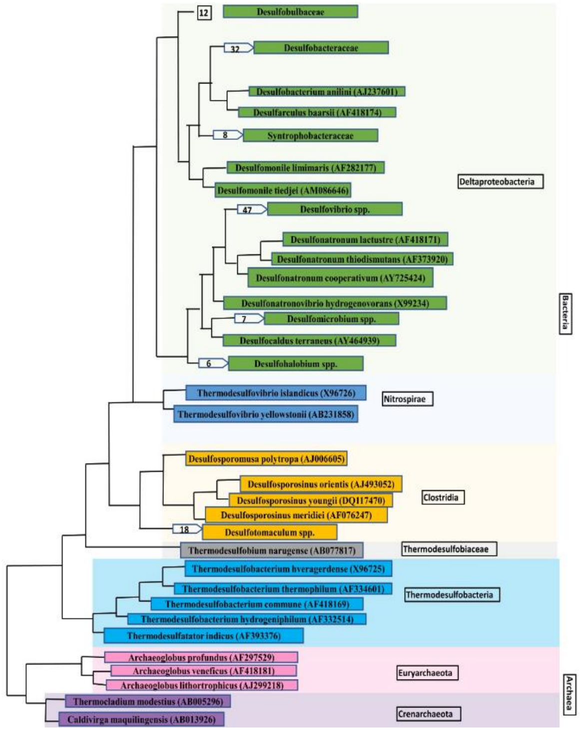

Fig. 1: Phylogenetic tree illustrating SRB species according to the identification technology [84].

1.1.1.3. Iron Bacteria

The aerobic iron bacteria are the 3rd collection of microorganisms which, has related to microbiological deterioration. Two forms are included, the pursued microorganisms in the species Gallionella, and the filamentous microorganisms in the species Sphaerotilus, Crenothrix, Leptothrix, Clonothrix, and Lieskeella [85]. Both types contain chemo-lithotrophic autotrophs, gaining energy from the oxidation process of Fe^{2+} to Fe^{3+}, which consequences in deposition of ferric hydroxide. They have associated with the development of hard iron oxides deposits, inside water pipelines [86]. The Gallionella has been stated to be interrelated to the decomposition of stainless steel, predominantly at or near of weld seams, where bacterial deposits are rich in mutually manganese and iron [87]. Assorted bacteria in an extra to the sulphate reducing, sulphur-oxidizing, and iron bacteria, microorganisms in the species Pseudomonas and pseudomonas-like bacteria have been conveyed in assembly with corrosion cases. The strain of Pseudomonas isolated from corroded pipeline systems carrying crude oil was originated to reduce ferric iron to soluble ferrous iron, thus repeatedly revealing a clean surface to a destructive atmosphere [88]. Pseudomonas species are most predominant in industrial water environments along with numerous other slime-forming bacteria, where their principal role appears to be in colonizing metal surfaces, so generating oxygen-free environments which harbour SRB. The all categories of microorganisms which have this capacity may be considered hypothetically corrosive organisms. A diversity of hydrogenase-positive, photosynthetic, and non-photosynthetic microorganisms have been substantiated to the laboratory for their corrosive effect by the cathodic polarization technique and by measurement of iron loss subsequent progress of the rust [89]. Laboratory studies, proved that, several heterotrophic bacteria which form acid metabolites, H_2, and CO_2 have been stated to show an important role during the deterioration of carbon steel pipelines [90].

1.1.2. Fungi

From a biological corrosion viewpoint, one of the greatest important fungi is Cladosporium resinae, which is elaborated in the deterioration of aluminium essential to fuel tanks of subsonic aircraft, leading to wing interface at the bottom of fuel tanks and uses components of the fuel (C_1-C_{16} alkanes) and inorganic constituents, dissolved in water, for nutrients since, the aluminium corrosion is caused by carboxylic acid production by C. resinae [91-95].

1.1.3. Algae

Algae are significant fouling microorganisms and though there are comparatively scarce reports of direct corrosion by algae, they would seem to have the potential for persuading corrosion by benefit of their role in creation of oxygen, eroding organic acids and nutrients for other corrosive microorganisms, as their role in slime formation [96]. The corrosion of numerous types of welded mild steel and 304 stainless-steel samples by two classes of blue green algae Nostoc parmelioides and Anabaena sphaerica and a classes of red algae Graciollasia species have been assessed [97]. Cathodic polarization studies on three strains of hydrogenase-positive Chlorophyta and three strains of hydrogenase-positive Cyanophyta specified that the microorganisms were talented to operate cathodic hydrogen. It is found that, under fit microalgal mats collected of Oscillatoria species, colonial diatoms, and Enteromopha species, the pH is elevated to high values, which tend to decrease the decomposition rate [98].

1.2. Mechanisms of Microbiological Corrosion

The mechanisms by which microorganisms persuade corrosion fundamentally include the basics of electrochemical mechanisms which, is previously discussed, namely, the removal of electrons via oxygen or hydrogen ions. Several schemes have been projected to clarify this mode of action, the prime one being the classical cathodic depolarization theory as seen in Fig. 2.

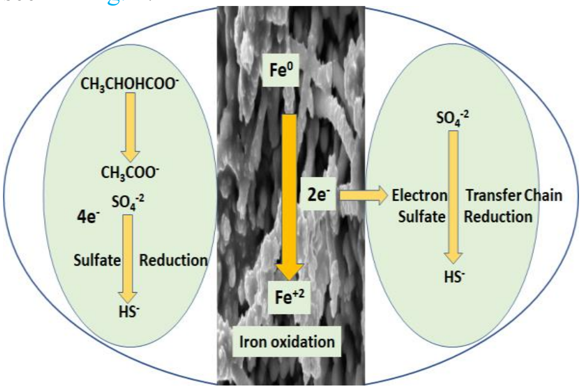

Fig. 2: Mechanism for microbial deterioration by SRB utilization of electrons from iron oxidation for sulphate reduction [102].

1.2.1. Cathodic depolarization theory

1.2.1.1. Classical Theory

Rendering to the realities that underneath biofilm deterioration in deoxygenated soils was allied with hydrogen sulphide, that hydrogen sulphide was produced by SRB, and that these bacteria could employ molecular hydrogen for the reduction process of sulphate and sulphur, which proposed a cathodic depolarization theory to an interpretation for this corrosion [99]. Fig. 3a,b shows the SEM of SRB and their nanowire respectively. The crucial step in this theory comprises the elimination of hydrogen by the hydrogenase system of the SRB has gotten in Fig. 4 and the following equations:

$8H_2O = 8OH^- + 8H^{+electron}$ (8)

$2e + Cu^{2+} = Cu$ (9)

$4Fe = 4Fe^{++} + 8e$ (anodic reaction) (10)

$8H^+ + 8e = 8H$ (cathodic reaction) (11)

$SO_4^{--} + 8H = S^{--} + 4H_2O$ (cathodic depolarization in presence of bacteria) (12)

$Fe^{++} + S^{--} = FeS$ (anodic reaction) (13)

$3Fe^{++} + 6(OH)^- = 3Fe(OH)_2$ (anode) (14)

$4Fe + 4SO_4^{--} + 4H_2O + 6H_2 = 4FeS + 6(OH)_2 + 8(OH)^-$ (15)

Rendering to the scheme, the gotten proportion of rusted iron to FeS must be 4:1, but it is originated to differ from 0.9:1 to almost 50:1 and the rust product of iron oxide or hydroxide are rarely originated though, by means of batch cultures of several hydrogenase-positive species of SRB, designated a direct relative amongst hydrogenase action and the rate of corrosion [100]. The film of sulphide was found on iron surface, generate approximate protection against corrosion, when the organisms were growing in a lactate mineral salts electrolyte comprising sulphate. This film was originated to break the resulting corrosion rates presented no relationship to the hydrogenase activity of the microorganism and the highest corrosion rates being gained with a halophilic microorganism of with low hydrogenase action.

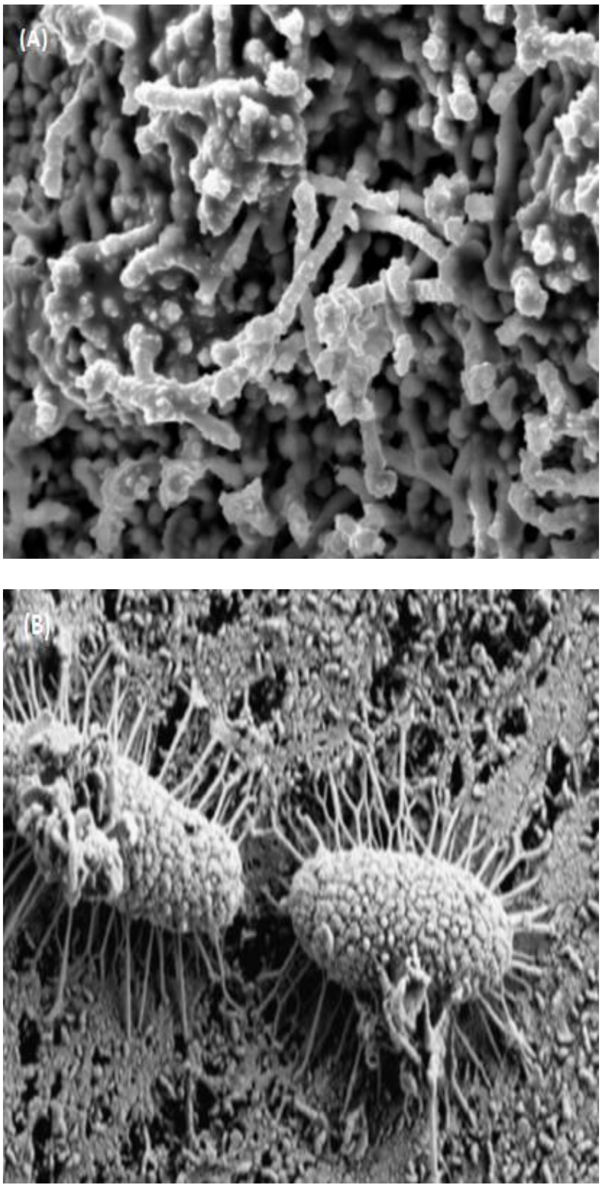

Fig. 3: SEM Image illustrate the (A) produced SRB which from iron surface and (B) and nanowires produced by SRB to capture electrons from iron surface [103].

1.2.2. Other MIC Mechanisms due to SRB

The FeS possibly will be designed as a layer on the iron surface of the aggressively rising cultures of SRB low in soluble iron or as majority FeS in cultures high in soluble iron. Generally, the film usually inhibits corrosion, but with an increase in the rate of corrosion, it may break down. The prime films seem to be collected of mackinawite (FeS) and siderite ($FeCO_3$), the final being protective. In the case where soluble iron has been added to the culture, forming bulk iron and avoiding film creation, the corrosion rates are very high [101-103]. In this study, FeS was the chief corrosive agent in the semi-continuous culture scheme and the logarithm of the rate of corrosion was unswervingly correlated to the logarithm of the solvable iron cations in the media. The inspiration of deterioration by chemically prepared iron sulphides was originated to decrease with time but could be re-established in the attendance of SRB. The role of microorganisms could be depolarized the molecular hydrogen of FeS in interaction with the iron or to convey FeS continually into interaction with the iron by cellular movement see Fig. 4. The agent of depolarization process was a steamy type, since it is expected to be H_2S, because the addition of H_2S back into the de-gassed cultures presented the identical forms of polarization curves as before de-gassing [104, 105].

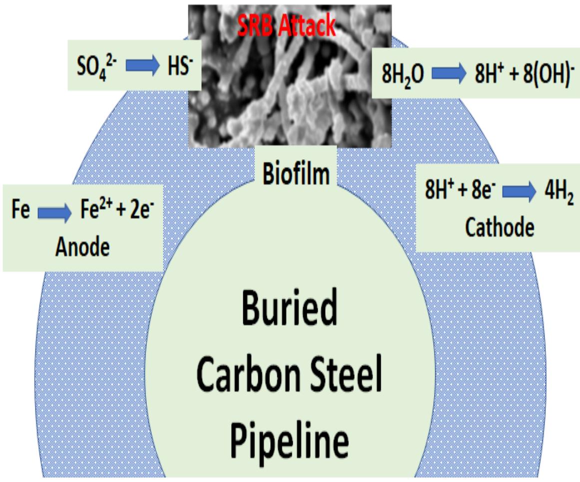

Fig. 4: Schematic design of microbiological deterioration by SRB and the mode of action by direct contact of cytochrome nanowires and the metallic surface [104].

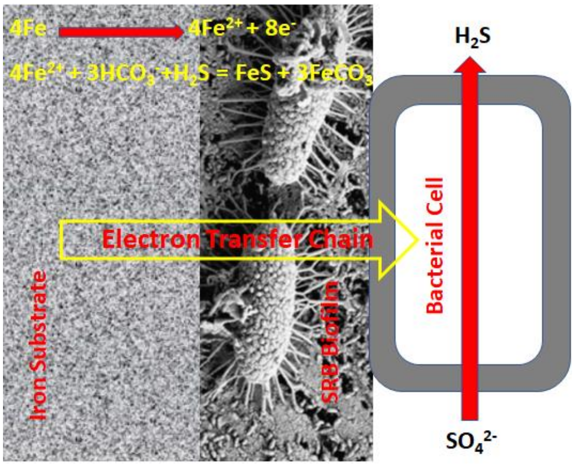

Figure 5: Microbial deterioration outstanding to through electron acceptance by SRB from iron corrosion product [105].

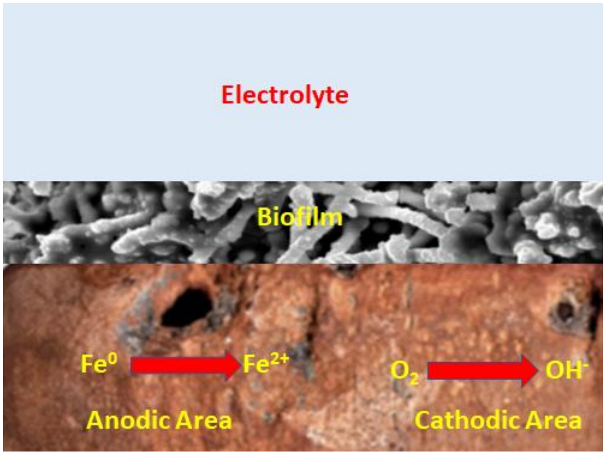

Figure 6: Diagram of pitting corrosion outstanding to the development of an oxygen concentration cell by oxygen diminution underneath the biofilm [106].

1.2.2.1. Concentration cell formation

A varied diversity of both micro and macro-organisms can colonize on the superficial of immersed metals. At the current period, examination of this development regarding to the metabolic action of microbes is a very active field for assessments in this area. The biofilm formation to a metallic superficial by aerobic microorganisms diminishes the oxygen content at the surface, thus resultant in an oxygen differential cells are establishing corrosion. This phenomenon is clearly noticed in the inner surfaces of flow channels and pipes in heat exchangers. Based on this behaviour the pipes were blocked by the accumulated biomass of macro- and microorganisms, resulting in a problem stated to as biofouling [106]. The anaerobic corrosion may be started outstanding to the oxygen concentration under the biofilms may be so depleted and then, SRB could be established see Fig. 9. Estimations of the penetration of the biofilms of microorganisms and their connected extracellular polymers, which yield anaerobiosis below the biofilms, vary from 10 to 100 pm. Nearly, any category of microorganisms which can colonize a surface may therefore be measured as a potential corrosion initiator. Procedures are being industrialized to recognize the microorganisms inside the biofilm in situ. These embrace the proof of identity of lipids distinguishing unique fatty acid contours of fungi, algae, and bacteria, including the SRB and fluorescent antibody techniques [107]. Practices have been advanced to quantify the activity of microorganisms, mainly sulphate reducers, in situ**.** Furthermore, the obstruction of water in pipelines by biofouling, limit of potable water stream in water-distribution pipelines may result in the development of tubercles. Tubercles are deposits of magnetite (Fe_3O_4) and goethite [FeO(OH)] in water pipelines which defence the superficial of pipes from oxygen, thus creating oxygen concentration cells. The small anodic zone beneath the tubercle often rusts strictly, resulting in puncture of the pipe [108].

2. Prevention and Control

2.1. Selection and Control of Environment

When imaginable, the location in which metals are to be used should be judged for corrosivity then, choice of reduced amount of corrosive environment would thereby improve later corrosion resistance. If metals are set up in interaction with soil, the assessment of the soil as corrosive would permit the appropriate protecting procedures to be reserved. In this case, several aspects have been measured such as redox potential, soil resistivity, pH, see Fig. 7, temperature see Fig. 8 and water content. However, water content has a joint relation with soil resistivity that can be associated with aggressive corrosion [109-111]. Possibly the greatest dependable technique for testing soil moisture content is to use test specimens, in case time is available, or using electrochemical procedures, if a quick assessment is required. The defence against SRB **i**n case of short pipelines, may be controlled by escaping of anaerobic conditions, by using lime, which delivers an enough alkaline atmosphere to avoid the progress of SRB [112]**.**

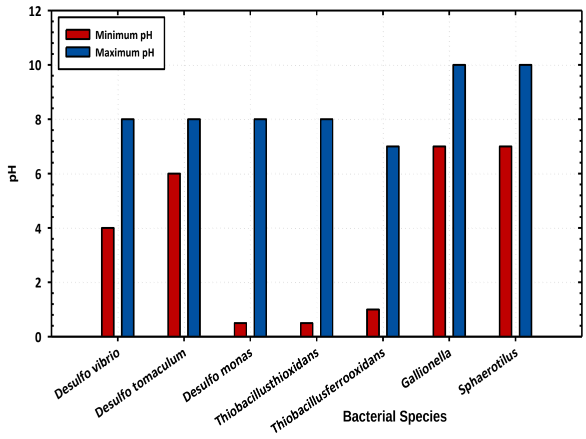

Fig. 7: Effect of pH on the different species of microbially influenced bacterial cells

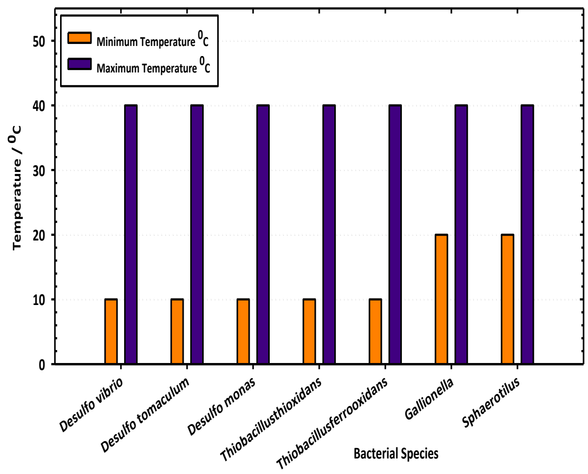

Fig. 8: Effect of temperature on the activity of microbially influenced bacterial cells

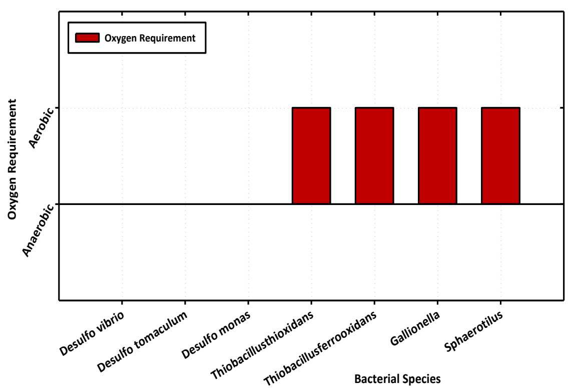

Fig. 9: Effect of oxygen requirements on the activity of microbially influenced bacterial cells

2.2. Coating

Using of defensive coatings to offer a block between the metallic superficial and its corrosive environment. This technique is an old system but effective measure of protection. Several materials that have been working comprise coal tar epoxies and enamels, asphaltic bitumen's, epoxy resins, and various cements. These materials are efficient, but failures have happened due to poor application through the mechanical damage and/ or from handling and backfilling. However, some problems have concerned with presence of SRB in pipeline leaks corrosion occurring beneath dis-bonded plastic tape coatings, so cathodic protection of coated pipe must be subjected to act as a complementary technique for protection of pipelines against corrosive soils [113, 114].

2.3. Cathodic Protection

Cathodic protection technique is working through application of an electric current to metallic structures to counteracts natural weathering. The current is supplying enough flow of electrons to the metallic structures, so the metal cations cannot escape from the anode. Two approaches for achieving cathodic protection, the first type is concerned with using sacrificial anodes as Al, Mg and/or zinc, which corrode by supplying the electrons to protect steel structures. The second type is concerned with using impressed current technique by applying any kind of cheap anodes, since the existed electrons are supplied from a rectifier [115]. The cathodic protection criteria for the shield of carbon steel pipelines in the soil, a potential of about - 0.85 V, regarding to a $Cu-CuSO_4$, half-cell, is frequently sustained. If the soil is corrosive a high risk of microbiological deterioration is clearly noticed, so the potential of about -0.95 V is suggested. If the corrosion, in which SRB were concerned, of pipelines below dis-bonded plastic tape coatings was recommended in which cathodic protection potentials were even above - 1.00 V. In cases where copper structures have been cathodically protected in a marine environment, the fouling has arisen as a result of the anticipation of the Cu ion development that normally prevents biofouling. In repetition, it is normal, however, to use cathodic protection on coated structures and the small shield current will be conditioned to guard only those uncoated, such as minor pinholes [116, 117].

2.4. Biocides

These chemicals are recommended to inhibit microbial growth in closed systems as tanks and recirculating cooling systems. Currently, there are numerous biocides or biostats in use which include oxidizing agents as chlorine and ozone, phenolics, aldehydes, metal organic compounds such as organo-tins, heavy metal salts, and quaternary ammonium compounds. Several potential compounds against microbial deterioration in the equipment of oil and gas fields such as system of oil recovery have been outlined. In case of fuel tanks of aircraft, organoborane compounds, potassium dichromate, and glycol monomethyl ether have been conveyed to be effective in avoiding fungal corrosion [118]. Generally, the governor of microorganisms that form films that consequence in probable corrosion is much more problematic and needs considerable progressive concentrations of inhibitory factors than the regulator of microorganisms in the aqueous phase. Use of several well-matched inhibitory composites in rotation or instantaneously may be supplementary operative than continual use of a single compound since the prospect of microbial immunity may be reduced. A conveyed case of effective corrosion control in a different cooling water system was gotten by using an organic film corrosion inhibitor, a poly acrylate phosphonate dispersant, and a mixture of two biocides used instantaneously. Finally, it is recommended that, the biocides should be compatible with the injected corrosion inhibitor [119, 120].

2.5. Biocide Enhancers

It is well recognized that, the sessile bacterial cells in the forming biofilm are far more difficult to eliminate than planktonic bacterial cells which suspended in the liquid phase. This phenomenon is particularly accurate for mixed-culture conservational biofilms since biofilms engagement several resistance mechanisms against antimicrobials. To control this case, a much higher concentration is mandatory to execute sessile cells [121]. In flow systems the whole execute of microorganisms is not established because water flow will provide microbes again thus, biofilms will rebound back, so that cyclic injection of biocide is required. Repetitive actions using the same biocide may indorse those strains that are more tolerant to the biocide, causing biocide injected dosage growth over time. It is desired to improve the injected biocide to get more efficacy towards biofilm mitigation. Surfactants are commonly used in a biocide blend already. When used alone, some chemicals are not biocidal or only inadequately biocidal against dangerous microbes however, they can enhance the efficacy of a prevailing biocide significantly [122].

2.5.1. D-amino acids

The D-amino acids present in plants, microorganisms, and even in humans, so their normal presence is supposed to be nature's way to increase the molecular variety to normalize the biological functions. These acids were originated to scatter the biofilms in addition to inhibit P. aeruginosa and Desulfovibrio sp. biofilms instead of complete prevention but originate a good result against biofouling. It is found that the D-tyr expressively repressed the initial bacterial attachment and biofilm formation thus dropping membrane biofouling in nanofiltration application [123]. Other reports proved that, the D-met and D-tyr are insufficient to scatter sulphate reducing D. vulgaris biofilm on carbon steel. Since, after they are joint with a biocide, the composite treatment is far more effective. In additions, at 500 ppm of the D-Phenylalanine enhanced 80 ppm THPS in the extenuation of a sulphate reducing D. vulgaris biofilm on carbon steel. The antibiotics were evaluated to be improved by D-amino acids in contradiction of pathogenic biofilms [124]. It is recommended that, using a D-amino acid mixture for the consortia of industrial biofilm, since separate D-amino acids are less probable acceptable to improve biocides because of diverse bacteriological classes respond to dissimilar D-amino acids. The D-amino acids presented respectable harmony with improved oil retrieval compounds in a lab., test and were originated to improve biocides against aerobic biofilms from a cooling water system [125, 126]. In case of oxidizing biocides, a consecutive test is recommended since chlorine can react with D-amino acids. Till the present the dispersal mechanism of D-amino acids has not been completely understood. Some trial to know the mechanism theorized that the D-ala terminus in the microbial cell wall is replaced by further D-amino acids that prime to biofilm dispersal, so the replacement is measured to influence the remodelling of bacteria cell wall. Regardless of the deficiency of a considerate of the actual mechanisms, there is no doubt about the efficacy of D-amino acids in biofilm treatment, especially as a biocide enhancer [127, 128].

2.5.2. Norspermidine

The norspermidine is naturally arises in some algae, bacteria and plants and it can inhibit development of biofilm. Exogenous norspermidine at 25 µM was originated to hinder a S. epidermidis biofilm creation by ascribing to negatively charged or neutral sugar remains producing the exopolysaccharides to breakdown. Norspermidine at a developed concentration (100 µM) possibly will take down a developed S. epidermidis biofilm. Norspermidine at 5mM was described to prevent a Streptococcus mutants biofilm creation by tumbling the cell viability and fluctuating its basic biofilm construction [129, 130]. The biofilm possibly will be stripped by a mixture of 500 µM norspermidine and 500 µM D-tyr in a 6-month-old wastewater system. In addition, a biocide enhancer, 500 µM norspermidine was originated to improve 0.01 ppm Ag^{+} to treat a biofilm conglomerate from another wastewater treatment system, while 1 ppm silver ion used alone failed to remove biofilms [131]. Norspermidine was originated to improve Cu^{2+} against microbial biofilms on reverse osmosis membranes. These consequences propose that norspermidine may be practiced for treating industrial biofilms since norspermidine is low-priced. Other oxidizing as chlorine or non-oxidizing biocides as glutaraldehyde and quaternary ammonium salts may be assessed with norspermidine against industrial intractable biofilm conglomerates. The effect of norspermidine is back to the amine functional group which attack with some biocides as chlorine and/or glutaraldehyde, since a consecutive treatment may be approved. It is highly recommended to check the chemical compatibility before field trials [132].

2.5.3. Chelators

Chelating agents can be applied as biocide enhancers to impede biofilm creation, since the highly famous chelating agent ethylenediaminetetraacetic acid EDTA has been testified to augment antibiotics in the handling of biofilms on medical drips. It is obviously noted that, EDTA at 1.25 mM was originated to improve a 12.5 µg/mL antimicrobial peptide in the treatment of P. aeruginosa. The EDTA is destructive for metallic structures at a high concentration, so sodium salt is applied, or the solution's pH must be accustomed to nearby neutral previously use. Extra chelator ethylene diamine di-succinate EDDS, which is voluntarily environmental, is progressively substituting EDTA due to EDTA's slow biodegradation in freshwater systems [133]. A trisodium salt of EDDS at 2000 ppm discriminating 30 ppm glutaraldehyde in the treatment of a sulphate reducing D. desulfuricans biofilm on carbon steel, since it is non-toxic and willingly biodegradable, so it is likely for industrial applications. Nevertheless, chelators need high concentrations due to the profusion of ions in the fluid under treatment, which can lower the chelator's convenience [134, 135].

2.6. Bacterial phage treatment

Bacteriophages have been verified as anti-biofilm agents, particularly for corrosive biofilm and contaminations on medicinal implantation surfaces. The mode of action of bacteriophages is depending on using phage depolymerases to lyse the microbial cells and they can even spell the persisted cells in biofilms that produced contaminations. Another role of bacteriophages since it can eliminate the attached microorganisms of the used membranes in wastewater treatment systems [136]. It is found that a bacteriophage at 105 - 106 PFU/mL (PFU Plaque Forming Units) isolated from a wastewater treatment plant was conveyed to eliminate a Delftia tsuruhatensis ARB-1 biofilm, thus growing the water flux through the membrane. Bacteriophages can work alone or with other agents to realize better effectiveness. It displayed respectable antibacterial action against an E. coli biofilm. Phage can augment antibiotics to treat biofilm pollutions representing phage-antibiotic synergy. The bacteriophage (SAP-26) at 109 PFU/mL is combined with 0.6 ppm rifampicin attained an additional log drop of sessile S. aureus cells associated with each of them used alone [137]. The mixture of T4 phage and cefotaxime realized suggestively higher efficiency than the antibiotic used alone in the extermination of an E. coli biofilm. Its relics to be understood whether viruses directing other microorganisms as fungi will be industrialized for field applications in the future. For the field requests connecting a diversity of microorganisms, a 8cocktail of phage must be applied for improving effectiveness [138]. Furthermore, host cell population densities should be satisfactorily high to facilitate phage spread. Although phage may reach achievement in medical treatment which often includes a precise bacterial species, the large-scale use of phage cocktails in manufacturing situations that frequently anchorage mixed-culture biofilms may be too expensive and unpretentious species can willingly fill the void. Its leftovers to be understood whether the phage technology will overawe the steeplechases for field disposition [139].

2.7. Quorum-sensing inhibition

Quorum sensing is a communication mechanism among microorganisms that organizes their performance as biofilm creation, motility, sporulation, antibiotic resistance, bioluminescence and virulence factors. This progression is reliant on the biofilm thickness and the meditation of signal molecules [140]. Quorum sensing embarrassment is operative in regulating the biofilm development since, it can interpose quorum sensing by diverse approaches:

1- Decrease the act of the regulatory gene of the synthesis quorum detecting sign fragment
2- Destroy the signal molecule.
3- Modulate the binding of the signal to receptor sites
4- Block receptor sites with antagonistic signal analogues

The furthermost considered quorum sensing approach is enzymatic deprivation of quorum sensing signal molecules. Natural products as alkaloids, coumarins, phenolics, quinones, saponins, tannins and terpenoids have been verified for quorum sensing [141]. Nevertheless, utmost of the natural quorum detecting inhibitors is fashioned in very minor amounts and may have poisonousness. To avoid the toxicity of some natural composites, there is an increase in studies of bio or chemically synthesized inhibitors. Based on these researches, numerous artificial composites have been originated to normalize quorum sensing [142]. The consumption of artificial inhibitors can be further applied and a supplementary cost-effective means for quorum sensing. It is well recognized that, in field applications the species of microbial cells are diverse, so their population assemblies will familiarize to quorum sensing with remaining alive types not approachable to the quorum detecting inhibitors. Cost is an extra foremost apprehension because numerous quorum sensing inhibitors will expected be required for miscellaneous culture of field biofilms [143].

2. Conclusions

Microbial corrosion primes to great commercial fatalities and main conservational problems in several production sectors. Numerous discrete modes of actions have been acquainted for microbial corrosion. A healthier considerate of the emphasizing microbially influenced corrosion mechanisms are important for microbial corrosion forensics and effective management of corrosion. Microbial corrosion can facilitate the corrosion by prevailing corrosive agents as O_2, CO_2 and H_2S by damaging the protective chemical passivation films on the metallic surfaces. Microorganisms in microbiological deterioration are judged by means of conventional bacteriological approaches along with state-of-the-art molecule biology means. Outstanding to their innumerable resistance mechanisms, sessile bacteria in the biofilms are far additional resilient to biocide treatment than planktonic cells. Numerous biocide ornamental performances have been inspected to use biocides more efficiently. Novel biological resources as phage technology are being investigated. Separately from microbiological and molecular biology tools, many electrochemical procedures can be applied to inspect microbial corrosion performances and biofilm mitigation. However, they should be used carefully, and their results should be authenticated by non-electrochemical data. The greatest problematic hypothesize is the imitation of corrosion under matching circumstances as first observed in the practical situation. Often, the field conditions are not known and the corroded sample, usually well dry, is all the indication obtainable since the field conditions do exist, it is very hard to replicate them. The temperature disparity, for example critical temperature in the development of corrosive biofilm is usually not known, and several constraints which existed in large field systems may be impossible to replicate due to the extremely large number of them, some of which may only happen at the original corrosion site. The researcher always faces the possibility of having corrosion arise in the laboratory under situations quite different and with unrelated mechanisms to those which he is wearisome to study. For illustration, in the assessment of the aerobic deterioration of mild steel, the morally oxidative mechanism may dominate any corrosive effect of microorganisms so, the predominant mode of action has not been completely established. The features of the problem are being documented along with the enlarged difficulty of discovering biocides which will penetrate the biofilms in low concentration.

3. Conflicts of interest

The author declare that he has no conflict of interest.

4. Formatting of funding sources

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