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REVIEW

Microbiologically Influenced Corrosion: A Concern for Oil and Gas Sector in Africa

Ini-Ibehe N. Etim[1,2,15] · Demian I. Njoku[2,3,4,15] · Paul C. Uzoma[5,15] · Sharafadeen K. Kolawole[6,15] · Olajire S. Olanrele[7,15] · Okpo O. Ekarenem[8,15] · Bright O. Okonkwo[9,15] · Alexander I. Ikeuba[10,15] · Inime I. Udoh[11,15] · Chigoziri N. Njoku[2,12,15] · Iniobong P. Etim[13,15] · Wilfred Emori[14,15]

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Abstract

Corrosion and corrosion-related studies in energy production facilities and installations are underreported in Africa, and the existence of microbiologically-influenced corrosion (MIC) is rarely investigated. This review aims to stimulate a conscious awakening of African governments, private organisations, research institutions, professionals and budding researchers, and other key players in the energy sector on the dangers of unabated MIC-based materials degradation in energy production facilities. The content herein, unmasks the principles of MIC in the oil and gas industry from a general perspective, it further elaborates on the existence in Africa with emphasis on the various types of bacteria implicated in biocorrosion processes, the existing characterisation methods with detailed information of the spectroscopic and surface morphology techniques, impact of MIC to the industry and environment with case studies from typical African experiences, the established abatement measures and recommendations and as wells as MIC prospects for the oil and gas sector in Africa.

Keywords Microbiologically-influenced corrosion · Africa · Oil and gas · Bacteria · Sulphate-reducing bacteria

✉ Demian I. Njoku
demianifeanyi@gmail.com

✉ Paul C. Uzoma
pauluzoma@futo.edu.ng

✉ Okpo O. Ekarenem
oekerenam@gmail.com

✉ Wilfred Emori
emoriental@yahoo.com

[1] Marine Chemistry and Corrosion Research Group, Department of Marine Biology, Akwa Ibom State University, P. M. B. 1167, Ikot Akpaden, Nigeria

[2] Africa Centre of Excellence in Future Energies and Electrochemical Systems (ACE-FUELS), Federal University of Technology, PMB 1526, Owerri, Nigeria

[3] Department of Industrial Chemistry, Madonna University, Elele, Nigeria

[4] Center for Corrosion and Protection of Materials, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

[5] Department of Polymer and Textile Engineering, Federal University of Technology, P.M.B. 1526, Owerri, Nigeria

[6] Mechanical Engineering Department, School of Engineering and Technology, Federal Polytechnic, Offa, P.M.B 420, Offa, Nigeria

[7] Department of Chemical Sciences, Mountain Top University, Km 12 Lagos-Ibadan Expressway, Ibafo, Ogun State, Nigeria

[8] Department of Pure and Applied Chemistry, Veritas University, Abuja, Nigeria

[9] Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 34141 Daejeon, Republic of Korea

[10] Materials Chemistry Research Group, Department of Pure and Applied Chemistry, University of Calabar, Calabar, Nigeria

[11] School of Environmental and Chemical Engineering, Shenyang Ligong University, Shenyang 110159, China

[12] Department of Chemical Engineering, Federal University of Technology, PMB 1526, Owerri, Nigeria

[13] Department of Physics, University of Calabar, Calabar, Nigeria

[14] School of Materials Science and Engineering, Sichuan University of Science and Engineering, Zigong 643000, Sichuan, People's Republic of China

[15] Nigerian Alumni Association of the Institute of Metal Research, Chinese Academic of Sciences (NAAIMCAS), Calabar, Nigeria

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1 Introduction

Microbiologically-influenced corrosion (MIC) or biocorrosion is often described as the study of the corrosion phenomenon associated with bacterial activities in marine environments [1, 2]. The issue of MIC covers a wide area, from the destruction of materials to huge financial losses through the high cost of maintenance orchestrated by the effects of bacteria [3]. In this regard, some key reports from established literatures account for these material losses, for example, Li et al. [4] reported the degradation of a concrete structure by microbial activities. A recent investigation by Wu et al. [5] also proved the destructive capability of microbes in cracking pipeline steel. Jia et al. [6] further stated that MIC is one of the known issues in the oil and gas sector since it enhances the rapid degradation of steel and other maritime structures. The destruction tendency of these bacteria varies depending on the type of bacteria associated in the corrosion mechanism.

Some of the bacteria that are associated with biocorrosion in the oil and gas environments are sulphate-reducing bacteria (SRB) [7], manganese-oxidizing bacteria (MOB) [8], iron-oxidizing bacteria (IOB) [9], acid-producing bacteria (APB) [10], metal-reducing bacteria (MRB) [11], metal-depositing bacteria [12], and slime-producing bacteria (SPB) [13]. Amongst the bacteria that are related to MIC, SRB is reported to be the common harmful bacteria known in MIC research [14, 15]. SRB have been reported living in anaerobic environments with well adaptive features [16]. The existence of SRBs in limited oxygen environments is an important phenomenon for corrosion studies. It is reported that most of the marine construction, oil and gas drilling and other maritime activities are domiciled in these anoxic regions [17]. The growing concern of SRBs is mostly linked with oil and gas industry that have their vessels plying in the marine waters where most of the vessel parts are submerged in the anoxic regions.

The oil and gas sector is a prominent field where crude oil is drilled and processed for onward distribution to relevant users. The oil and gas sector also incorporates several pipelines that transport hydrocarbons and other by-products from production points to large markets. The benefits of transporting natural gas, crude oil, and all forms of petroleum products with oil pipelines as the main and reliable operation have been well established in the industry [17, 18]. Eminent issues encountered in this sector are linked to the enhanced corrosion in oil and gas installations which occur at many sites within the material due to differences in physical, chemical, and metallurgical properties of these material sites [19]. The damage on the surface of the material is always depicted with pits [20, 21]. The pits on the materials are usually as a result of MIC phenomenon which has adverse effect on the oil and gas sector.

In localized corrosion involving pitting, the substrate breaks out in an enhanced process due to the wear off pertaining to its passive film. Many alloys and steel are adopted because the produce oxide films (passive film) of a few nanometers on the substrate surface that have the potential to reduce corrosion. Notwithstanding, the oxide layer is prone to degradation which enhances the substrate breakdown [22, 23]. Pitting related corrosion is known to enhance the cracking or perforation of metal surfaces resulting in a spontaneous breakdown of the structural parts [24]. Pitting corrosion often occur as a result of dominance anions like S^{2-} [25] and chloride ions (Cl^{-}) [26, 27].

The significant of the present study seeks to elaborate and present the recent information on the biocorrosion within the oil and gas sector and how prominent it is in Africa. This review will be beneficial to the society as it tends to expatiate the basic MIC phenomenon and the need for multinational industries, research institutes, and marine regulatory bodies to key into this aspect of research in Africa.

2 Microbiologically-Influenced Corrosion Associated with Oil and Gas Sector in Africa

This section highlights few information regarding MIC link with oil and gas environment and its peculiar existence in Africa. The basic MIC occurrence in the oil and gas sector is mostly related with the production stages since the materials are generally exposed to the various stages. It is important to note that the different production stages of basic crude oil have been estimated to consume approximately 8% of metals found in the world, and uniquely within oil and gas sector is associated with an increase in the rate of biocorrosion processes [28]. Microorganisms through their adhesions and growths on substrate influences biocorrosion processes observed in the metal through the formation of corrosion cells. They seek regularities on metal surfaces where they attach themselves and secrete corrosive by-products such as hydrogen sulphide, sticky polymers, enzymatic products and other metabolites which deteriorate metals [29].

Also, microorganisms ubiquitously occupy most of the crude oil structures and their storage facilities. The pipelines beneath the ground, vessels plying the seawater, and other structures adopted in the oil and gas services enables a limitless and primarily non-oxygenated environment for these microorganisms to proliferate. The main technical issues observed from microorganism activities within the engineered marine area is the effect on materials lifespan. The oilfield microbes influence structures lifespan especially over a wide biochemical process. The corrosion processes

affecting structure lifespan has been reported to range from 20 to 30% of the entire corrosion-linked expense in the oil and gas sector in Africa [30]. Retrospectively, a series of research carried out has ascertained the roles of microbial corrosion within structural materials adopted in the oil and gas environment.

In a related research by Mand and Enning [31], the effect of an oil-related microorganism on chemically mitigated carbon substrate pipelines, which is conventionally used to transport crude oil was examined. The study revealed that while microorganisms promoted the uneven corrosion of steel samples, they rarely inflicted corrosion morphologies consistent with that of the pipelines. The study further showed that the corrosion inhibitors broadly adopted for the mitigation of acid gas (H_2S, CO_2) corrosion in oil surroundings influences microorganisms' proliferation and activities. The Mitigated carbon material prevented biofilm being formed and showed negligible corrosion rate as < 0.002 mm Fe^o per year, regardless of being kept for 15 months in an oil environment having a wide microbial habitat. Other aspect showed that the physical hunt of corrosion inhibitor concentration in the environment produced severe and notably localized corrosion of about 0.93 mm Fe^o per year directly below biofilms control by organisms like SRB and methanogenic archaea.

Report by Agarry et al. [32] showed the activities regarding microorganisms on the corrosion processes of substrate within various artificially-made crude oil environments and operating conditions in Nigeria, West Africa. The results revealed that high acidity (pH < 6) and high alkalinity (pH > 8) favor the growth and activities of microorganisms, which in turn favor the promotion of MIC. While the increase in salinity and nitrate concentration of crude oil media hinder the growth and activities of microorganisms in the corrosion of many substrates. According to the results, more severe pitting corrosion of substrate occurred within a crude oil field that is more acidic than a crude oil environment with more salinity and nitrate concentration.

Rajasker et al. [33] worked extensively on the bacterial deterioration of naphtha and its effect on corrosion observed around storage oil tank. The corrosion findings were evaluated using weight loss and gravimetric methods, and the result showed that uniform corrosion and higher corrosion rate of coupons were observed in naphtha with water which harbors microorganisms than in naphtha only (almost no microorganism environment).

In view of the highlighted studies, it is generally inferred that the oil field microbial habitat indicates a great issue to material lifespan, and there is a broad view perception in the crude oil sector that the production of biofilms is a key instrument for MIC [30, 34]; hence mitigation of MIC in pipelines and other structural materials solely targets the extinction and mitigation of metal-attached microbes, that is accomplished via several methods such as periodic biocide utilization and mechanical approach (pigging). Interestingly, MIC records high corrosion rate in substrates, especially downstream areas of processing structures which eradicates the oil-linked natural gas. Consequently, mitigation-drive researches are areas that need intense and urgent attention to avoid structural degradation and accidents in worst scenarios.

3 Concept of Microbiologically-Influenced Corrosion

Microorganisms linked with MIC are widespread within parameters such as pressure, temperatures, pH and salinity [35]. Majorly, these attacks are driven by climatic conditions with warmer climates being more affected. Apart from titanium, most metals and their alloys are prone to MIC e.g. Fe, Cu, Ni, and Al [35]. Microbes found in aqueous environments metabolize nutrients using oxygen or other compounds like sulphur or iron leading to a change in electrochemical conditions which enhances material corrosion. MIC is of particular concern in industries associated with seawater, surface water, municipal water, grey water and well water, these industries include water treatment, marine, paper industries and many others [36, 37].

The main types of microbes commonly associated with MIC are SRB, MRB, MDB, APB, SPB, and Fungi. The SRB are anaerobic bacteria that reduce many compounds like sulphites, sulphates, thiosulphates, and converts some elemental sulphur to sulphides in anaerobic environment as seen in many theories. Some theories regarding the mechanism of MIC corrosion exist, yet the recognized theory relates to the fact that sulphides replace in the corrosion product and maintain a stationary anode formed beneath the sulphide layer. The MRB combine with the elements within the corrosion product films on substrate surfaces in a manner that the corrosion product film is removed by a relatively stable formed film; thereby producing a stationary anode in the studied region. The MRB further participated in the biochemical transformation of known oxides of substrate like manganese and iron. The SPB secretes extracellular polymeric substances (EPS), or produce biofilms, by which differential oxygenated concentration media are notably formed. Furthermore, the APB release vast numbers of either organic or inorganic acids leading to the formation of a by-product of its metabolism. Also, Fungi are known to secrete organic acids and are thus capable of enhancing MIC [38].

Despite tremendous research efforts committed to MIC in recent times, the concept of MIC remains a subject of great controversy and there remains a gap between the current interpretations of MIC and the application of these research

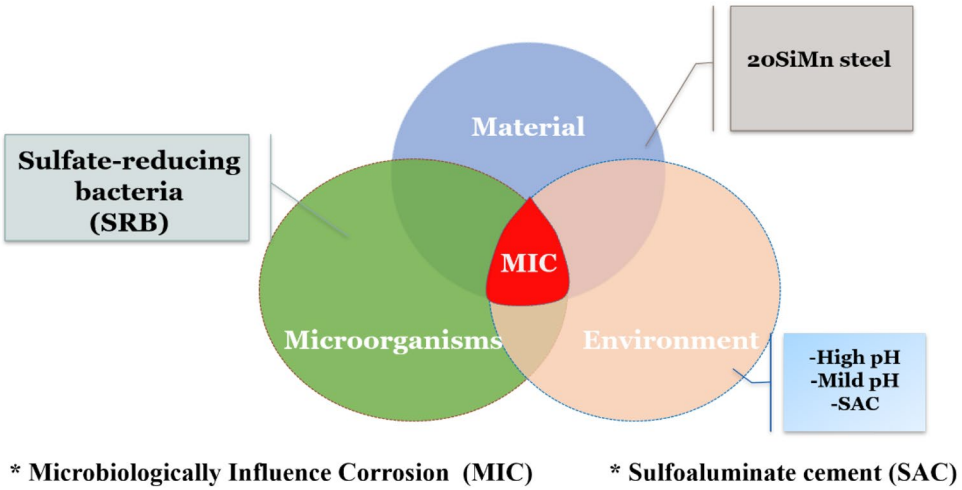

Fig. 1 Overview of MIC mechanism where the microorganisms, media and metal overlap

findings in contemporary practical situations. These issues are complicated since limited universally accepted standard measuring techniques are adopted to excellently assess this form of corrosion. Several research information on MIC is available in recent time. From the available reports [39, 40] it is obvious that for the proliferation of MIC, three important factors are important and must overlap. These factors include a suitable combination of (i) the microorganism (microbiology), (ii) media (Chemistry) and (iii) metal/alloy (Metallurgy) as shown in Fig. 1.

Most research attempts on MIC are often carried out by experts in one of these three areas, thus leaving a lot of unanswered questions in other aspects, and understanding the MIC principles. The contribution of MIC to corrosion are somewhat complicated since abiotic corrosion often occurs simultaneously in addition to MIC. Also, most corrosion tests carried out in media like aqueous conditions with temperatures recorded at 100 °C are analyzed where microorganisms thrives [41, 42]. MIC is an issue in various sectors notably where biofilms adhere on the substrate. MIC is enhanced especially where there is high proliferation of microbial activities, and also dominated in stagnant water body, steady flow media and at low temperatures. Despite the large volume of research available on MIC, a notable gap still exists between the available information and proactive ways to distinguish and mitigate the real issues linked with MIC [41, 43].

Out of all the adverse consequences of MIC, the impact of the MIC on concrete structures in sewer media in relationship with the oil and gas sector is an enormous issue to present society. Aside from the industrial losses, environmental and other problems initiated by MIC have attracted great attention depending on the bacteria associated in the corrosion process [42, 44].

4 Bacteria Associated with MIC

According to Little and Lee [45], the microbes implicated in MIC are normally the descents of these three main groups: bacteria, archaea, and eukaryota. The commonest ones amongst them include archaea, SRB, methanogens, APB, MRB, acetogenic organisms, hydrocarbon-degrading prokaryotes (HDP), nitrate-reducing bacteria (NRB), nitrite-oxidizing bacteria (NOB), metal-oxidizing bacteria (MOB), and also fermentative hydrogen sulphide-producing bacteria (HSPB).

4.1 Sulphate-Reducing Bacteria and Archaea (SRB)

The SRB and archaea consist of wide, uniquely different physiological category of mainly anaerobe prokaryotes having similarities in their ability to respire anaerobically using sulphate as their key terminal electron acceptor based on the listed reaction [46]:

$$4AH_2 + SO_4^{2-} + H^+ \rightarrow 4A + HS^- + 4H_2O \quad (1)$$

The above reaction occurs in a dissimilatory fashion where SO_4 is converted to S^-, rather than assimilatory. The SRB and archaea are widespread and exist entirely around the anaerobic environment [47]. The unique role of the microbes is quite important in the global study of sulphur cycle. It is noted that in marine sediments, their roles make up for half the entire carbon mineralization processes. The cellular structure of SRB is majorly diverse, possessing structures like spheres, rods, and vibrio shapes, and are adopted as an essential classification feature. The genus specie, *Thermo desulfobacterium,* is regarded as one of the known deep-branch bacterial classification and incorporate basically SRB [46, 48]. The pathway to sulphate reduction

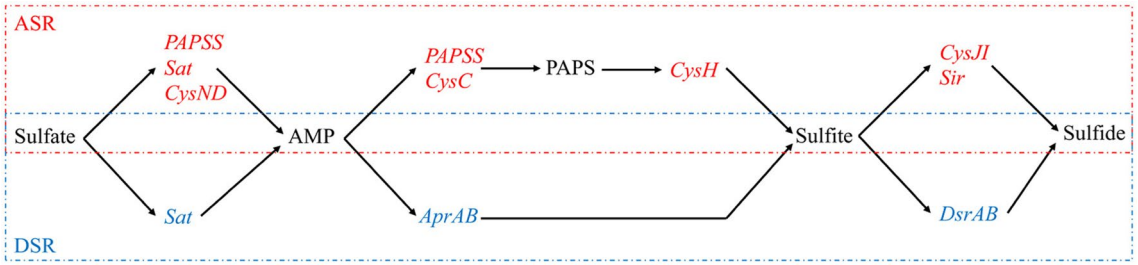

Fig. 2 The SRB dissimilatory pathway [49]

shows a complex mechanism, as schematically depicted in the work of Zhou et al. [49] (Fig. 2).

4.2 Methanogens

Methanogens, classified into five groups of *Methanococcales*, *Methanobacteriales*, *Methanosarcinales*, *Methanomicrobiales* and *Methanopyrales*, are the only group of microorganisms on earth producing a huge amount of methane. According to Thauer et al. [50], averagely over 1 billion tons of methane yearly are produced worldwide via methanogenic archaea in anaerobic surroundings, like swamps, paddy fields, sediments, landfills and the organic-addictive tracks of insects and animals. Invariably, about 2% recorded for net CO_2 fixed yearly as biomass via photosynthesis in the value of about 70×10^9 tonnes of carbon yearly, produces mainly methane [50, 51]. According to Enzmann et al. [52] these classes of microorganisms markedly survive within a broad extreme surroundings such as hydrothermal vents or saline lakes, smoke chimneys and biogas plants. For the corrosion mechanism observed in methanogen-influenced MIC (Mi-MIC), An et al. [53] proposed that the corrosion product deposition mechanism is as follows:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad (2)$$

where it was suggested that CO_2 typically converts to carbonic acid and bicarbonate consequent moving to the marine environment, where the limited volume of CO_2 gases needs the function relating to the carbonic anhydrase being converted to bicarbonate and also to CO_2 enabling methanogenesis. More importantly, the biotic and abiotic reactions that occur in neutral seawater show that the former reaction entails the formation of carbonic anhydrase (HCO_3) and hydrogenase (H_2) while the latter reaction leading to production of magnetite (Fe_3O_4) and siderite ($FeCO_3$) as corrosion products [53].

4.3 Acid-Producing Bacteria (APB)

APB are special type of microbes that are effective within the pH value of 9.5. These types of bacteria are known to represent acid-induced pattern of corrosion involving the metal oxides dissolution. The commonest examples of acid-driven by these types of bacteria include hydrogen sulphide (H_2S), sulphurous acid (H_2SO_3), sulphuric acid (H_2SO_4), and their site of attack are usually on aluminium alloys, iron and low alloy steels. MIC induced by APBs is generally governed by the overall reaction given in Eq. (3) below:

$$H_2S + Fe \rightarrow FeS + H_2 \quad (3)$$

In order for the stated chemical reaction to take place, it is a requirement that the exposed iron surface interacts with secreted H_2S observed in the biofilm. The chemical reaction then produces a corrosion product of iron sulphide and waste product of hydrogen gas [54].

4.4 Hydrocarbon-Degrading Prokaryotes (HDP)

The HDP are microorganisms that adopt hydrocarbons for source of energy which enhances proliferation, although they also require other essential nutrients that could be in short supply in the ecosystems such as nitrogen and phosphorus [55]. These sets of bacteria usually degrade both the aromatic and aliphatic C–H hydrocarbon links by the occurrence of oxygen through molecules that has specific group of oxygenases. Meanwhile, as these oxygenases show inherently membrane bound form, their cells are directly related with more water insoluble components. These bacteria are known to exude enormous value usages in mitigation of oil pollutants, secretion of surface-key agents, increased oil recovery, adoption of hydrocarbons mainly as materials for environmental fermentation measures, and they are also said to likely contribute significantly to the biodegradation of the oil, which is possibly enhanced via the production of EPS [55, 56].

4.5 Acetogenic Organisms

In the analysis of the roles relating to acetogens in the biocorrosion of steels, Mand et al. [57] discovered that storage of pipeline samples having sulphate and bicarbonate in serum containers with different metal coupons placed in a media of 90% N_2 and CO_2 led to the production of methane and acetate. Furthermore, storage of the samples in serum containers has the solution with bicarbonate and steels, yet limited sulphate, which showed that the production of acetate compound before that of methane. Thus, they concluded that microbe habitat analysis of nutrient-rich compounds indicates the occurrence of acetobacterium, with acetotrophic methanogens and hydrogenotrophic. Hence, a pipeline container, having little or limited organic carbon, which contains sulphate and bicarbonate, regardless will be prone to SRB-induced corrosion, since acetate is produced at the material surface.

4.6 Nitrate-Reducing Bacteria (NRB)

These are bacteria that obtain electrons via reducing nitrate in a non-oxygenated environment. The biofilm produced by NRB changes the uniform corrosion rate and pitting depth of the metal, which is often believed to be as a result of the role of extracellular electron transfer (EET). These bacteria adopts electron produced by iron during oxidation where the nitrate within the bacteria readily accept these electrons as shown in the pair of Eqs. 4 and 5 below [58]:

$$\text{Oxidation reaction}: \mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-} \tag{4}$$

$$\text{Reduction reaction}: \mathrm{NO}_3^{-} + 8\mathrm{e}^{-} + 10\mathrm{H}^{+} \rightarrow \mathrm{HN}^{4+} + 3\mathrm{H}_2\mathrm{O} \tag{5}$$

Similarly, Mohd Zaidi et al. [59] corroborated the ability of NRB to denitrify (removal of nitrate) in anaerobic conditions in carbon steels where they reduce the capacity of insoluble irons to soluble ones, and this main activity of NRBs enables the sustenance of their metabolism.

4.7 Nitrite-Oxidizing Bacteria (NOB)

Nitrite-oxidizers majorly composed of up to six bacterial genera, including, *Nitrospira Nitrobacter*, *Nitrococcus*, *Nitrotoga*, *Nitrolancetus* and *Nitrospina*, and they simply convert nitrite to nitrate [60]. Conventionally, nitrifying microbes described as obligate chemolithotrophs that thrive only in the presence of ammonia or nitrite. Consequently, nitrification is linked with their environmental formation and sizes, and they are therefore believed to depend on nitrate-reducing microbes or ammonia oxidizing as their sources of nitrite. For their metabolism, Koch et al. [61] asserted that their genetic inventory utilizes hydrogen (H_2) as a supplementary medium for aerobic respiration that thrives on H_2 with no nitrite. Meanwhile, carbon dioxide fixation occurs having H_2 serving as the main donor.

4.8 Metal-Oxidizing Bacteria (MOB)

Chamritski et al. [62] assessed the influence of metal-oxidizing bacteria on pitting corrosion of substrate and concluded that this kind of corrosion is often related with the increase in open-circuit potential (OCP) and which usually involves an manganese-oxidizing bacteria (MnOB) and iron-oxidizing bacteria (IOB). The results showed that the oxidation of $FeSO_4$ with $Ca(ClO)_2$ results to the formation of an iron-based film on some samples with surface film composition resembling those produced by microbial activity. In the same line of thought, Emerson [63] suggested that IOBs such as photopherotrophs and zetaproteobacterias undergoes anoxygenic photosynthesis employing Fe (II) as a donor in the presence of light and hence, aides in surface colonization of steel surfaces together with some microbes associated with MIC.

4.9 Hydrogen Sulphide-Producing Bacteria (HSPB)

Microorganisms that produce H_2S or organic acids during their metabolic activities naturally promote corrosion by acid attack. These metabolites reduce the local pH in the biofilm, which directly relates to an increase in metal dissolution. This type of degradation is generally referred to as chemical MIC (or CMIC) or metabolite MIC (M-MIC). Such microorganisms promoted corrosion reactions through the formation of aggressive corrosive metabolites such as hydrogen sulphide (H_2S), organic acids, ammonia (NH_3), nitrite, phosphine (PH_3), hydrogen peroxide, and other enzymes such as lyases and catalases that catalyse cathodic reactions and enhance oxygen reduction reactions thus promoting high corrosion rates [64, 65].

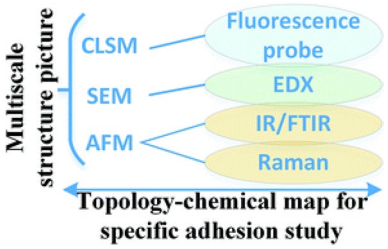

Fig. 3 Various characterisation methods adopted for microbial corrosion analysis. Retrieved from Huang et al. [66]

5 Established Characterisation Methods for Biocorrosion Assessment

5.1 Biofilm Characterisation Methods

The analysis of biofilms helps in enhancing and understanding biofilms formation, and its major activities. It also increases the ability to control surface colonization. To visualize the surface features or morphology of microbial biofilms, microscopic techniques such as optical microscopy (OM), scanning electron microscope (SEM), and confocal laser scanning microscopy (CLSM) and their derivatives are the most employed techniques. However, recalling that biofilms are made up of aggregates of microorganisms sandwiched in EPS containing biopolymers such as polysaccharides, proteins, nucleic acids, lipids etc., spectroscopic methods such as Fourier transform infrared spectroscopy (FTIR) and RA/enhanced Raman spectroscopy (RAMA) and their derivatives which identify the fingerprints of the biofilms' EPS have been used to analyze biofilms. To characterize their adhesion forces or/and shear forces (physic-chemistry) including their corrosion acceleration or retardation effects, electrochemical impedance spectroscopy, surface chemistry (contact angle), AFM etc., are employed. Figure 3 summarizes some of the methods for characterizing biofilms [66, 67].

5.1.1 Spectroscopic Methods

5.1.1.1 ***Infrared Spectroscopy*** Because the absorption of high-energy radiation (gamma-rays, X-rays, and ultraviolet) leads to photodecomposition of biomolecules and cell death, radiation in the visible, near-infrared, mid-infrared, and radio frequencies are the preferred absorption spectrometry to detect living microorganisms in aqueous environments [68]. Infrared spectroscopy being a non-destructive technique is ideal for characterizing the chemistry of living cells. It is well established that FTIR identifies the functional moieties in organic molecules depending on their vibration modes at different infrared wave numbers. It therefore reveals the presence or absence of certain functional groups, protonated functional groups, or modification of the functional groups by new interactions of the biofilm. Thus, it aids in the elucidation of functional groups on Gram-negative and Gram-positive bacteria using FTIR spectroscopy, absorption bands corresponding to the inherent components of biofilms such as the proteins, lipids, polysaccharides, polyphosphate groups, and other carbohydrate functional groups on the bacterial cells are identified and compared along different conditions.

5.1.1.1.1 Application of FTIR on Biofilm Analysis

FTIR technique has been employed for the observation of biofilms. It is a non-destructive technique and the spectrum are gained in situ and in real-time. It reveals the changes in a system due to bacterial protonation and deprotonation as a function of pH or how contaminants sorb to minerals/bacteria, or for tracking the precipitation of a mineral or the breakdown of a contaminant in a system [69]. Ojeda et al. [70] investigated the application of reflectance micro-FTIR as a powerful tool for the characterisation of biofilm in opaque solid surfaces. The obtained data upon comparison with the conventional FTIR techniques, such as the transmission micro-FTIR, attenuated transmitted reflectance (ATR-FTIR), and KBr pellets revealed essentially similar results. Although additional spectroscopic data was suggested as complementary techniques, the reflectance micro-FTIR spectra were used to suitably differentiate commune biofilms on stainless steel (attached) from the "free" (not attached) bacteria (from planktonic suspensions) employing mostly the absorption peaks corresponding to the signals emanating from the carboxylate anions and carbonyl groups [70]. Further studies employed ATR-FTIR method to investigate intact Gram-negative and Gram-positive bacterial cells surface functional group chemistry of including their isolated cell walls as a function of pH, growth media, and growth phase (for intact cells only). The results affirmed the previous understanding that the de-protonation of both phosphates and carboxylates give-rise to the negative charge of bacterial surfaces and changes in the pH of solution only exhibit minimal effect on the secondary structure of the cell wall. The FTIR results showed the uniformity of the functional group chemistry of the different studied classes of bacterial surfaces and the dominant functional groups on the studied bacterial surfaces were amide, carboxyl, hydroxyl, phosphate, and carbohydrate related moieties [70].

Alvarez-Ordóñez et al. reviewed the use of FTIR as a powerful tool to analyze the molecular compositions and stress responses in foodborne pathogenic bacteria [71]. The review gave an intensive overview of the current achievements and advances in data-processing capacity of FTIR spectroscopy method such as in the assessment of the mechanisms of bacterial inactivation by antimicrobial agents and various food processing technologies, in the monitoring of the spore and membrane features of foodborne pathogens in changing environments, to identify in food related environments stress-injured microorganisms, to investigate the dynamic changes in bacterial populations, and tolerance responses [71]. Nevertheless, the authors reiterated that despite the great potential of FTIR technique in in microbial ecology studies, complementary techniques are essential due to the complex compositional and structural variations associated with FTIR.

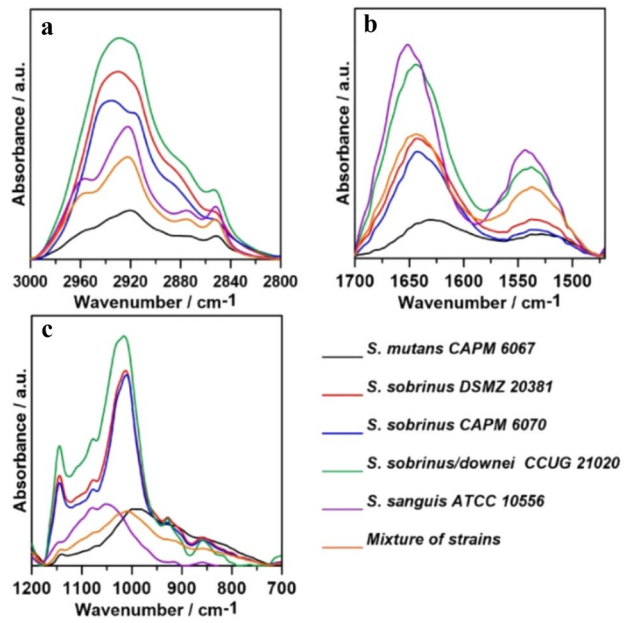

Fig. 4 The relative intensity of FTIR spectra of the fingerprints regions of: (**A**)—lipid region (3000–2800 cm^{-1}), (**B**)—Amides I and II region (1700–1470 cm^{-1}), and (**C**) carbohydrate region (1200–700 cm^{-1}). Retrieved from Gieroba et al. [72]. Another example of FTIR plot is shown in Fig. 5

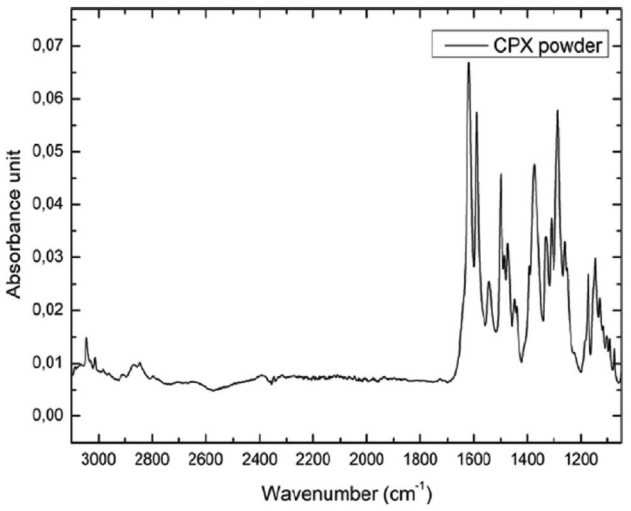

Fig. 5 FTIR spectra of ciprofloxacin powder [73]

Gieroba et al. [72] applied FTIR and Raman spectroscopy and mapping to analyze biofilms produced by bacteria of the genus Streptococcus. By comparing the relative intensity of the FTIR spectra of the fingerprints regions of lipid, Amides I and II region, and carbohydrate region, the main changes between the samples were identified, as illustrated in Fig. 4.

Tugarova et al. [74] employed FTIR spectroscopy to study the biofilms formed by rhizobacterium *Azospirillum brasilense* Sp245 and its mutant, *Azospirillum brasilense* Sp245.1610. The results revealed that the biofilm of the wild-type strain of *Azospirillum brasilense* Sp245 contained moderate amounts of poly-3-hydroxybutyrate (PHB), while the mutant strain had diminished contents in the biofilm. This was ascribed to the possible changes during fatty acids synthesis, and the amount of biomass and the relative content of lipopolysaccharide antigens in matured biofilms.

5.1.1.2 ***Raman Spectroscopy*** Raman spectroscopy is often used in combination with FTIR for biofilms and bacteria analyses [75]. It is a nondestructive technique which is based on the effect of inelastic light scattering by molecules. It provide fingerprints for whole organism which could be used in the characterisation and identification [75]. Interestingly many biomolecules of importance including carbohydrates, proteins etc., exhibit distinct spectral features [76, 77]. RAMAN requires no or minimal sample preparation.

Although Raman spectroscopy exhibits limited sensitivity, with typical quantum efficiency in the order of 10^{-6}–10^{-8}, its sensitivity is dramatically enhanced (enhancement factors in approaching 10^{3}–10^{6}, and under certain conditions, even up to ~10^{14}) if a molecule is attached or in the immediate proximity to metallic (usually Ag or Au) substrate. This technique is known as Surface-Enhanced Raman Scattering (SERS) [75].

5.1.1.2.1 *Application of Raman on Biofilm Analysis*

Raman is one of the spectroscopic techniques that have been employed to monitor the formation of biofilms, the physiology of the microorganisms within biofilms, and/or the interactions of biofilms with their environments. Wickramasinghe et al. [78] evaluated the active components of the matrix of mono-species biofilms of selected *Pseudomonas fragi* (*P. fragi*) and *Pseudomonas lundensis* (*P lundensis*) strains with combined chemical analysis and Raman spectroscopy approaches. Raman detected the difference between the planktonic and biofilm bacteria biochemistry using the difference in the carbohydrate's levels between biofilm and planktonic bacteria. This was supported by previous studies of the Raman spectra of *Klebsiella pneumonia, Escherichia coli*, and *Pseudomonas aeruginosa* biofilms which revealed larger amounts of polysaccharides in biofilms compared to the planktonic cells [79]. Figure 6 shows the scatter plots of principal component analysis of the Raman spectra from planktonic cells and biofilms of the different bacterial strains.

Keleştemur et al. [80] reviewed the applications Raman and FTIR techniques with other complementary techniques for the characterisation of the compositions and structures of some biofilms. The review highlighted the importance of Raman and FTIR spectroscopic methods, especially in

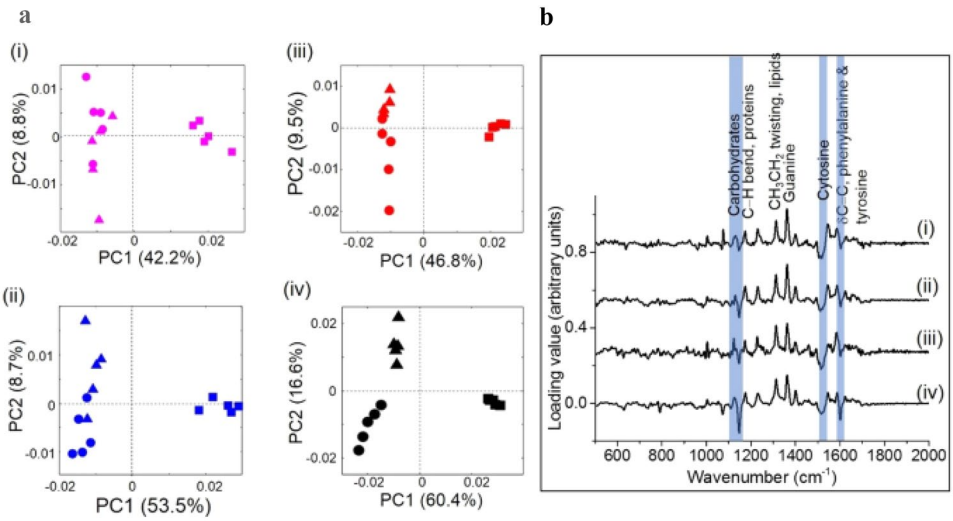

Fig. 6 **a** Scatter plots of principal component analysis of the Raman spectra from planktonic cells and biofilms of the four bacterial strains: (i) *P. fragi* 1793, (ii) *P. fragi 1832*, (iii) *P. lundensis* 1822 and (iv) *P. lundensis ATCC* 49968. (square, planktonic cells; circle, biofilms grown at 10 °C; triangle, biofilms grown at 25 °C). **b** The loading plots. The corresponding PC1 loading plots of each strain exhibit the spectral differences of each comparison: (i) *P. fragi* 1793, (ii) *P. fragi* 1832, (iii) *P. lundensis* 1822 and (iv) *P. lundensis* ATCC 49968 (retrieved from Wickramasinghe et al. [78])

combination with other microscopic techniques for an in-depth comprehension of the complex nature of the biofilms. Jung et al. [81] studied the antibiotic effects of *Pseudomonas aeruginosa* biofilm with Raman and the data were analyzed with multivariate analysis. The technique was able to show the changes in biochemical properties and distinguished between changes induced in *P. aeruginosa* biofilms using three antibiotic agents. Raman and FTIR spectroscopy were applied in the analyses of the biofilms produced by bacteria of the genus Streptococcus by Gieroba et al. [72]. The study confirmed that the combination of Raman and FTIR spectroscopies was quite effective for bacterial product characterisation and revealed the potential of applying a non-invasive spectral optical technique for investigating bacterial adhesion and biofilm production on tooth enamel, affording a valuable tool for measuring dental pathologies, such as caries, in vivo. Ebert et al. [82] correlated fast Raman spectroscopic data for clinical *Staphylococcus aureus* isolates from 47 patients with different disease backgrounds with their biofilm-forming characteristics. The results showed the most spectral differences occur in the fingerprint region between 750 and 1150 cm^{-1}. Linear correlation of biofilm optical density (OD) values was obtained by interpolating the partial least square regression (PLSR) analysis on the Raman spectra of the three categories of biofilm formation. Chao and Zhang [83] employed surface-enhanced Raman scattering (SERS) spectroscopy to reveal the chemical changes associated with biofilm formation from initial attachment to mature biofilm. Herein, SERS based on silver colloidal nanoparticles was used to investigate the variations of the chemical components of the biofilm matrix associated with the different growth phases, including initially-attached bacteria, colonies, and matured biofilm. From the varying (increasing) intensities and appearance probabilities of related marker peaks in the SERS spectra, the increase of carbohydrates, proteins, and nucleic acids with the growth of the biofilm of the three bacteria were assessed. The authors revealed that SERS harnesses the chemical information of biomolecules without requiring any external labeling, as well as noninvasive analysis of biological samples and imaging of cells. Very many reports from the literature revealed that Raman spectroscopy and its related advanced versions are suitable for probing biofilm properties and growths, especially when complemented with other microscopic techniques. Raman spectroscopy was instrumental in the identification of the biochemical composition and structure of biofilm matrices. For instance, the spectra of the biofilms of two endodontic pathogens reveal the presence and variations of proteins, carbohydrates, nucleic acid and fatty acids in all samples. Meanwhile, the spectroscopic differentiation of the biofilms-biomolecules was achieved via the variations in the spectra expression of the biomolecules. Ivleva et al. [84] carried out an overview of different Raman micro-spectroscopic techniques i.e., resonance Raman micro spectroscopy and surface enhanced Raman scattering micro-spectroscopy, for the in situ detection, visualization, identification, and chemical characterisation of biofilms. The feasibilities and limitations in biofilm research were also presented. The critical review highlighted the advances in the application of Raman micro-spectroscopy for biofilm

characterisation in different fields of research including biology and environmental microbiology. Also, divulging the advancement in Raman micro-spectroscopy sensitivity through resonance effect, SERS, and the combination with stable-isotope labelling allowed for improved analysis of complex biofilm matrices and enhanced knowledge of a variety of biofilm properties. Another review by Bodelón et al. [85] highlighted the advances in the application of SERS spectroscopy in label-free detection and imaging of quorum sensing-regulated processes of the human opportunistic pathogen Pseudomonas aeruginosa.

5.1.2 Microscopic Methods

Microscopic methods help view samples and objects that are not visible by the unaided eye. Optical, electron and scanning probe microscopies are the three main divisions of this group of techniques. The optical microscopy (OM) and electron microscopy (EM) create images utilizing the, reflection, refraction, and diffraction of electromagnetic radiation/electron beams upon interactions with a specimen. This is achieved via wide-field irradiation of the sample (i.e. (OM) and (TEM)) [86] or by scanning of a fine beam over the sample (i.e., confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM)).

5.1.2.1 ***Optical Microscopy (OM)*** The OM utilizes light in the visible region and a combination of lenses to visualize and magnify images of samples of small size. It is the oldest version of microscope dated around seventeenth century. OM is a very simple technique because it uses visible light such that samples are visualized directly by the eye; though, in an attempt to improve the contrast and resolution of images, many complex designs have been produced in recent times.

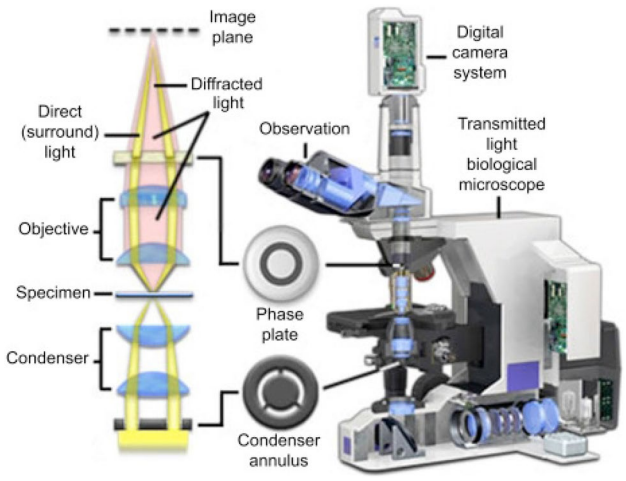

Fig. 7 Phase contrast microscope configuration (retried from Gianfrancesco [87])

In some designs, observed or formed images from OM are obtained with the aid of ordinary light-sensitive cameras to form a micrograph. Previously, images are captured by the simple photographic film but modern technologies permit the capture of digital images. In recent times, digital OM that uses a CCD camera to visualize a sample, and the image are revealed on a computer screen without requiring eyepieces [87]. Figure 7 illustrate the components of a typical modern, OM-two examples of grade 91 martensitic steel and A617 super-alloy light microstructures. There are three famous categories of microscopy: scanning probe, optical, and electron. The other kinds of microscopy that do not utilize visible light include SEM and TEM.

5.1.2.1.1 *Application of Optical Microscopy in Biofilm Analysis*

Although there are many advanced techniques used to view biofilm formation in recent times, OM which happens to be the cheapest, simplest, and oldest technique for biofilm viewing and study have been employed for biofilms characterisation. A typical example and assembly are found in the work of Cortizo et al. [88]. Herein, conventional OM coupled with a glass flow cell, was adapted to image biofilm microstructures including roughness, thickness and biofilms density on thin strata evaluations. The results revealed the initial stages in the development of the colonies of the consortium of oral microorganisms such as biofilm formation, cell attachment, growth and adhesion. From the OM observation, biofilm development after many hours revealed the motility of the studied species (*P. fluorescens*) and the environmental transformations of the interface by the cells already attached, which played important roles in the attachment process. A typical OM assembly and its image distortion adapted from Wu et al. [89] is shown in Fig. 8.

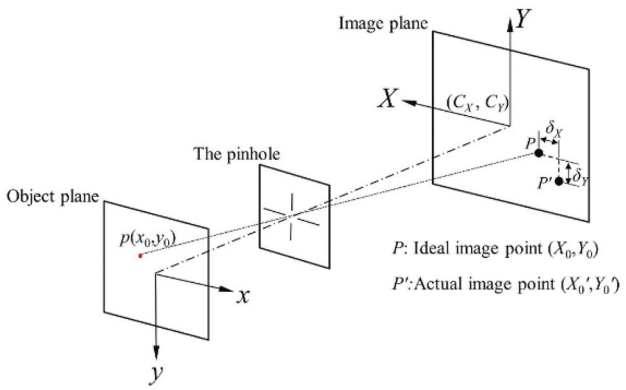

Fig. 8 Illustration of an image distortion in a pinhole model of optical microscope. The (C_X, C_Y) represent origin of the coordinate, while the point p (X_0, Y_0) on the object plane is imaged to P (X_0, Y_0). The deviation of the image point P (X_0, Y_0) led to P' (X_0', Y_0') [89]

Walker and Keevil [90] employed a light microscope which combined both epifluorescence and differential interference contrast (DIC) to examine the biofilm on coupons. The results showed that this technique could differentiate the bacteria as discrete cells or as micro-colonies on the surface of a glass coupon which was immersed in the laboratory chemostat.

5.1.2.2 ***Confocal Microscopy (CM)*** Confocal Microscopy (CM) is a fluorescence imaging technique that utilizes a laser point source to scan a sample and a pinhole to reduce the collection of light from outside the focal plane. Confocal microscopy has proven to be a powerful tool for investigating the structure of biofilm due to its excellent capability to afford real-time visualization of the fully hydrated live sample. It has the potential to observe in-situ growth rates of biofilm. Furthermore, it affords 3D images which reveals the diversity of biofilm architecture.

5.1.2.2.1. *Application in Biofilm Analysis*

If live/dead cells are properly stained, it is possible to visualize/quantify the biofilm viability on both transparent and opaque surfaces. It has been reported to possess the capacity for real-time imaging living samples after full hydration [66]. Mountcastle et al. [91] viewed CLSM as an open-source tool for automated biofilm viability analysis [91]. The results reveal the capability of present technique to afford reliable imaging of biofilm growth and cell viability assessment, critical for the development and analysis of novel antimicrobial strategies. Alhede et al. [92] employed CLSM in combination with some other microscopic techniques to reveal comprehensive visual impressions of biofilm structures and compositions [92]. Herein, the limitation of one technique was complemented by another technique to contain the actual properties of the bacteria. For instance, the restricted magnification which is a limitation of CLSM method are resolved by the use of SEM provides high-magnification spatial images, while the requirement of dehydration of the samples for SEM analysis (during preparation) alters the morphology and complemented by CLSM. The findings revealed the importance of combining spectroscopic techniques for complete biofilm characterisation, and also outlined the advantageous contributions of each method compared to another in terms of obtaining a more realistic biofilm structure. They compared conventional SEM, Focused Ion Beam (FIB)-SEM and CLSM with SEM techniques [cryo-SEM and environmental-SEM (ESEM)] that do not require dehydration. A typical CLSM biofim morphology is shown in Fig. 9.

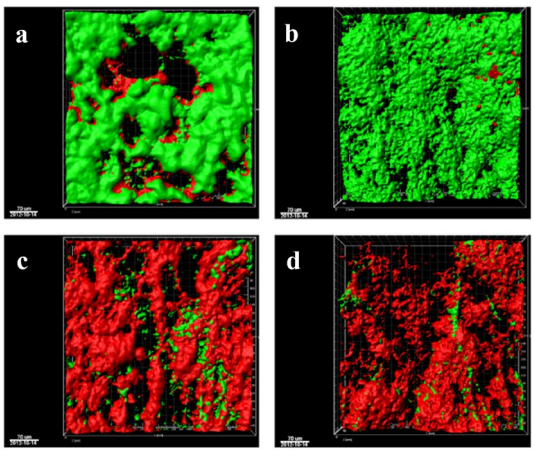

Fig. 9 Morphology of biofilm using CLSM: **a**, **b** bio-side biofilm and **c**, **d** water side biofilm adapted from Fox [93]

Reichhardt and Parsek [94] adopted CLSM for the study of *Pseudomonas aeruginosa* microbial mechanism and its matrix formation. They recounted how they employed CLSM to investigate the biomolecules of a biofilm matrix with structural and chemical properties that are specific to their function. Azeredo et al. [95] highlighted the many imaging morphology adopted in recent times to investigate cell viability and biofilm formation, and also highlighted their merits and demerits. They maintained that CLSM is one of the known techniques used to characterize biofilm formation and quantification amongst other spectroscopic methods. According to Dhayakaran and Neethirajan [96], CLSM is a technique of choice for structure–function microscopic studies holding the prime advantage of providing three-dimensional imaging of hydrated, living, undisturbed microbial biofilms. Hence, reliable quantification of the structural properties of biofilm is possible. Aided by staining procedures, CLSM allows for both quantification and visualization of biofilms [96]. Additionally, reports revealed the capacity regarding CLSM, especially when combined with other spectroscopic methods, in investigating the biofilm production of microorganisms like *Pseudomonas aeruginosa* within several media [97]. It also showed the usability of this technique to study the biofilm on different strata such as rubber substrata, glass, steel, polystyrene, and ceramic. The study also further revealed the importance of CLSM and other complementing microscopic techniques in understanding the substratum characteristics which influence biofilm structure.

5.1.2.3 ***Scanning Electron Microscopy (SEM)*** The SEM is a highly sensitive and advanced analytical tool that outweighs traditional light microscopy. The standard array of magnifying lenses in a compound microscope enables sample magnification by up to 1000x, using visible wavelengths of light in the 400–700 nm range. This helps to optically resolve points in a specimen that are no closer together than 200 nm. Topographical features in closer proximity than this lower

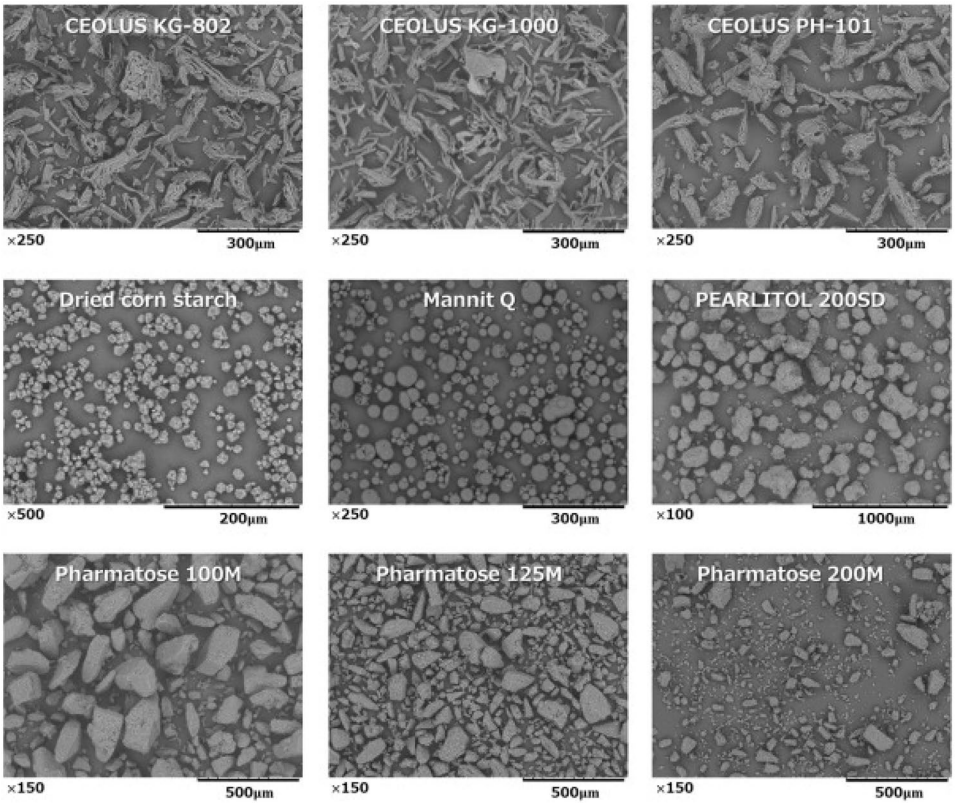

Fig. 10 SEM morphology of a typical substrate surface [101]

detection range cannot be distinguished with any degree of reliability. The wavelength of the traditional microscopy range was a limiting factor as the need for nanoscale material characterisation and elemental topography measurements became increasingly prevalent worldwide. Scanning electron microscopy was developed as a result, providing novel methods of sample imaging via electron scanning.

5.1.2.3.1 *Application of SEM on Biofilms Analysis*

SEM is a robust analytical tool with a wide range of research and commercial applications. It is largely adopted in the characterisation of bacterial biofilms on different surfaces. Mokobi [98] utilized SEM to characterize the biofilm of *Scardovia wiggsiae*. With a minimal modification of the conventional protocol, SEM preserved the biofilm architecture and allowed investigations at very high magnifications (order of nanometers) and with the appropriate resolution. Report by Gomes and Mergulhão [99] employed SEM technique to study how ampicillin application influences *Escherichia coli* formed around different surface substrate with unique characteristics, i.e., glass and silicone. Because of the significantly large magnification and resolution, this technique enhances a comprehensive analysis regarding the

Table 2 Different microscopic techniques used in biofilm analysis

S/N	Techniques	Application	Pros and cons	References
1	Optical Microscopy	Visualizes biofilm and its counts (quantitative)	Simple protocol but low resolution and magnification	[90]
2	SEM	Provides detailed biofilm images and high magnification	Sample preparation may require dehydration which may interfere with actual structural configuration and fails to analyze live cells	[104]
3	CLSM	Investigates biofilm structural features, identification of dead and live cells and offers 3-D configuration of the biofilm	Permits visualization of hydrated bacterial cells/biofilms and 3-D imaging	[103]
4	AFM	Adhesive force, topography determination and in-situ imaging of film analysis	A non-destructive technique with minimal treatment and the experimental condition allows living biofilm characterisation, but possible surface damages during imaging by the tip interaction	[105]

influence of antibiotic on the biofilm matrix, revealing antibacterial ability of drugs via the elongated variation between ampicillin-treated cells and the untreated cells induced by different levels of exposure. Donelli [100] highlighted how SEM method aids in the provision of information about localization and morphology in the entire biofilm morphology of a particular single cell bacteria, and also within the various stages of the biofilm adherence mechanism, microbial interactions, including EPS secretion. As illustrated in Fig. 10, SEM helps to differentiate and characterize multispecies biofilms developed on substrate surfaces.

Fernández-Delgado et al. [102] employed environmental SEM to analyze *Proteus mirabilis* microbes cultured using stainless steel and chitin. Likewise, Njoku et al. [103] employed SEM complemented with CLSM to study bacterial biofilm development on protective coatings. Different microscopic techniques used in biofilm analysis that have been employed in biofilm characterisation are listed in Table 2.

5.1.2.4 ***Atomic Force Microscopy*** The AFM is another type of microscopic method of surface analysis. It creates a highly magnified three-dimensional image of a surface. The magnified 3D image is generated by monitoring the motion of an atomically sharp probe as it is scanned across a surface of a sample. With the use of the AFM, there is a possibility of viewing features on a surface having a few nanometer-sized dimensions and also monitors the forces of attraction and repulsion between a probe and a sample surface [106].

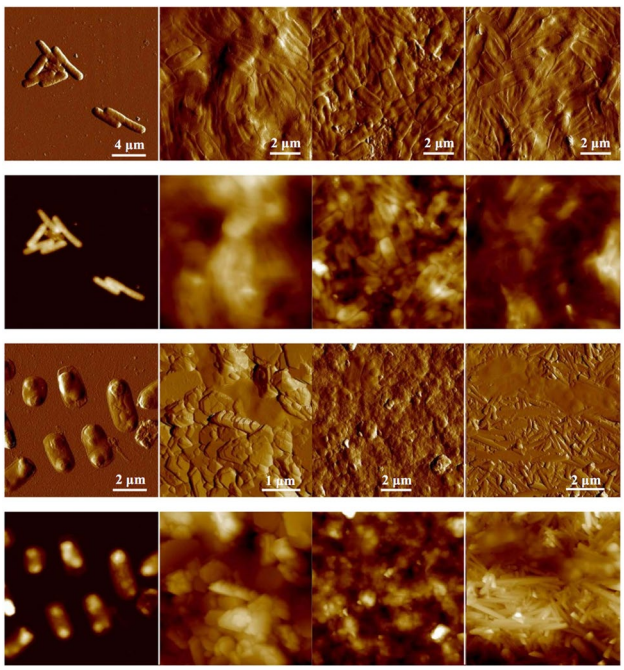

Fig. 11 AFM morphology indicating the peak and height measurements regarding *E. coli* [111]

5.1.2.4.1 *Application of AFM in Biofilm Analysis*

Lately, the AFM technique are adopted for imaging microbial cells [107], and also for measuring the microbial adhesion on varieties of essential minerals [108] and force measurements of biofilm on metal surfaces. The morphology give details based on the type of microbial media, and some surface part while information on the length and width of microbes are provided by the section mode [109]. AFM was used to view morphology of the substrate with biofilms, which produced a localized accumulation of sulphide [109, 110]. AFM has an advantage over SEM because it does not require a high vacuum and also provides higher resolution. Huang et al. [111] measured bacterial attachment and the development of biofilm on the clay-sized particles using the AFM, the results show diverse mechanisms between bacteria and minerals, and the surface contours of biofilms on the minerals were assessed as a function of time and available nutrients. AFM achieves high-resolution contour imaging of bacteria, biofilm, and corroded steel, and also be employed to quantify localized corrosion [112] as shown in Fig. 11.

5.1.3 Electrochemical Methods

Electrochemical measurements are generally adopted for MIC studies. The generated potential or current account for the possibility of the kinetics of reactions that happens at the substrate/electrolyte interface. It is established that some of these approaches correlate the physical characteristics of a given material before and after the substrate has been immersed in the corrosion media. Some of the techniques that will be elucidated in the study are open circuit potential (OCP), potentiodynamic polarization (PDP) and electrochemical impedance spectroscopic (EIS).

5.1.3.1 ***Electrochemical Impedance Spectroscopic (EIS)*** The EIS technique evaluates the corrosion mechanisms that takes place on a material and is mostly based on measuring the alternating current impedance within a small potential perturbation across a range of applied frequencies. For EIS evaluation, the impedance of medium (Z), and the phase angle occurring between the resulting current and the applied potential (δ) are examined as a function of applied frequency [113]. These unique quantities are then determined in relationship with the physical, electrochemical and chemical processes related to the electrochemical cell. To have maximum results, it is pertinent that the impedance and phase angle should be examined within a wide range of frequencies.

The unique benefit of the EIS technique compared to other corrosion monitoring techniques is that the amplitude of the potential wave is known to be small, this is in the order of ± 10 mV, thus the system to be measured is not disturbed [114]. The EIS technique is rapidly evolving as a result of the development of usable instruments and the capability of the technique in providing in-depth information on the corrosion mechanism and electrochemical cell performance.

5.1.3.1.1 *Application of Electrochemical Impedance Spectroscopic on Biofilm Analysis*

Most studies suggest that electrochemical measurements are applied for MIC studies especially as they detects the processes in biofilm adhered to the surface of a substrate [115]. Deyab [116] studied the excellent application of surfactant as an inhibitor in mitigating corrosion in oil-related saline environment. The study revealed an oil-related saline environment with the occurrence of SRB and no quaternary ammonium salt (QAS), that hydrogen sulphide secreted via the SRB combine with Fe compounds to produce sulphide as a product. The sulphide had high electrical conductivity, which decreased the electrolyte resistances (R_s). Through the inoculation of QAS to the oilfield produced water, the SRB activities decreased, and accordingly, the R_s increased. Zhou et al. [117] successfully carried out research on accelerating the role of microbial film on steel pipeline soil corrosion. Clearly, the charge transfer resistance (R_{ct}) of the specimen covering the corrosion product before the immersion (CP) reduced, and the corrosion process of the metal expanded by the actual Fe oxides, implying that the rate of corrosion rate of the CP specimen was much higher than that of the control specimen. With increased immersion time, new Fe oxides were formed in the micro-pores of the actual Fe oxides, and a total and compact corrosion product film was generated on the metal surface. Therefore, the corrosive ions diffusion in the corrosion product was impaired, and the rate corrosion of the CP specimen decreased with time, weakening the accelerating role of the main corrosion product. In a review conducted by Victoria et al. [118], on the corrosion of metal triggered by microbial activity-control options, EIS was proven to be a safe method to elucidate microbial corrosion because of the damage to the biofilm/microbial population was indicated to be negligible. This was attributed to the fact that EIS adopts low amplitude signals within a linear range [119]. The reported studies indicated that EIS is a unique technique that are adopted to study several processes in the MIC. Notwithstanding, some issues have been detailed with the use of EIS.

The main issue of EIS operation is observed in the complex data generated. Another disadvantage of MIC measurements is the inefficacy to spot a small thickness biofilm formed [21]. It is relevant to state that the existence of the activities of microorganisms in electrolytes generate steady alterations of the electrode surface, for instance, the development of biofilm, which in several cases lead to observed errors in the electrochemical measurements. Thus, to achieve reliable data in MIC studies, it is important to employ more electrochemical techniques or many complementary tests such as spectroscopic, microbial procedures or surface analytical methods.

5.1.3.2 *Potentiodynamic Polarization* Potentiodynamic polarization are described as a method where the potential of a working electrode is varied at chosen rates [120]. It is regarded as the most widely used polarization testing technique for measuring the corrosion resistance of materials. Potentiodynamic polarization is applied for an extended variety of functions. This technique provides significantly useful information concerning the corrosion rate, corrosion mechanisms and susceptibility of certain metals or alloys to corrosion in specified environments. Few known polarization exist as listed below [121]:

(a) Polarization based on activation: This is referred to as polarization induced through a gradual electrode reaction.
(b) Polarization based on concentration: This is referred to as the polarization induced by the changes in the concentration of either products or reactants close to an electrode surface.
(c) Polarization based on Ohmic measurement: This is referred to as the polarization produced by IR drops in the electrolyte or within the surface films, such as oxides or salts.

The polarization degree (η) is described as the overvoltage or overpotential as expressed in Eq. (1.33):

$$\eta = E - E_o \tag{6}$$

where E refers to the electrode potential for a certain mode of current flow and E_o refers to the electrode potential for zero current flow (also known as the OCP, rest potential or corrosion potential).

5.1.3.2.1 *Application of Potentiodynamic Polarization on Biofilm Analysis*

The PDP measurement are classified as one of the most frequently employed DC electrochemical methods in corrosion tests. In typical research carried out by Liu [122] on the X80 pipeline steel corrosion under SRB biofilms in simulated CO_2-saturated oilfield formed water with carbon source starvation, it was shown that the steel had a "passivating"

property in the tested condition. It was reasoned that the steel could be "passivated" in the test electrolyte when a layer of biofilm is detected on the sample surface. As the biofilms were made inactive through death, the corrosion potential of the metal shifted negatively. The anodic current density decreased relative to that obtained from the samples covered with biofilms. Therefore, an active SRB biofilm increases the corrosion rate of the metal [123]. When the biofilm was made inactive, there was decrease in the corrosion current densities and inhibition of the metal corrosion. Jia et al. [124] had in-depth research on the laboratory testing of augmented biocide reduction of an oilfield biofilm and its MIC of carbon steel in the presence of oilfield chemicals, and it was proven that PDP measurement are adopted to assess the performance of the biocide in the oil field. Comprehensive research by Zhou [117] explained the dominant role of microbial film on soil corrosion of pipeline steel. The obtained results showed that PDP was instrumental in elucidating the influence of microbial film on pipeline steel soil corrosion. This was confirmed by the Tafel curves highlighting that the influence of the original corrosion product and microbial film on the cathode polarization were more projecting than on the anode polarization.

5.1.3.3 ***Open Circuit Potential*** The OCP has been an important in-situ method for monitoring various electrochemical processes [125], such as corrosion of metals and alloys [126] and biocorrosion of metal [127]. OCP usually outlines the complex discharging activities that are related to the potential relaxation within the electrical double layer (EDL) of an electrode and/or with the pseudo-capacitor effects of chemisorbed electroactive species in the electrode process [125]. The experimental designs are usually made to attain an equilibrium setting, where all the anodic and cathodic reactions advance at an equal finite rate. Subsequently, the net current flow is zero and the voltage measured corresponding to these zero currents is referred to as the OCP.

5.1.3.3.1. *Application of Open Circuit Potential on Biofilm Analysis*

OCP is also a unique electrochemical method adopted for elucidating the corrosion behavior of metals. The OCP analysis on biofilm has been reported in many studies relating to the oil and gas sector. This method highlights the potential data depending on the growth variations of microorganisms. Jia et al. [124] presented a finding on the laboratory measurements of improved biocide mitigation of an oilfield biofilm and its MIC of steel in the presence of oilfield chemicals. The results showed that OCP measurement was stable for the different treatment days during the 7-days biofilm removal measurement period. A report by Liu [124] on corrosion inhibition and anti-bacterial effectiveness of benzalkonium chloride in artificial CO_2-saturated oilfield produced water presented the fluctuation of OCP measurements. The increase in OCP was attributed to the production of a protective thin biofilm while the reported decrease in OCP was due to biofilm death from starvation. In an extended study on microbial induced galvanic corrosion of the substrate underneath a deposit in simulated oilfield-produced water having *Desulfotomaculum nigrifican* [128], it was observed that regardless of the SRB present in the system, the OCP of the metal under the deposit had more negative compared with the bare substrate.

6 The Adverse Effect of MIC in Oil and Gas Sector

6.1 Impact on Offshore Structures

It has been assessed that MIC is liable for 40% of all internal pipeline corrosion in the oil and gas industry [129, 130]. Over the last two decades, MIC has caused pipeline leakages and facility failures, resulting in environmental damages [131, 132]. The 2006 Prudhoe Bay oil spill and the corrosion of deep-sea tsunami early warning systems are two prominent MIC-related cases, both of which resulted in major economic losses and ecosystem damage. Biocorrosion has been estimated to account for 10% of corrosion cases in the United Kingdom [133]. In Western Australia, MIC has reduced the lifetime of flow lines from the planned > 20 years to less than 3 years. MIC is a constant issue for corrosion engineers and scientists in a variety of fields, particularly in the oil and gas sector of the different continents, including Africa.

Offshore platforms are quite comparable to underground pipelines because both their outer and inner surfaces are exposed to corroding environments. In underground pipelines,

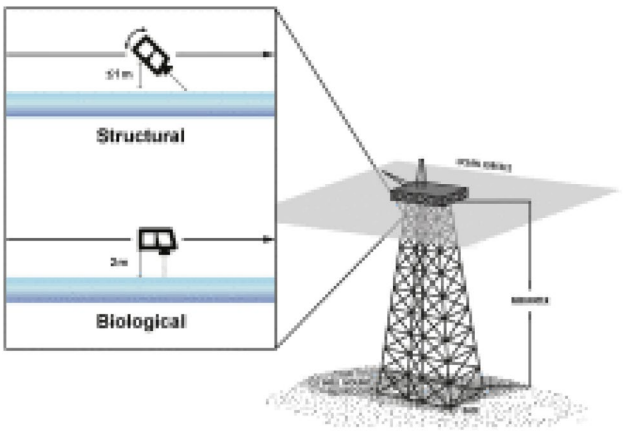

Fig. 12 A model sea-based oil rig prone to MIC [136]

Fig. 13 Oil damages and the destruction of vegetation cover in an oil-impacted region of Ogoniland in Nigeria [144]

Fig. 14 Alteration of the natural environment in an oil spill site in Kalaba Community in Okordia clan, Yenagoa Local Government Area of Bayelsa State, Nigeria [148]

the outer surfaces of the pipes are exposed to the soil, and the inner surfaces are subjected to the corrosive impact of the fluids that pass through, whether it is water or oil. However, in offshore platforms, the whole submerged component is exposed to seawater, and the inner surfaces of media like oil storage facilities or seawater injection systems might be regarded as areas where internal corrosion occurs [134, 135].

In an offshore platform, most of the common MIC problems include marine fouling, drill cuttings around the platform legs, and reservoir issues and some of the spots where these problems are most likely to occur are shown in Fig. 12.

In addition to the aforementioned problems, two major problems arise from bacterial proliferation in offshore structures: (1) the production of hydrogen sulphide (generated, for example, by SRB), which, in addition to being volatile and toxic, poses a risk to the safety of personnel, leads to corrosion and souring of products (crude oil, for example), affects the quality and market value/price, and (2) the production of bacterial metabolites which may lead to the quick material deterioration [137].

It is noteworthy that MIC has a greater impact on internal systems than it does on external surfaces, and the impacts are more obvious and faster. As a result, procedures for MIC control in oil and gas fields are recommended, such as thorough monitoring, periodic maintenance, and the reasonable use of biocides [138, 139].

6.2 Impact on the Environment

The negative effects of microorganisms on materials of all kinds, particularly metals, have considerable consequences leading to environmental degradation. The reviewed sector, in this case, represents industry noticeably impacting the environment. The activity of the oil and gas sector are inundated with issue relating to oil spillages, which is viewed as a major contributing factor to environmental degradation. Oil spillages are triggered by a degradation of oil storage tanks, pipelines, and offshore oil rigs, which in most cases is potentially the effect of MIC and not from anthropogenic activities. The resultant immediate and long-term environmental damage stretches for many decades. Oil spillages encourage the destruction of wildlife, air and water pollution, loss of biodiversity, degradation of farmlands, and disruption of marine ecosystems and coastal environments [140, 141]. An example of vegetation loss in a typical oil spill area in Ogoniland in the South–South region of Nigeria is given in Fig. 13. To date, there have been several reports of oil spillages in Nigeria with growing concern on the depletion of the natural environment [142, 143].

According to a 2006 report by United Nation Development Programme (UNDP), a total of 6817 oil spills occurred between 1976 and 2001, accounting for 3 million barrels of oil, in which over 70% was not recovered. About 2097 of the total oil spill incidents occurred only in the Niger Delta region of Nigeria [145]. In the past decade, reports have shown that more than 9343 incidents of oil spills occurred in the oil-rich Niger Delta region of Nigeria, meaning about a thousand spills each year, representing the highest rate globally [146]. This has led to serious environmental concerns and litigations. Between 1970 and 2000, the government of Nigeria reported oil spills of over 7000, with the natural environment yet to be fully restored. One of the oil companies with operations in Nigeria, Shell, which admittedly spilt 14,000 tons of oil by the year 2008, has suffered more than 1000 spill litigations [146].

The devastation of these incessant oil spills on the environment in the African continent cannot be overemphasized and often lead to pollution of land and water bodies, with attendant alteration of the natural environments. Figure 14 shows significant environmental degradation caused by an oil spill in Kalaba Community in Okordia clan, Yenagoa Local Government Area of Bayelsa State. Such environmental alterations hamper aquatic lives. The result is that water bodies are left deprived of fish. With the huge implication on the

environment and means of livelihood, there is a demand for companies to clean up the communities and also pay compensation. One case has a documented legacy: after major spills in 2008 and 2009, Shell Petroleum Development Company agreed in early 2015 to compensate the residents of the town of Bodo in the Niger Delta for environmental pollution with the sum of 76 million euros ($81 million) [147].

Depending on the nature of the oil spill and where it occurs, it will have distinct environmental effects. A marine oil spill, if released in the water, may degrade fast because the water supports dispersion, and emulsification, and is home to many microbial degradation processes. Typically, oil and oil products accumulate on water surfaces and float. In most cases, this leads to environmental pollution. Sometimes, small oil droplets may form and increase the surface contact with water and also affect the natural biodegradation of the spilt oil. However, oil spills on land may penetrate the ground reaching underground water, if there are no hindrances to such vertical movements. Where there are less permeable ground layers, the oil may also move laterally affecting the ground ecosystems. Moreover, underground oil spills from damaged pipelines and underground storage tanks affect underground water. Such underground spills trapped and provide sources of underground pollution. Clearly, with MIC among the major precursors of environmental degradation, there is a great concern.

Marine ecosystems are particularly altered by oil spillages. Many tonnes of petroleum oils are released frequently into the oceans on a global scale, with drilling, shipping rigs and other industrial activities accounting taking part. The presence of petroleum products in bodies of water naturally promotes wildlife oiling and exposure to harmful polycyclic aromatic hydrocarbons (PAHs), which are found in petroleum oils. Oil spills, for instance, have a major influence on seabirds. In an examination by Troisi et al. [149], the indicators of exposure and endocrine disturbance in oiled guillemots (*Uria aalge*) were found to be plasma PAH and thyroid-stimulating hormone (TSH). The authors noted that external oiling of seabirds causes mass mortality within days of a spill, while survivors face long-term chronic effects from PAHs present in the ingested oil. Despite significant efforts, survival rates for rehabilitated oiled birds are very low. PAHs disrupt thyroid homeostasis, which is known to be important in the regulation of energy metabolism.

7 Preventive Measures in Curtailing Biocorrosion

Maintaining cleanliness in industrial systems is the fundamental strategy utilized to avoid and control biocorrosion. However, as simple as the rule sounds, it is rarely applied except when done at the initial stages of installations and start-up [150]. Also, it is necessary to consider a complete approach to preventing biofouling; this involves considering the actions and growth of microorganisms, the physicochemical conditions at the metal-solution interface, as well as the chemical reactions taking place in the fluid. This is because, as seen in most systems, both biofouling and abiotic fouling happen simultaneously. Besides, the performance of the system is affected by the interaction between the inorganic corrosion products and biofouling [151].

For effective prevention and control strategy, the use of correct monitoring plans integrated with the appropriate field and laboratory microbiological equipment to understand the state of the systems and assess the biological and abiotic parameters is very essential. The strategy used to prevent and control biocorrosion should address the following key issues: (ii) suppressing microorganism growth and metabolic activities, and (ii) re-conditioning the environment to prevent microorganism adaptation. Common approaches employed in the prevention and control of biocorrosion include cleaning, use of biocides and ozone, antimicrobial and antifouling coatings, and cathodic protection.

7.1 Cleaning

Cleaning is done to remove deposits like slimes and scales from the metal surfaces. Slimy deposits are created when floating matter settle on metallic surfaces or sticks to them. They consist of pollutants such as oil, dirt, metal oxides, bacterial slimes, and deposits from chemical treatment processes (phosphate, iron, etc.) [150, 152]. It is strongly advised to utilize the filtration method to eliminate natural-occurring sedimentation or to apply dispersive chemicals to keep stuff suspended [150]. Coarse filters are used when the system contains large size particles. However, for systems that have a high level of microorganisms and a significant number of suspended matters, a set-up that involves an array of different filter sizes is recommended.

Scaling is the development of crystalline, hard deposits as a result of dissolved materials precipitating. The driving force for scale build-up depends on a change in temperature and pressure, pH, quality of water, flow velocity, chemical concentrations, and hydrodynamic conditions [153]. Calcium carbonates, sulfates, or silicates are typical precipitates. The scale removal process involves both mechanical and chemical approaches depending on the physical texture and composition, and location of the scale. The method adopted must be fast, non-destructive to the system, and active at preventing re-precipitation.

7.1.1 Chemical Approach

Chemical scale removal is the first and lowest cost approach especially when the scale is not easily accessible and/or the

mechanical approach is inefficient and costly to deploy. By adding various inorganic acids or substances, such as hydrochloric and sulfamic acids, which prevents the development of scale or change the crystalline structure and prevents the precipitation of $CaCO_3$. Ethylene diamene tetraacetic acid (EDTA) is one of the earliest scale removal acids. EDTA and its derivatives are very efficient for the removal of non-carbonate scales, calcium sulfates, and the mixture of calcium and barium sulfates [150, 154]. Besides, antiscalants derived from condensed polyphosphates, organophosphates, and polyelectrolytes are employed in scale prevention. The mechanisms of the scale inhibitory effect include chelation, dispersion, and inhibition [153, 155]. Impurities such as metal ions and organic molecules largely affect the rate of precipitation and the crystal structure. Hence, polyphosphates and polyacrylates compounds are known to adsorb onto growing $CaCO_3$ crystals and bind strongly to calcite growth sites [150, 153]. The PO_4^{3-} substitutes locally for CO_3^{2-} which alters the electrostatic field because of the extra negative charge and prevents crystal growth. By keeping minute particles of distorted crystalline material suspended, polymers like polyacrylates, polymethacrylates, and their co-polymers adsorbed onto the $CaCO_3$ crystals, inhibiting their growth and ultimately preventing scale formation. Other antiscalant compounds are nitrile trismethylene-phosphonic acid (AMP), 1-diphosphonic acid (HEDP), and 1-hydroxy-ethylidene-1 [155]. These phosphonates are reported to be more resistant to hydrolysis compared to the phosphosulphates [150].

The effectiveness of scale inhibitors is influenced by the alkalinity and hardness of the water, temperature, pH, and dosage. Additionally, they are judged on how well they work with biocidal substances used to prevent biofouling and corrosion inhibitors applied to keep the metal from corroding [150].

7.1.2 Mechanical Approach

This encompasses any technique that may physically remove surface deposits such as scales, slimes, sludge, and associated biomass. Besides, it removes biological and biocorrosion deposits together with the metal oxides from the surfaces. This method entails pigging in pipe production or injection lines, rubber spheres for heat exchangers, and high pressure blasting with sand, grit, or water. Mechanical cleaning includes the use of sandpaper, brushes, and chisels.

7.2 Biocides

Chemical substances called "biocides" have the ability to either kill or stop the growth of microorganisms. The requirements for the selection of an effective biocide are [156]; (i) it must be bactericidal, fungicidal, and algicidal making it effective against a broad spectrum of microorganisms, (ii) it will be able to permeate and separate microbial slime, (iii) it must be compatible with the environment (in terms of pH) and other products such as corrosion inhibitors, (iv) it will be low cost, easy to use, and safe to store, and (iv) it must possess appropriate biodegradability.

The effectiveness of the biocides strongly depends on the nature of the target microorganism and the conditions of the system. If a proper assessment of the environmental risk was not conducted prior to their use, biocides may have a negative effect on the ecosystem. This is because most biocides are intrinsically toxic and hard to degrade [157]. They stay longer in the natural environment and form complexes resulting in the pollution of areas far from the treatment spot [150]. Biocides are classified into the following:

7.2.1 Oxidizing Biocides

These include chlorine-based, bromine and its derivatives, hydroperoxides, and ozone [158]. It is highly recommended to estimate the oxidizing power of these biocides, their required dosage, and the treatment pattern (intermittent or continuous) before applying. Chlorine, which hydrolyzes to form hypochlorous acid (HOCl) and hydrochloric acid are used in gaseous form. The use of chlorine as a biocide is pH sensitive, hence, 6.5–7.5 is the ideal pH for efficient antimicrobial activity. Lower pH levels promote corrosion, whereas higher pH levels (9.5) tend to convert all chlorine to hypochlorous ions with little biocidal effect [150]. Sodium hypochlorite (NaOCl) is a powerful biocide that are used to disinfect tank surfaces and water [159]. However, it has been reported that in the presence of organic matter, its antimicrobial activity is reduced [160]. Furthermore, the use of NaOCL results in the formation of some carcinogenic organochlorinated compounds [161]. New strategies include Neutral Electrolyzed Oxidizing Water (NEOW), chlorine dioxide (ClO_2), and sodium dichloroisocyanurate (NaDCC). When compared to NaOCl, NEOW reduces the formation of byproducts, whereas ClO_2 is as effective as NaOCl and has a lower cost and benefit than Chlorine [162], it permeates the cell membrane to impede the metabolic process and does not produce harmful byproducts [163]. It is also less reactive to organic matter, less corrosive than chlorine, and prevents enzymatic browning [164]. However, it has a high pH dependency and degrades on exposure to sunlight [162, 165].

Early reports have shown the ability of bromine to immobilize *Escherichia coli* (*E. coli*), terminate spore-forming bacteria, molds, and yeasts, and disinfect water [166]. Bromine element itself has not been commercialized for large use in the control of microorganisms because it is a fuming liquid and corrosive. However, particularly in water treatment, there are a variety of safer and lesser hazardous

bromine-based biocides strategies to choose from which include liquid products such as sulfamic acid-stabilized bromine and stabilized hypobromite, liquid two-component systems such as activated sodium bromide (NaBr), and solid hydantoin-based technologies and single-feed [167]. Bromine and its derivatives have stronger biocidal activities in the presence of ammonia, lower volatility, and are more compatible with the additives used in cooling water [150].

At low concentrations, ozone is a better oxidant than chlorine for water treatment. Ozone has a high oxidative power, making it highly effective against the majority of bacteria and biofilms found in industrial systems. Mohamed et al. [158] discovered that using ozone reduces the number of bacteria and algae live cells in a cooling tower by 99%. Other studies have shown that, under certain conditions, ozone has a shorter contact time and is effective at immobilizing viruses, bacteria, cysts, and protozoans [168]. Ozone is also used as a disinfectant in public water plants, to control fouling in seawater, to oxidize reduced metals, and to treat synthetic organic compounds [158, 169]. To keep the system clean, a high dose of ozone (5 mg/L) used for 5 min in seawater cooling tubes (titanium, aluminum, and epoxy coating) is sufficient. Furthermore, a low ozonation dosage (0.2–0.5 mg/L) keeps fouling at a tolerable acceptable level [170]. Because it is used up immediately after generation and does not attack the majority of structural metals, including mild steel, ozone is the recommended biocide because it exhibits the least residual concentration in the system [150].

7.2.2 Non-oxidizing Biocides

Non-oxidizing biocides use other methods to deactivate bacteria instead of oxidizing the electrochemical reaction of the bacteria. They are more persistent and do not rely on pH conditions. They include combinations of biocides and some dispersants prepared to remove specific bacteria or biofilm. Examples of available non-oxidizing biocides are acroleine [171], glutaraldehyde [172, 173], isothiazolones [174], quarternary ammonium compounds [175], etc. It also includes organo-sulfur compounds like methylene-bisthiocyanate [176]. The system properties, operating and flow conditions, and the type of structural materials present in the system all influence product selection and performance.

The resultant outcome from the use of biocides in the prevention of biocorrosion in a closed system is not adequate. This is because, since biocorrosion normally occurs beneath the biofilms, sessile organisms inside the biofilms have more resistance to biocides than those in a planktonic community [177]. Besides, biofilms are known to greatly increase resistance to antimicrobial agents [178]. The prolonged use of a single biocide will eventually lead to more resistance to microorganisms growing inside the biofilms. This will necessitate the use of more biocides, which may result in the initiation and propagation of localized corrosion [179]. In addition, the inherent toxicity of most biocides causes a negative environmental impact and might inactivate unintended organisms.

The use of environmentally beneficial anticorrosion biofilms was adopted as one of the effective strategies to mitigate the effects of toxic biocides [180]. The mechanisms as outlined by Guo et al. [181] include; (i) the formation of biofilms that will act as a diffusion barrier, preventing metal dissolution, (ii) aerobic respiration microorganisms use to remove corrosive agents such as oxygen, (iii) inhibiting the growth of SRB using antimicrobials derived from biofilms, and (iv) biofilms forming protective layers such as polyglutamate. Furthermore, the use of naturally occurring compounds, such as plant and food extracts, is one of the non-toxic and environmentally acceptable strategies for biocorrosion control and prevention [182, 183]. Most plants and food oils and aqueous extracts have the capability of inhibiting the actions of fungi, yeast, filamentous, and bacteria [184]. Many traditional food preservatives, antiseptics, and disinfectants, including ginger, cinnamon, black cumin, garlic, pepper, cumin, tamarind, onion, and others, have been shown to have antimicrobial effects [185, 186].

7.3 Coatings

One of the most effective strategies employed to prevent corrosion is by coating the system with corrosion-resistant materials. It has been reported that protective coating accounts for the majority of the total cost of corrosion control [187]. Since the introduction of biocorrosion as a disastrous phenomenon, protective coatings have been used as a major strategy in protecting surfaces from biocorrosion, particularly where the use of other measures are not efficient [187]. Protective coatings are commonly classified as inorganic or organic. Galvanizing and metalizing are examples of inorganic coatings, whereas organic coatings (also known as polymer coatings) include polyurethane, epoxy resins, acrylic resin, silicones, fluorinated compounds, and so on. Polymer coatings are well-known for their high corrosion resistance and barrier properties [188]. Good substrate/coating adhesion is necessary for enhanced protective ability and durability since the presence of moisture under a poorly bonded coating may possess microbial contaminations, and provide favorable conditions for microbial growth. Besides, defects or crevices of polymer coatings are preferential sites of localized corrosion [189]. In general, antibacterial and anticorrosion agents are added to the polymer matrix to give the polymer coatings biocidal and anticorrosion properties that inhibit bacterial adhesion, biofilm formation, and corrosion [118]. Also, the use of superhydrophobic coatings [190] and polymers that conduct electricity, such as polyaniline,

polypyrrole, and polythiophene, are used to prevent and control biocorrosion have been reported [181, 191].

7.4 Cathodic Protection

Cathodic protection is an efficient electrochemical method used in protecting steel substrates from oxidative corrosion [192, 193]. It entails applying an external opposing corrosion current to the target metal. The use of cathodic protection raises the pH at the metal/solution interface, resulting in the release of hydroxyl ions and a decrease in the solubility of magnesium and calcium compounds [150]. This causes the development of calcareous deposits. The interaction between the biofilms and the inorganic deposits lead to structural changes and re-distribution of the deposits. It results in the increment of the current needed to sustain protection. The galvanic anode system and impressed current system are the two ways of deploying cathodic protection. In the galvanic anode method, the protective current is applied to the destinated material attached to the low-potential galvanic anode. Because the galvanic anode is less durable, this method cannot be used in an environment where the material is actively corroded. The impressed current approach is used to apply the protective current from the DC power supply and is used as a long-term corrosion protection technique [194]. Cathodic protection is employed at buried and immersed storage tanks, pipelines, ship's hulls, cooling water systems, well-casting, reinforced concretes, offshore rigs and platforms, and flood defenses and lock gates.

8 MIC Prospects for the Oil and Gas Sector in Africa

In recent times, MIC has gained considerable global attention, but its prospect has not been fully elucidated for the African oil and gas sector. There is an utmost need to carefully highlight the information gap and areas of interest regarding MIC and make important recommendations for the African oil and gas sector.

Huge gaps in MIC research are known to exist, most of which are related to differences between laboratory and field studies. Others include the communication gap that exists between microbiologists, chemists, engineers, and electrochemists, as well as the gap between key published MIC research from laboratory experiments and few reproducible results [195].

It is important to acknowledge that laboratory experimental results have contributed immensely and provided a lot of interesting findings linked to microorganism-metal interactions and their respective media adopted. The list of microorganisms associated with MIC is growing, but the gaps in the everyday understanding of MIC are not. Many publications exist on most continents, but literature is particularly scarce in Africa, so MIC reports in the African oil and gas sector are uncommon. According to the MIC publications, alternating metal substrates and using microorganisms with various permutations of media conditions have failed to improve the fundamental understanding of MIC. Rather, some poorly designed and described experiments are published in the literature, cited and referenced in the next journal publication, and so on, prompting researchers to stop asking questions. For example, the cathodic depolarization theory (CDT) [196], which was first published many decades ago as a mechanism for MIC studies, has been frequently cited in the intervening years. Other reports [20, 21] carefully examined the CDT and concluded that the CDT for the role of SRB in carbon substrate corrosion was incorrect. According to Blackwood [197], despite the long history of MIC research, researchers are still not satisfied with its fundamental mechanisms, particularly in non-SRB anaerobes. Etim et al. [1] also clarified the significance of a new mechanism hypothesized by Gu [198], known as the biocatalytic cathodic sulfate reduction theory (BCSR). In the BCSR approach, MIC occurs primarily as a result of sulfate reduction reactions at the cathodic site, which accepts electrons donated at the anodic site via the iron dissolution process with the assistance of a biocatalyst and the interface of SRB biofilm [199, 200].

Another peculiar concern about the MIC mechanism is the role of interfacial electron transfer that occurs between the corroding substrate surface and the bacteria involved in MIC. Many issues concerning electrolyte composition and the number of redox mediators present in the system make this reaction complex and contentious. In laboratory experiments, microbial change of electrolytes, linked to either or both an alteration in the production of redox mediators or critical pitting potential, must be considered as the cause of corrosion-related changes.

In this regard, the government, industries, and researchers are expected to provide more insight into the need to mitigate the negative impact of MIC in the African oil and gas sector. Non-detection of MIC in the oil and gas industry could result in severe harm to humans, material loss, and environmental degradation caused by bacteria adhering to marine structures. Most importantly, the knowledge from MIC research will aid the government in providing funds in this area of research, as it will yield positive results in the various oil and gas sectors and avoid the unexpected effect as a result of negligence.

9 Conclusion

Generally, the trending issues regarding MIC research has been clearly elucidated in the course of the review. One of the pertinent issues of MIC as discussed is the deterioration

of metals within the oil and gas sector in Africa. The review further highlights the key information of MIC and its prospect for the oil and gas sector, the established characterisation techniques necessary for biocorrosion assessment in Africa, and the potential concerns that MIC possess to this sector. The detailed information reported in the study will assist governments and international organisations to seek proper ways to curb the menace of MIC.

10 Limitations of the Study

1. Limited information on MIC mechanism and its applications in recent years within African continent was a major issue, thus the similarities and differences in previous research was not detailed in the study.
2. Lack of available data on the material deterioration associated with MIC in oil and gas sector was another notable limitation.
3. Inadequate survey regarding each of the relevant oil and gas industry.

11 Recommendation for Future Studies

1. Government and multinational companies should collaborate with research institutes and provide enabling environments for MIC studies that will aid provide more useful information for further studies.
2. Adequate procedures for MIC mitigation in oil and gas sectors are recommended, for instance periodic maintenance, monitoring and the ideal use of bacteriostatic agents (such as chlorine-related compounds, phenolics, aldehydes, and quaternary ammonium sulphates compounds).
3. Periodic survey should be carried out within African continent to detect the MIC activities, its mechanism and proffer techniques to curb its spread.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose.

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