Pakistan J. Zool., pp 1-8, 2023. **DOI**: https://dx.doi.org/10.17582/journal.pjz/20230205110237

Severe Pitting Corrosion of Carbon Steel Caused by Sulfate Reducing Bacteria in Aqueous Medium

Sanaullah Sattar[1], Ali Hussain[2]*, Javed Iqbal Qazi[2], Arshad Javid[1] and Shahid Mehmood[1]

[1]Department of Wildlife and Ecology, University of Veterinary and Animal Sciences, Outfall Road, Lahore, Pakistan
[2]Institute of Zoology, University of the Punjab, Quaid-i-Azam Campus, Lahore, Pakistan
[3]Department of Poultry Production, University of Veterinary and Animal Sciences, Outfall Road, Lahore, Pakistan

ABSTRACT

The current study was conducted to assess the corrosive action of SRB on carbon steel coupons in aqueous media with and without the addition of nutrients of Postgate B medium. For the purpose, SRB strain was isolated from a highly polluted wastewater stream flowing in Lahore, Punjab, Pakistan. The bacterial isolate was motile, Gram-negative, non-spore former and identified as *Desulfovibrio vulgaris* after 18 S rRNA gene sequencing. The corrosive action of the bacteria was assessed in a 60-day trial of anaerobic incubation. After an incubation period of 60 days, it was found that CR was significantly higher for the coupons that were dipped in inoculated media. For these coupons, the average CR appeared as 210 ± 17 µg dm^{-2} d^{-1}. However, CR was significantly lower (210 ± 17 µg dm^{-2} d^{-1}) for the coupons dipped in inoculated water only (Fig. 2). In un-inoculated vials having nutrients, CR appeared higher (97 ± 16 µg dm^{-2} d^{-1}) as compared to those without nutrients (48 ± 21 µg dm^{-2} d^{-1}). Bacterial growth appeared higher in nutrient added vials. At termination of the experiments, total viable counts for SRB were 2.7 ± 0.3 × 10^{9} CFU mL^{-1} in vials supplemented with nutrients. However, no bacterial growth was seen in nutrient-deprived vials. No change in pH was observed in all vials except those which were inoculated under optimum provision of nutrients. In these vials, pH changed from neutral to slightly basic in range (7.0 ± 0.5 to 6.0 ± 0.5). SEM analysis of the coupon which was recovered from a vial supplemented with nutrients revealed severe pitting corrosion of the steel coupon. Our findings will be helpful in understanding and protecting bacterial corrosion of water-dipped metallic bodies.

Article Information
Received 05 February 2023
Revised 18 March 2023
Accepted 10 April 2023
Available online 01 June 2023
(early access)

Authors' Contribution
SS methodology. AH supervision. JIQ co-supervision. AJ data analysis. SM data compilation.

Key words
Bacterial corrosion, Biocorrosion, Biodeterioration and biodegradation, Biosulfidogens, Metal corrosion

INTRODUCTION

Microbiologically influenced corrosion (MIC) is a type of corrosion that is caused by the presence of microorganisms, such as bacteria, fungi, and algae. These microorganisms can produce various by-products, such as acids, gases, and enzymes, that can corrode metal surfaces (Usher *et al*., 2014; Kiani *et al*., 2019; Kokilaramani *et al*., 2021). One common type of MIC is sulfate-reducing bacterial (SRB) corrosion, which occurs when SRB use sulfates as an electron acceptor in their metabolism and produce hydrogen sulfide (H_2S) gas. The H_2S gas can then react with water and oxygen to form sulfuric acid, which can corrode metal surfaces (Dou *et al*., 2018; Gu *et al*., 2019; Luo *et al*., 2023).

It is difficult to quantify the exact annual cost of MIC globally, as it depends on a variety of factors such as the type of industry, the type of microorganisms involved, and the location of the corrosion. However, it is estimated that MIC can account for a significant portion of the total cost of corrosion, which is estimated to be around 3% of the global gross domestic product (GDP) (Yazdi *et al*., 2023; Zhu *et al*., 2023). In the United States, the total annual cost of corrosion is estimated to be around $276 billion, and it is believed that a significant portion of this cost is due to MIC (Bhaskaran *et al*., 2005; Thompson *et al*., 2007; Chevallier *et al*., 2023). In the oil and gas industry, MIC is a major concern as it can cause corrosion of pipelines and other infrastructure, leading to costly repairs and disruptions in service (Popoola *et al*., 2013; Askari *et al*.,

---

* Corresponding author: ali.zool@pu.edu.pk
0030-9923/2023/0001-0001 $ 9.00/0

2019). MIC can also cause corrosion in a variety of other industries, including the marine, water treatment, and power generation industries (Jia *et al*., 2019; Etim *et al*., 2022).

SRB can cause corrosion of a variety of metals, including iron, steel, copper, aluminum, and zinc (Zarasvand and Rai, 2014; Sun *et al*., 2017; Sattar *et al*., 2023). The type of corrosion that occurs can depend on the specific characteristics of the metal, the environment in which the corrosion takes place, and the type and concentration of SRB present (Beech and Sunner, 2007; Javaherdashti, 2011; Jia *et al*., 2019; Zhao *et al*., 2022). Some of the different types of corrosion that can be caused by SRB include pitting corrosion, crevice corrosion and galvanic corrosion (Lane, 2005; Alamri, 2020).

MIC can occur in a variety of environments, including marine, freshwater, soil, and industrial settings (Coetser and Cloete, 2005; Ibrahim *et al*., 2018). It can affect a wide range of metal structures, including pipelines, tanks, ships, and offshore platforms (Loto, 2017; Kannan *et al*., 2018). MIC can be difficult to detect and diagnose, as it often occurs in hidden or hard-to-reach areas and may not be visible until significant damage has already been done (Little *et al*., 2006; Xu *et al*., 2020). Keeping in view the metal-damaging potential of SRB, the current study was designed to isolate and characterize an indigenous SRB strain from wastewater and to check its corrosive action on a comparatively corrosion-resistant form of steel (carbon steel).

MATERIALS AND METHODS

Bacterial isolation and identification

The SRB species was isolated from a wastewater stream (Hudiara Drain) passing through Mohlanwal, Lahore, Pakistan. In order to isolate SRB, water (approximately 100 mL) was collected for the purpose, placed in a sterile glass container, and brought to the lab. Using the Postgate B medium (concentration in g L^{-1}: $CaSO_4$, 1.0; $FeSO_4.7H_2O$, 0.5; KH_2PO_4, 0.5; $MgSO_4.7H_2SO_4$, 2.0; NH_4Cl, 1.0; Ascorbic acid, 0.1; sodium lactate, 3.5; Thioglycolic acid, 0.1; yeast extract, 1.0) and the dilution-to-extinction technique described by Postgate (1984), the bacteria were isolated in deep agar.

Motility detection, Gram's staining, and endospore staining were used to phenotypically describe the bacterial pure culture. Following that, 16S rRNA gene sequencing was used to identify the bacterial strain at the molecular level. SRB growth was revived for this purpose in Postgate B medium. Following Hussain *et al.* (2014), total genomic DNA from freshly grown bacterial cells was isolated and amplified using universal primers [27f (5′-AGAGTTTGATCMTGGCTCAG-3′) and 1492r (5′-GGTTACCTTGTTACGACTT-3′)]. After that, the amplified gene was sequenced by Macrogen, Korea. Together with reference sequences retrieved from the NCBI GenBank database, a phylogenetic tree using neighbor-joining methods was constructed for the bacteria isolated for the current investigation.

After molecular identification, the bacterial growth was optimized for temperature, pH and inoculum size. Optimum growth was found at 30 °C in the medium having pH 7 and inoculated with 1.7×10^6 C.F.U. mL^{-1} of the medium.

Preparation of carbon steel coupons

Carbon steel coupons (CSCs) were the small pieces of CS that were used for studying corrosion. CSCs (1 × 1 × 0.1 cm) for the current study were obtained from the Department of Metallurgy and Materials Engineering, University of the Punjab, Lahore, Pakistan. First of all, the coupons were thoroughly cleaned with analytical grade acetone (Cat. No. 10014, Merck, Germany) following Bano (2008) to remove any dirt, oil, or other contaminants that could affect the corrosion rate (CR). The surface of the coupons was then prepared to ensure that the CR is uniform. This was done by polishing the surface of the coupons with polishing paper (Cat. No. WD240, Caswell, Taiwan). After polishing, the coupons were cleaned with a lint-free paper towel, washed with ethanol (Cat. No. 100983, Merck, Germany) and dried completely at 80 °C for 10 min in an electric oven. The weight of the coupons was then measured before and after the corrosion test to determine the amount of metal that has been lost due to corrosion following Zuo and Wood (2004).

Experimental design

The corrosive impact of SRB was studied in water with and without the provision of nutrients of Postgate B medium. The experiments were conducted in serum bottles of 20-mL capacity. For the purpose, half of the total serum bottles were filled upto the brim with Postgate B medium, while remaining half of the bottles were filled with distilled water. At start of the experimental trial, pH was adjusted between 7.0 and 7.5. After pH adjustment, one cleaned coupon was inserted in each bottle, all the bottles containing distilled water and postgate B medium were properly capped with butyl rubber stoppers, sealed with aluminum crimp seals, sterilized by autoclaving and cooled at room temperature. After this, half of these vials were inoculated with freshly cultivated SRB culture @ 5 % (v/v) harbouring around 1.7×10^6 C.F.U. mL^{-1}, while remaining vials were kept uninoculated as control group. All the vials were then incubated at 30 °C for 60 days.

At end of the testing period, coupons were extracted aseptically from the bottles. Following Angeles-Chavez *et al.* (2001), Clark's solution (Sb_2O_3, 20 g; $SnCl_2$, 50 g; HCl, 774 mL) was used to clean the coupons from corrosion products and other impurities. Clean coupons were thoroughly dried after rinsing in distilled water and weighed to determine weight reduction. After that, the rate of corrosion (µg dm^{-2} d^{-1}) was calculated using the following formula as reported by Majumdar *et al.* (1999).

$$C = \frac{W1 - W2}{AT}$$

Where, C represents CR (µg dm^{-2} d^{-1}), while W1 and W2 are initial and final weights of coupons, respectively. Surface area of the coupons and the experimental period (days) are represented by A and T, respectively.

After determining CR, SRB growth was also estimated in Postgate B medium following Postgate (1984).

Scanning electron microscopic analysis of the corroded coupon

In order to study surface morphology and type of corrosion, the corroded coupon was analyzed by SEM. To prepare a metal coupon for SEM analysis, the coupon was cleaned for the removal of any dirt or other contaminants. The coupon was then coated with a thin layer of palladium to make it electron-conductive. Once the coupon was prepared, it was placed in the SEM and scanned to generate an image of the surface. The SEM facility at Institute of Chemical Engineering and Technology, University of the Punjab, Lahore, was availed for the said purpose.

RESULTS AND DISCUSSION

The current study was conducted to assess the corrosive action of SRB on CSCs in aqueous media with and without the addition of nutrients of Postgate B medium. For the purpose, SRB strain was isolated from a highly polluted wastewater stream flowing in Lahore, Punjab, Pakistan. The bacterial isolate was motile, Gram-negative, non-spore former and identified as *Desulfovibrio vulgaris* after 18 S rRNA gene sequencing. A phylogenetic tree was constructed to show its neighbour-joining microbial species as shown in Figure 1. It is well known that SRB are commonly found in aquatic environments, including wastewaters and can contribute to the production of hydrogen sulfide gas, which has a strong, unpleasant odour (Karunakaran *et al*., 2016; Hamoda and Alshalahi, 2021; Jantharadej *et al*., 2021; Aalto *et al*., 2022). In polluted wastewaters, the presence of SRB can be an indicator of the presence of organic matter and can be used as a measure of the effectiveness of wastewater treatment processes. However, the presence of SRB in wastewaters can also have negative impacts. For example, the production of hydrogen sulfide can lead to corrosion of infrastructure, such as pipes and treatment facilities (Wiener and Salas, 2005; Foorginezhad *et al*., 2021; Wang *et al*., 2023).

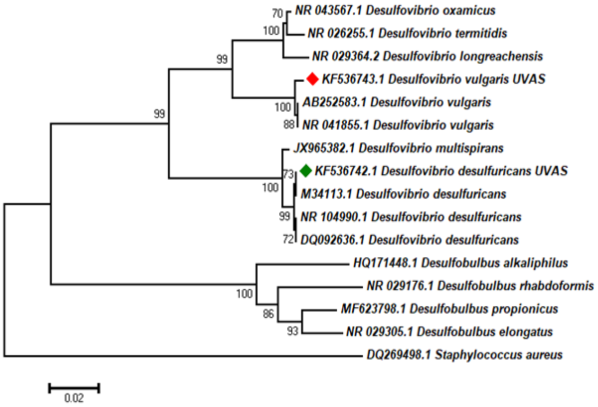

Fig. 1. Neighbour-joining phylogenetic tree of *Desulfovibrio vulgaris* isolated from Hudiara Drain for the current study along with reference sequences recovered from the NCBI GenBank database. The phylogenetic tree was derived from 16S rRNA gene sequences. Bootstrap support values at each node are indicated by numbers (percentage of 1,000 replicates). Values above 70% are displayed only. The bar represents 0.02 substitutions per nucleotide position. The bacterial isolate for the present investigation is spotted in red colour. *Staphylococcus aureus* was used as an outgroup.

After an incubation period of 60 days, it was found that CR was significantly higher for the coupons that were dipped in inoculated media. For these coupons, the average CR appeared as 210±17 µg dm^{-2} d^{-1}. However, CR was significantly lower (210±17 µg dm^{-2} d^{-1}) for the coupons dipped in inoculated water only (Fig. 2A). In un-inoculated vials having nutrients, CR appeared higher (97 ± 16 µg dm^{-2} d^{-1}) as compared to those without nutrients (48 ± 21 µg dm^{-2} d^{-1}) as shown in Figure 2B. In a previously reported study, CR was higher (249 ± 2 µg dm^{-2} d^{-1}) than that of current study (Sattar, 2023). In that study, incubation period, pH and temperature were similar to those of the current study. However, coupon composition and bacterial species were different. In that study, mild steel coupons were used instead of CSCs. In mild steel coupons, the lower percentage of carbon makes microbial action more stronger (Mehanna *et al*., 2009; Chaerun *et al*., 2023; Golafshani *et al*., 2023). In addition, the rate of corrosion is expected to vary both with the type and ecology of SRB (Beech and Sunner, 2007; Madirisha *et al*., 2022). There are several factors that can contribute to the corrosion of metal structures by SRB. These include the presence

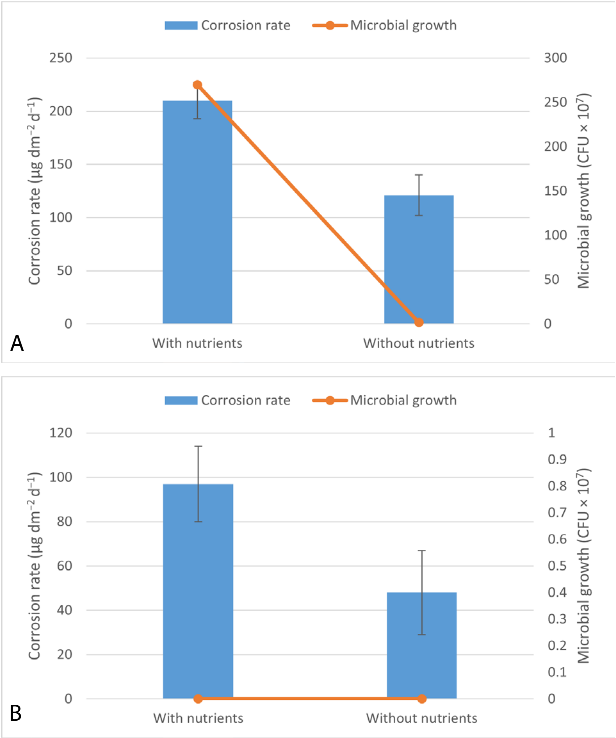

Fig. 2. Corrosion rate and SRB growth pattern in inoculated (A) and un-inoculated (B) vials with and without nutrients after an incubation period of 60 days.

of organic matter that can serve as a food source for the bacteria, the pH and temperature of the environment, and the availability of nutrients such as sulfur and hydrogen (AlAbbas *et al*., 2013; Enning and Garrelfs, 2014; Lv *et al*., 2021). CR can also be influenced by the type of metal, the presence of other microorganisms, and the presence of other corrosive agents (Javaherdashti, 2011; Jia *et al*., 2019; Zhao *et al*., 2022).

SRB growth appeared higher in nutrient added vials. At termination of the experiments, total viable counts for SRB were 2.7 ± 0.3 × 10^9 CFU mL^{-1} in vials supplemented with nutrients. However, no bacterial growth was observed in nutrient-deprived vials. No change in pH was observed in all vials except those which were inoculated under optimum provision of nutrients. In these vials, pH changed from neutral to slightly basic in range (7.0 ± 0.5 to 6.0 ± 0.5). It has been reported that during SRB growth, medium pH changes towards alkalinity (Hussain and Qazi, 2016; Hussain *et al*., 2016).

At termination of the experiment, of all the coupons, a highly corroded coupon was analyzed through SEM. SEM analysis of the coupon which was recovered from a vial supplemented with nutrients revealed severe pitting corrosion of CS (Fig. 3). Pitting corrosion of CS by SRB

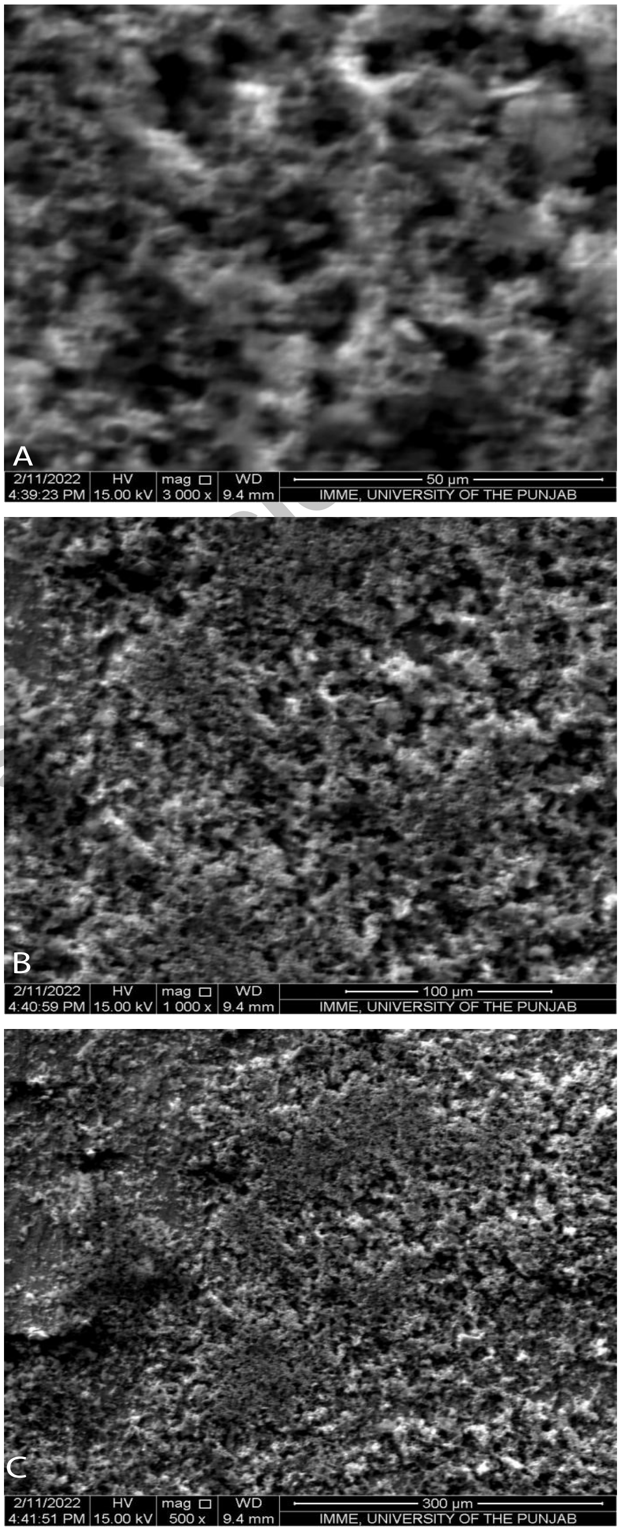

Fig. 3. SEM analysis of the corroded metallic coupon showing severe pitting corrosion at different magnification powers, 50 µm (A), 100 µm (B) and 300 µm (C).

can be a serious problem in certain environments, particularly in the oil and gas industry (Wang and Melchers, 2017; Kannan *et al*., 2018; Qi *et al*., 2023; Wan *et al*., 2023; Zulkafli *et al*., 2023). SRB consume sulfates as a source of energy and produce hydrogen sulfide as a byproduct. This hydrogen sulfide can react with the iron in CS to form iron sulfide, which can lead to pitting corrosion (Sherar *et al*., 2011; AlAbbas *et al*., 2013; Giorgi-Pérez *et al*., 2021). Pitting corrosion is a type of localized corrosion that occurs when small, deep pits form on the surface of the metal. These pits can weaken the metal and make it more susceptible to failure (Frankel and Sridhar, 2008; Alamri, 2020; Messinese *et al*., 2022).

CONCLUSION

In the current study, severe pitting corrosion of carbon steel was caused by SRB and observed in nutrient-supplemented vials. The pits on the coupon surface were studied by SEM. In order to prevent pitting corrosion caused by SRB, it is important to control the presence of these bacteria in the environment. This can be achieved through the use of biocides, which are chemicals that are toxic to bacteria. It is also important to maintain the pH of the environment at a level that is not conducive to the growth of SRB. In addition, using corrosion-resistant materials or coatings can help to protect CS from pitting corrosion caused by SRB.

ACKNOWLEDGEMENT

We acknowledge the support of Department of Metallurgy and Materials Engineering, University of the Punjab, Lahore, Pakistan, for providing mild steel coupons.

Funding

The study received no funding.

IRB approval

The current research work was approved by Board of Studies of Department of Wildlife and Ecology, University of Veterinary and Animal Sciences, Lahore.

Ethical statement

The current research work didn't involve any animal model and thus ethical statement was not needed.

Statement of conflict of interest

The authors have declared no conflict of interest.

REFERENCES

Aalto, S.L., Suurnäkki, S., von Ahnen, M., Tiirola, M. and Pedersen, P.B., 2022. Microbial communities in full-scale woodchip bioreactors treating aquaculture effluents. *J. environ. Manage*., **301**: 113852. https://doi.org/10.1016/j.jenvman.2021.113852

AlAbbas, FM., Williamson, C., Bhola, S.M., Spear, J.R., Olson, D.L., Mishra, B. and Kakpovbia, A.E., 2013. Influence of sulfate reducing bacterial biofilm on corrosion behavior of low-alloy, high-strength steel (API-5L X80). *Int. Biodeterior. Biodegrad*., **78**: 34-42. https://doi.org/10.1016/j.ibiod.2012.10.014

Alamri, A.H., 2020. Localized corrosion and mitigation approach of steel materials used in oil and gas pipelines. An overview. *Eng. Fail. Anal*., **116**: 104735. https://doi.org/10.1016/j.engfailanal.2020.104735

Angeles-Chavez, C., Romero, J.M., Amaya, M., Martinez, L. and Perez, R., 2001. New strain of anaerobic bacteria and its association with corrosion pitting of X52 pipeline steel. *Br. Corros. J*., **36**: 292-296. https://doi.org/10.1179/000705901101501631

Askari, M., Aliofkhazraei, M. and Afroukhteh, S.A., 2019. Comprehensive review on internal corrosion and cracking of oil and gas pipelines. *J. Nat. Gas. Sci. Eng*., **71**: 102971. https://doi.org/10.1016/j.jngse.2019.102971

Bano, A.S., 2008. *Microbiologically influenced corrosion of buried mild steel pipes and its prevention through bacterial antibiosis*. PhD thesis, University of the Punjab, Lahore, Pakistan.

Beech, I.B. and Sunner, J., 2007. Sulphate-reducing bacteria and their role in corrosion of ferrous materials. In: *Sulphate-reducing bacteria environmental and engineered systems*. Cambridge University Press, Cambridge, UK, pp. 459-482. https://doi.org/10.1017/CBO9780511541490.017

Bhaskaran, R., Palaniswamy, N., Rengaswamy, N.S. and Jayachandran, M., 2005. Global cost of corrosion. A historical review. *Corros. Mater*., **13**: 621-628. https://doi.org/10.31399/asm.hb.v13b.a0003968

Chaerun, S.K., Rizki, I.N., Hartomo, W.A. and Widyanto, B., 2023. Biocorrosion behaviour of carbon steels by tropical microbes in the presence of corrosion-inhibiting bacterium. *Hayati J. Biosci*., **30**: 1-6. https://doi.org/10.4308/hjb.30.1.1-16

Chevallier, E., Augée, L., Boyer, Q., Labeau, M.P. and Moreau, P., 2023. Fast optimization of polymers to boost adhesion and corrosion prevention in hexafluoride conversion coatings for aluminium. *J. Mater. Sci*., **1**: 1-4. https://doi.org/10.1007/s10853-022-08071-1

Coetser, S.E. and Cloete, T.E., 2005. Biofouling and biocorrosion in industrial water systems. *Crit. Rev. Microbiol*., **31**: 213-232. https://doi.org/10.1080/10408410500304074

Dou, W., Jia, R., Jin, P., Liu, J., Chen, S. and Gu, T., 2018. Investigation of the mechanism and characteristics of copper corrosion by sulfate reducing bacteria. *Corros. Sci*., **144**: 237-248. https://doi.org/10.1016/j.corsci.2018.08.055

Enning, D. and Garrelfs, J., 2014. Corrosion of iron by sulfate-reducing bacteria: New views of an old problem. *Appl. environ. Microbiol*., **80**: 1226-1236. https://doi.org/10.1128/AEM.02848-13

Etim, I.I., Njoku, D.I., Uzoma, P.C., Kolawole, S.K., Olanrele, O.S., Ekarenem, O.O., Okonkwo, B.O., Ikeuba, A.I., Udoh, I.I., Njoku, C.N. and Etim, I.P., 2022. Microbiologically influenced corrosion: A concern for oil and gas sector in Africa. *Chem. Afr*., **3**: 1-26. https://doi.org/10.1007/s42250-022-00550-x

Foorginezhad, S., Mohseni-Dargah, M., Firoozirad, K., Aryai, V., Razmjou, A., Abbassi, R., Garaniya, V., Beheshti, A. and Asadnia, M., 2021. Recent advances in sensing and assessment of corrosion in sewage pipelines. *Process Saf. environ. Prot*., **147**: 192-213. https://doi.org/10.1016/j.psep.2020.09.009

Frankel, G.S. and Sridhar, N., 2008. Understanding localized corrosion. *Mater. Today*, **11**: 38-44. https://doi.org/10.1016/S1369-7021(08)70206-2

Giorgi-Pérez, A.M., Arboleda-Ordoñez, A.M., Villamizar-Suárez, W., Cardeñosa-Mendoza, M., Jaimes-Prada, R., Rincón-Orozco, B. and Niño-Gómez, M.E., 2021. Biofilm formation and its effects on microbiologically influenced corrosion of carbon steel in oilfield injection water via electrochemical techniques and scanning electron microscopy. *Bioelectrochemistry*, **141**: 107868. https://doi.org/10.1016/j.bioelechem.2021.107868

Golafshani, M.G., Tavakoli, H., Hosseini, S.A. and Akbari, M., 2023. MD and DFT computational simulations of Caffeoylquinic derivatives as a bio-corrosion inhibitor from quince extract with experimental investigation of corrosion protection on mild steel in 1M H_2SO_4. *J. mol. Struct*., **1275**: 134701. https://doi.org/10.1016/j.molstruc.2022.134701

Gu, T., Jia, R., Unsal, T. and Xu, D., 2019. Toward a better understanding of microbiologically influenced corrosion caused by sulfate reducing bacteria. *J. Mater. Sci. Technol*., **35**: 631-636. https://doi.org/10.1016/j.jmst.2018.10.026

Hamoda, M.F. and Alshalahi, S.F., 2021. Assessment of hydrogen sulfide emission in a wastewater pumping station. *Environ. Monitor. Assess*., **193**: 1-6. https://doi.org/10.1007/s10661-021-09116-9

Hussain, A., Hasan, A., Javid, A. and Qazi, J.I., 2016. Exploited application of sulfate-reducing bacteria for concomitant treatment of metallic and non-metallic wastes: A mini review. *3 Biotech*, **6**: 119. https://doi.org/10.1007/s13205-016-0437-3

Hussain, A., Shakir, H.A. and Qazi, J.I., 2014. Anaerobic biodegradation of sulphate employing animal manure as a cost-effective growth substrate. *J. Anim. Pl. Sci*., **24**: 913-918.

Ibrahim, A., Hawboldt, K., Bottaro, C. and Khan, F., 2018. Review and analysis of microbiologically influenced corrosion: the chemical environment in oil and gas facilities. *Corros. Engi. Sci. Technol*., **53**: 549-563. https://doi.org/10.1080/1478422X.2018.1511326

Jantharadej, K., Limpiyakorn, T., Kongprajug, A., Mongkolsuk, S., Sirikanchana, K. and Suwannasilp, B.B., 2021. Microbial community compositions and sulfate-reducing bacterial profiles in malodorous urban canal sediments. *Arch. Microbiol*., **203**: 1981-1993. https://doi.org/10.1007/s00203-020-02157-7

Javaherdashti, R., 2011. Impact of sulphate-reducing bacteria on the performance of engineering materials. *Appl. Microbiol. Biotechnol*., **91**: 1507-1517. https://doi.org/10.1007/s00253-011-3455-4

Jia, R., Unsal, T., Xu, D., Lekbach, Y. and Gu, T., 2019. Microbiologically influenced corrosion and current mitigation strategies: A state of the art review. *Int. Biodeterior. Biodegrad*., **137**: 42-58. https://doi.org/10.1016/j.ibiod.2018.11.007

Kannan, P., Su, S.S., Mannan, M.S., Castaneda, H. and Vaddiraju, S., 2018. A review of characterization and quantification tools for microbiologically influenced corrosion in the oil and gas industry: current and future trends. *Ind. Eng. Chem. Res*., **57**: 13895-13922. https://doi.org/10.1021/acs.iecr.8b02211

Karunakaran, E., Vernon, D., Biggs, C.A., Saul, A., Crawford, D. and Jensen, H., 2016. Enumeration of sulphate-reducing bacteria for assessing potential for hydrogen sulphide production in urban drainage systems. *Water Sci. Technol*., **73**: 3087-3094. https://doi.org/10.2166/wst.2016.026

Kiani, Khouzani, M., Bahrami, A., Hosseini-Abari, A., Khandouzi, M. and Taheri, P., 2019. Microbiologically influenced corrosion of a pipeline in a petrochemical plant. *Metals*, **9**: 459.

https://doi.org/10.3390/met9040459

Kokilaramani, S., Al-Ansari, M.M., Rajasekar, A., Al-Khattaf, F.S., Hussain, A. and Govarthanan, M., 2021. Microbial influenced corrosion of processing industry by re-circulating waste water and its control measures. A review. *Chemosphere*, **265**: 129075. https://doi.org/10.1016/j.chemosphere.2020.129075

Lane, R.A., 2005. Under the microscope: Understanding, detecting, and preventing microbiologically influenced corrosion. *J. Fail. Anal. Prev*., **5**: 10-12. https://doi.org/10.1361/154770205X65891

Little, B.J., Lee, J.S. and Ray, R.I., 2006. Diagnosing microbiologically influenced corrosion: A state of the art review. *Corrosion*, **62**: 1006-1017. https://doi.org/10.5006/1.3278228

Loto, C.A., 2017. Microbiological corrosion: Mechanism, control and impact. A review. *Int. J. Adv. Manuf. Technol*., **92**: 4241-4252. https://doi.org/10.1007/s00170-017-0494-8

Luo, R., Jiang, Y., Von, Lau, E. and Wu, G., 2023. Microscopic influence mechanisms of polysaccharide on the adsorption and corrosion inhibition performance of imidazoline on metal surface. *Appl. Surf. Sci*., **613**: 155798. https://doi.org/10.1016/j.apsusc.2022.155798

Lv, M., Chen, X., Li, Z. and Du, M., 2021. Effect of sulfate-reducing bacteria on hydrogen permeation and stress corrosion cracking behavior of 980 high-strength steel in seawater. *J. Mater. Sci. Technol*., **92**: 109-119. https://doi.org/10.1016/j.jmst.2021.02.039

Madirisha, M., Hack, R. and Van der Meer, F., 2022. The role of organic acid metabolites in geo-energy pipeline corrosion in a sulfate reducing bacteria environment. *Heliyon*, **20**: e09420. https://doi.org/10.1016/j.heliyon.2022.e09420

Majumdar, I., D'Souza, F. and Bhosle, N.B., 1999. Microbial exopolysaccharides, effect on corrosion and partial chemical characterization. *J. Indian Inst. Sci*., **79**: 539-550.

Mehanna, M., Basséguy, R., Délia, M.L. and Bergel, A., 2009. Effect of Geobacter sulfurreducens on the microbial corrosion of mild steel, ferritic and austenitic stainless steels. *Corros. Sci*., **51**: 2596-2604. https://doi.org/10.1016/j.corsci.2009.06.041

Messinese, E., Casanova, L., Paterlini, L., Capelli, F., Bolzoni, F., Ormellese, M. and Brenna, A., 2022. A comprehensive investigation on the effects of surface finishing on the resistance of stainless steel to localized corrosion. *Metals*, **12**:1751. https://doi.org/10.3390/met12101751

Popoola, L.T., Grema, A.S., Latinwo, G.K., Gutti, B. and Balogun, A.S., 2013. Corrosion problems during oil and gas production and its mitigation. *Int. J. Ind. Chem*., **4**: 1-5. https://doi.org/10.1186/2228-5547-4-35

Postgate, J.R., 1984. *The sulfate-reducing bacteria*. Cambridge University Press, Cambridge.

Qi, H., Shi, Q., Peng, R., Sun, T., Zhang, Z., Li, L. and Xie, X., 2023. Effect of one sulfate-reducing bacterium SRB-Z isolated from Pearl River on the corrosion behavior of Q235 carbon steel. *Coatings*, **13**: 478. https://doi.org/10.3390/coatings13020478

Sattar, S., 2023. *Corrosive impact of sulphate-reducing bacteria on mild and carbon steels in fluid, semi-fluid and solid media*. PhD thesis, University of Veterinary and Animal Sciences, Lahore, Pakistan.

Sattar, S., Hussain, A., Qazi, J.I., Javid, A., and Mehmood, S., 2023. Sulfate reducing bacterial corrosion of mild steel in liquid and solid media. *Pakistan J. Zool*., 7 pages. https://doi.org/10.17582/journal.pjz/20220713160735

Sherar, B.W., Power, I.M., Keech, P.G., Mitlin, S., Southam, G. and Shoesmith, D.W., 2011. Characterizing the effect of carbon steel exposure in sulfide containing solutions to microbially induced corrosion. *Corros. Sci*., **53**: 955-960. https://doi.org/10.1016/j.corsci.2010.11.027

Sun, H., Shi, B., Yang, F. and Wang, D., 2017. Effects of sulfate on heavy metal release from iron corrosion scales in drinking water distribution system. *Water Res*., **114**: 69-77. https://doi.org/10.1016/j.watres.2017.02.021

Thompson, N.G., Yunovich, M. and Dunmire, D., 2007. Cost of corrosion and corrosion maintenance strategies. *Corros. Rev*., **25**: 247-262. https://doi.org/10.1515/CORRREV.2007.25.3-4.247

Usher, K.M., Kaksonen, A.H., Cole, I. and Marney, D., 2014. Critical review: Microbially influenced corrosion of buried carbon steel pipes. *Int. Biodeterior. Biodegrad*., **93**: 84-106. https://doi.org/10.1016/j.ibiod.2014.05.007

Wan, H., Zhang, T., Xu, Z., Rao, Z., Zhang, G., Li, G. and Liu, H., 2023. Effect of sulfate reducing bacteria on the galvanic corrosion behavior of X52 carbon steel and 2205 stainless steel bimetallic couple. *Corros. Sci*., **7**: 110963. https://doi.org/10.1016/j.corsci.2023.110963

Wang, N., Fang, H., Xue, B., Wu, R., Fang, R., Hu, Q. and Lv, Y., 2023. Automatic damage segmentation framework for buried sewer pipes based on machine vision: case study of sewer pipes in Zhengzhou, China. *J. Infrastruct. Syst*., **29**(1): 04022046. https://

doi.org/10.1061/(ASCE)IS.1943-555X.0000729

Wang, X. and Melchers, R.E., 2017. Long-term under-deposit pitting corrosion of carbon steel pipes. *Ocean. Eng.*, **133**: 231-243. https://doi.org/10.1016/j.oceaneng.2017.02.010

Wiener, M.S., and Salas, B.V., 2005. Corrosion of the marine infrastructure in polluted seaports. *Corros. Eng. Sci. Technol.*, **40**: 137-142. https://doi.org/10.1179/174327805X46931

Xu, Y., Dhaouadi, Y., Stoodley, P. and Ren, D., 2020. Sensing the unreachable: Challenges and opportunities in biofilm detection. *Curr. Opin. Biotechnol.*, **64**: 79-84. https://doi.org/10.1016/j.copbio.2019.10.009

Yazdi, M., Khan, F. and Abbassi, R., 2023. A dynamic model for microbiologically influenced corrosion (MIC) integrity risk management of subsea pipelines. *Ocean. Eng.*, **269**: 113515. https://doi.org/10.1016/j.oceaneng.2022.113515

Zarasvand, K.A. and Rai, V.R., 2014. Microorganisms: Induction and inhibition of corrosion in metals. *Int. Biodeterior. Biodegrad.*, **87**: 66-74. https://doi.org/10.1016/j.ibiod.2013.10.023

Zhao, J.L., Sun, D., Arroussi, M., Lian, T.Y., Zhang, X.R., Yang, C.G. and Yang, K., 2022. Effect of anodic polarization treatment on microbiologically influenced corrosion resistance of Cu-bearing stainless steel against marine *Pseudomonas aeruginosa*. *Corros. Sci.*, **207**: 110592. https://doi.org/10.1016/j.corsci.2022.110592

Zhu, Z., Chu, H., Guo, M.Z., Zeng, Y., Li, X., Yu, X., Xiao, H. and Wang, P., 2023. Antibacterial performance of electrodeposited Cu@ Cu_2O coatings on concrete using printed circuit board wastewater. *J. Clean. Prod.*, **383**: 135373. https://doi.org/10.1016/j.jclepro.2022.135373

Zulkafli, R., Othman, N.K., Yaakob, N., 2023. Localised corrosion of API 5L X65 carbon Steel in marine environments: The role of sulfate-reducing bacteria (SRB). *J. Bio Tribo-Corros.*, **9**: 12. https://doi.org/10.1007/s40735-022-00730-9

Zuo, R. and Wood, T.K., 2004. Inhibiting mild steel corrosion from sulfate-reducing and iron-oxidizing bacteria using gramicidin-S-producing biofilms. *Appl. Microbiol. Biotechnol.*, **65**: 747-753. https://doi.org/10.1007/s00253-004-1651-1