microbiology research

MDPI

Article

Indicators of the Microbial Corrosion of Steel Induced by Sulfate-Reducing Bacteria Under the Influence of Certain Drugs

Nataliia Tkachuk [1,*], Liubov Zelena [2] and Yaroslav Novikov [1]

[1] Department of Biology, T.H. Shevchenko National University "Chernihiv Colehium", 14013 Chernihiv, Ukraine; y.novikov@chnpu.edu.ua
[2] Department of Virus Reproduction, Danylo Zabolotny Institute of Microbiology and Virology, NAS of Ukraine, 03680 Kyiv, Ukraine; zelena@nas.gov.ua
* Correspondence: n.tkachuk@chnpu.edu.ua; Tel.: +380-661730260

Abstract: Microorganisms cause microbiologically influenced corrosion, for the prevention of which bactericide inhibitors are used. The aim of the work was to study in vitro the sensitivity of SRB *Desulfovibrio oryzae* NUChC SRB1 to different concentrations of dimethyl sulfoxide (DMSO), and evaluate the indicators of the microbial corrosion of steel induced by this bacterium in the presence of the pharmaceutical drugs DMSO and paracetamol. The sensitivity of SRB *D. oryzae* to 1–100% DMSO (*v*/*v*) was studied via the dilution method in Postgate's "C" liquid medium. The corrosion activity of *D. oryzae* against steel 3 was investigated under DMSO and paracetamol treatment at a final concentration of 45% (*v*/*v*) and 0.2% (*w*/*v*), respectively, according to the ability of bacteria to form a biofilm on the surface of the steel samples (via the crystal violet method) and the effect on the corrosion rate (via the gravimetric method). It was revealed that DMSO affected *D. oryzae* NUChC SRB1 and exhibited bactericidal properties (at a concentration range of 10–100%, *v*/*v*) and antibiofilm properties (at a concentration of 45%, *v*/*v*). Despite its antibiofilm properties confirmed by the reduction in bacterial biofilm mass, anticorrosion features were not observed in the model 35-day conditions of the microbial corrosion of steel in an anaerobic environment with bacterial sulfate reduction. Paracetamol (0.2%, *w*/*v*) did not affect biofilm formation by SRB under these conditions, and significantly contributed to an increase in the rate of the microbial corrosion of steel. The prospect of further research is to assess the effect of DMSO and paracetamol on the indicators of microbial corrosion induced by SRB under the influence of the concentrations of these compounds found in wastewater, to clarify the possible additional causes of damage to the equipment of treatment plants. Further research should also be directed at investigating the antimicrobial properties of complexes of compounds with DMSO, which should be considered as an ecological solution to the problem of microbiologically influenced corrosion prevention.

Keywords: bactericide; biofilm; dimethyl sulfoxide; microbiologically influenced corrosion; paracetamol; sulfate-reducing bacteria

Academic Editor: Juan Ayala

Received: 26 December 2024
Revised: 12 January 2025
Accepted: 14 January 2025
Published: 16 January 2025

Citation: Tkachuk, N.; Zelena, L.; Novikov, Y. Indicators of the Microbial Corrosion of Steel Induced by Sulfate-Reducing Bacteria Under the Influence of Certain Drugs. *Microbiol. Res.* **2025**, *16*, 21. https://doi.org/10.3390/microbiolres16010021

1. Introduction

The microbiologically influenced corrosion (MIC) of metals and steels develops under the influence of microorganisms belonging to various ecological trophic groups [1–4]. At the same time, a significant part of research on this issue emphasizes the drastic role of sulfate-reducing bacteria (SRB) in this process [5–8]. The involvement of SRB in MIC processes occurs through various mechanisms, including participation in electrochemical reactions, the formation of corrosion-active compounds, and biofilms [9]. Bacterial biofilms

are developed on solid surfaces and are the advantageous form of microorganism growth compared to the free-floating (planktonic) form, providing bacterial population with some benefits such as resistance to bactericides [10–13]. Bactericides with anticorrosion properties are bioactive compounds, and are used to protect against MIC [14–16]. When choosing an MIC bactericide inhibitor, its antibiofilm properties may be an advantage [16–18]. Currently, various drugs are studied as possible antimicrobial and anticorrosive agents [19–21] as a part of the "green" solution [21]. Different approaches are used to analyze the effects of various chemical compounds. To predict the effects in natural and industrial aquatic and soil environments, microbial toxicity tests were suggested as additional to other laboratory tests, in particular, biodegradation tests [22]. Various standardized tests are recommended to detect toxicity, and luminescent bacteria are used as organism indicators of contamination [22,23]. Standardized anaerobic bacterial inhibition tests are being considered, in particular by determining biogas production [22]. However, the agar dilution method and broth microdilution method are also recommended for determining the antimicrobial susceptibility of anaerobic bacteria [24]. In particular, the serial dilution method is sensitive and provides good results of the antimicrobial properties of chemical compounds against bacteria-agents of MIC [25].

Dimethyl sulfoxide (DMSO) and paracetamol are bioactive compounds and possess antibacterial [26–28], antibiofilm [29–32], anticorrosive [33–36], and toxic [37–39] properties. DMSO (Figure 1) is a chemically synthesized, widely used solvent that is also used in medicine, pharmacology, and cosmetology [40–43], and is a by-product of the wood industry [44], contained in wastewater of some industries [37,45], and also found in the environment as a result of dimethyl sulfide oxidation in water and soil [40,46].

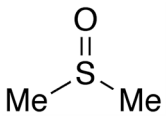

Figure 1. Structural formula of dimethyl sulfoxide (Me—methyl) [47].

Paracetamol (acetaminophen) (Figure 2) is a pharmaceutical drug widely used in medical practice [48].

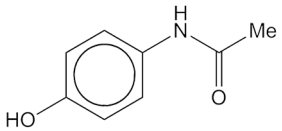

Figure 2. Structural formula of paracetamol (acetaminophen) (Me—methyl) [49].

Paracetamol is one of the most popular drugs that relieves pain and fever [48], and is found in surface waters, groundwater, and wastewater [50]. Given the antibacterial and antibiofilm properties of DMSO and paracetamol for a number of bacteria, it is appropriate to investigate their effect on the process of MIC, with an emphasis on SRB as the main component of sulfidogenic corrosively active communities [3]. This study also has special significance for its the information on the anticorrosive properties of DMSO and paracetamol.

Previously, *Desulfovibrio oryzae* strain NUChC SRB1 was isolated from the ferrosphere of a steel structure that corroded in the soil and identified [51]; its biofilm-forming properties on artificial polymeric materials polyethylene terephthalate [52,53] and polypropylene [54] were investigated. The sensitivity of *D. oryzae* NUChC SRB1 to different concentrations of DMSO in vitro and the indicators of the microbial corrosion of steel induced by this bacterium in the presence of DMSO or paracetamol have not been studied, which determined

the aim of this study. In this study, the minimum inhibitory and bactericidal concentrations of DMSO against *D. oryzae* NUChC SRB1 were studied in vitro; additionally, the impact of DMSO and paracetamol on *D. oryzae* NUChC SRB1 and its ability to form biofilm on steel 3 and induce the corrosion process in an anaerobic environment with bacterial sulfate reduction were evaluated. The obtained results deepen the knowledge in the field of microbiologically influenced corrosion caused by SRB in the presence of biologically active compounds.

2. Materials and Methods

2.1. Bacterial Strain, Medium, and Cultivation Conditions

A 5-day-old culture of *D. oryzae* strain NUChC SRB1 (accession number in GenBank is MT102713.1) [51] with a turbidity of 0.5 McFarland was prepared in sterile 0.85% NaCl. The liquid Postgate's "C" medium was used in the experiments [55]. The composition is given in Table 1.

Table 1. Composition of Postgate's "C" medium (the main medium) [55].

Compound	Mass, g/L of Distilled Water
KH_2PO_4	0.5
NH_4Cl	1.0
Na_2SO_4	4.5
$CaCl_2 \times 6H_2O$	0.06
$MgSO_4 \times 7H_2O$	0.06
sodium lactate	3.5
sodium citrate	0.3

Additional solutions were sterilized separately (0.5 atm for 20 min), which were added to the main sterile medium immediately before inoculation: yeast extract 5% solution (add 10 mL/L of main medium), $FeSO_4 \times 7H_2O$ 5% solution in 1% hydrochloric acid (add 10 mL/L of main medium); 1 mM $Na_2S \times 9H_2O$ or 1 g of sodium ascorbate with 0.5 mL of a 1% solution $Na_2S \times 9H_2O$ in a 1% solution of $NaHCO_3$. The nutrient medium should be transparent. The pH of the medium at a level of 7.5 provided neutralization with a 5% solution of HCl or sodium carbonate [55]. An indicator of the development of SRB was the blackening of the culture medium. Cultivation took place under anaerobic conditions and at a temperature of 29 ± 2 °C.

2.2. Medicinal Products Used in the Study

The medicinal product "Dimexide" (manufactured by PJSC "Galychpharm", Lviv, Ukraine), containing 100% DMSO, was used in further studies.

The medicinal product "Infulgan" (manufactured by LLC "Yuria-Pharm", Kyiv, Ukraine), containing 10 mg/mL paracetamol in an aqueous solution with excipients citric acid monohydrate, sodium citrate, sorbitol (E 420), and sodium sulfite anhydrous (E 221), was used in further studies.

2.3. Study of the Sensitivity of SRB to DMSO

The study on the sensitivity of *D. oryzae* strain NUChC SRB1 to aqueous DMSO solutions was carried out by the dilution method. In the first series of experiments (first passage), 10% of the volume of a 5-day culture of *D. oryzae* NUChC SRB1 (0.5 McFarland) was added to tubes with sterile liquid Postgate's "C" medium and an appropriate concentration of DMSO (from 1% to 100% *v*/*v*) to obtain a final bacterial cell count of 1.5×10^7 cells/mL. In the first series of experiments, the minimum inhibitory concentration of DMSO was

determined as the lowest concentration at which no growth of SRB was observed. In the second series of experiments (second passage), solutions from the tubes of the first series were subcultured into tubes with sterile liquid Postgate's "C" medium and the minimum bactericidal concentration of DMSO was determined as the lowest concentration at which bacterial growth did not occur after subculture. The cultivation in both series of studies lasted 14 days. The blackening of the medium was used as an indicator of SRB growth.

The scheme of the experiment to study the sensitivity of SRB to DMSO is presented in Figure 3.

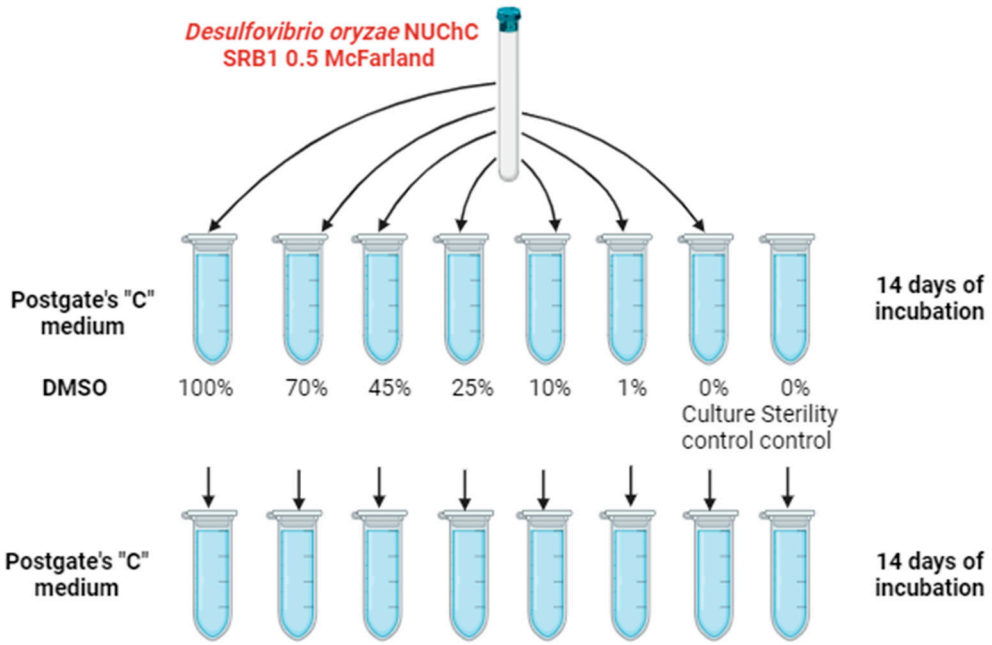

Figure 3. Scheme of the experiment to study the sensitivity of SRB to DMSO.

2.4. Study of Microbiologically Influenced Corrosion Indicators Under the Influence of DMSO and Paracetamol

The indicators of microbiologically influenced corrosion under the influence of DMSO and paracetamol were studied using steel samples 3 of size 20 × 20 × 2.5 mm. The samples were sterilized with 96% ethyl alcohol for 1 min, washed with sterile distilled water, and placed into sterile liquid Postgate's "C" medium. A 5-day culture of *D. oryzae* NUChC SRB1 (0.5 McFarland) was added into experimental tubes with the steel samples in an amount of 2% of the total volume. The final concentration of DMSO in the experimental tubes was 45% (*v*/*v*), and paracetamol was 0.2% (*w*/*v*). Cultivation lasted 35 days at a temperature of 29 ± 2 °C. After cultivation, the biomass of the biofilm and the corrosion rate were determined.

To determine the biomass of the biofilm formed by the SRB on the surface of the steel samples, the crystal violet dye adsorption/desorption method, described earlier, was used [54].

The corrosion rate of the samples (W, mg/m^2 × h) was determined via the gravimetric method based on determining the difference in the sample mass before and after the experiment, and taking into account the sample surface area and the experiment time [56].

The scheme of the experiment is presented in Figure 4.

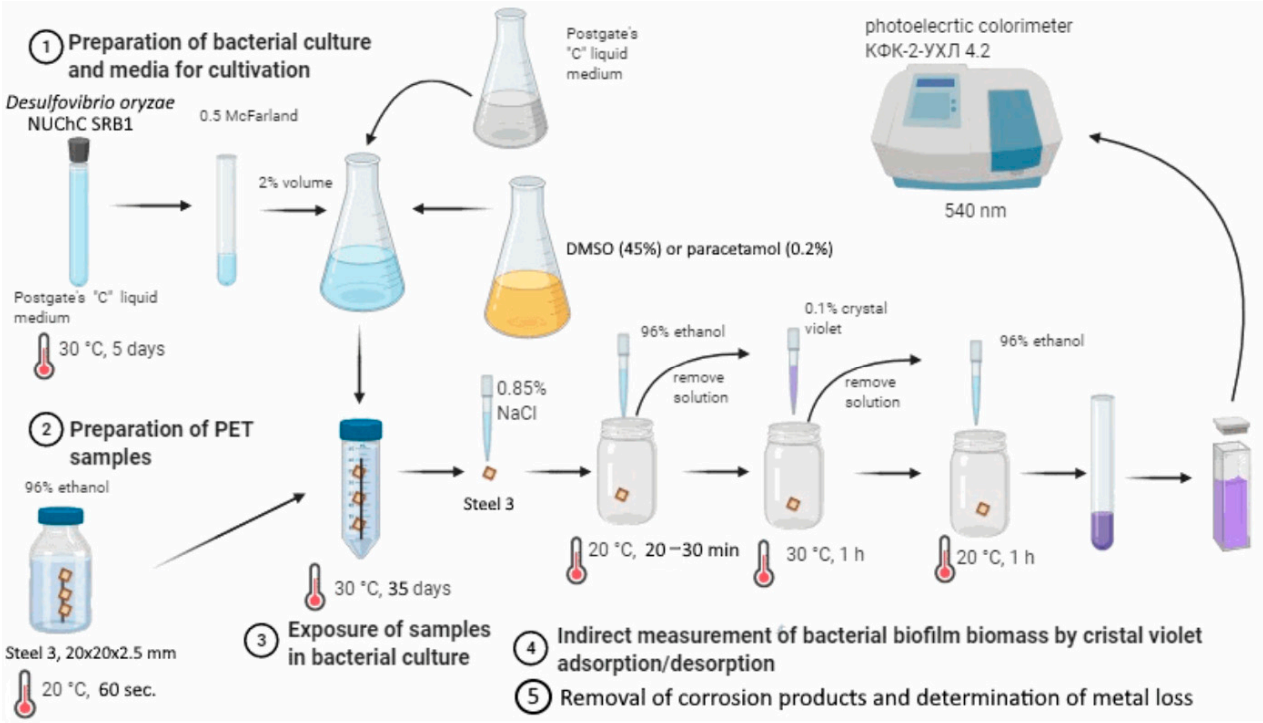

Figure 4. Scheme of the experiment to study the indicators of microbially induced corrosion under the influence of DMSO and paracetamol.

The experimental variants used in the model experiment of microbiologically influenced steel corrosion are given in Table 2.

Table 2. Variants of the experiment of microbially induced corrosion of steel 3 in a liquid Postgate's "C" medium.

Symbol	*D. oryzae* NUChC SRB1	Steel 3	DMSO	Paracetamol
I	– [1]	+	–	–
II	+ [2]	+	–	–
III	+	+	+	–
IV	–	+	+	–
V	+	+	–	+
VI	–	+	–	+

[1] "+"—component present; [2] "–"—component absent.

2.5. Statistical Analysis of the Results of the Study

The experiments were carried out in 4 replicates (n = 4). Statistical analysis of the data was carried out using Microsoft Excel 2010 program (the arithmetic mean value and standard error of mean (SEM) were calculated) and the scientific data analysis program Past v.4.10 [57]. The statistical significance of the differences was determined by Student's t-test and a one-way ANOVA. A 95% probability of differences ($p \leq 0.05$) was considered statistically significant.

3. Results

3.1. Sensitivity of SRB to DMSO by the Dilution Method

The results of the study of the sensitivity of SRB to different concentrations of DMSO are presented in Figures 5 and 6.

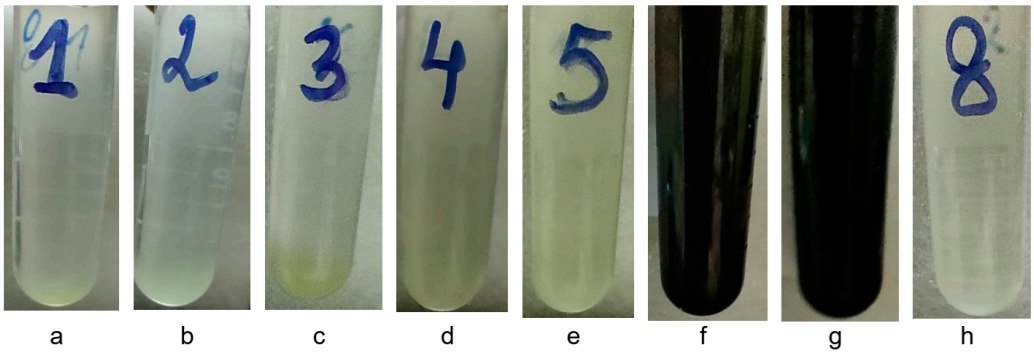

Figure 5. Growth of the culture of sulfate-reducing bacteria *D. oryzae* NUChC SRB1 in liquid Postgate's "C" medium (5th day of the first passage) with DMSO at the concentrations: (**a**) 100%; (**b**) 70%; (**c**) 45%; (**d**) 25%; (**e**) 10%; (**f**) 1%; (**g**) 0% (culture control); and (**h**) 0% (sterility control).

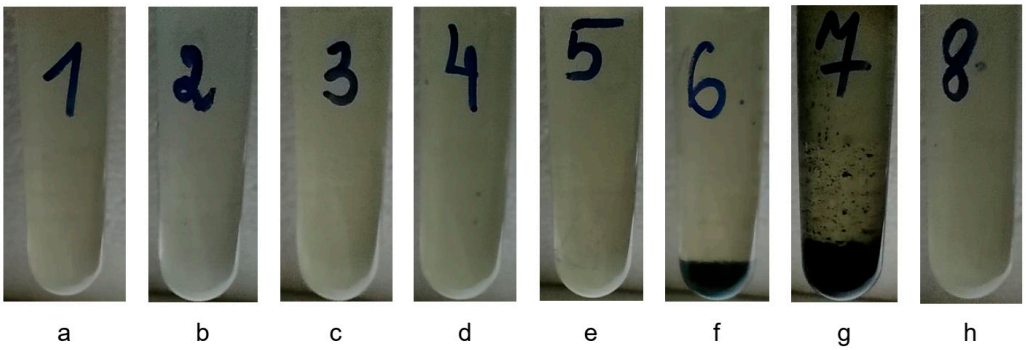

Figure 6. Growth of the culture of sulfate-reducing bacteria *D. oryzae* NUChC SRB1 in liquid Postgate's "C" medium (14th day of the second passage) with DMSO at the following concentrations: (**a**) 100%; (**b**) 70%; (**c**) 45%; (**d**) 25%; (**e**) 10%; (**f**) 1%; (**g**) 0% (culture control); and (**h**) 0% (sterility control).

It was found that DMSO at a concentration of 10% to 100% exhibited antibacterial properties against the studied SRBs (Figures 5 and 6). The minimum inhibitory concentration of DMSO for sulfate-reducing bacteria *D. oryzae* NUChC SRB1 was 10%. DMSO demonstrated bactericidal properties (after the subculture of the culture onto Postgate's "C" medium, no growth was observed and the medium did not turn black) at concentrations higher than 1%, and the minimum bactericidal concentration of this compound in our experiment was a concentration of 10% (Figures 5 and 6). The absence of antibacterial properties was noted for DMSO at a concentration of 1%; SRB grew both during the first and second passages (Figures 5 and 6).

3.2. Indicators of the Microbial Corrosion of Steel Induced by SRB Under DMSO and Paracetamol Treatment

The results of the study on the indicators of microbial corrosion of steel 3 induced by SRB *D. oryzae* in the presence of DMSO and paracetamol are shown in Figure 7 (biofilm biomass) and Figure 8 (corrosion rate).

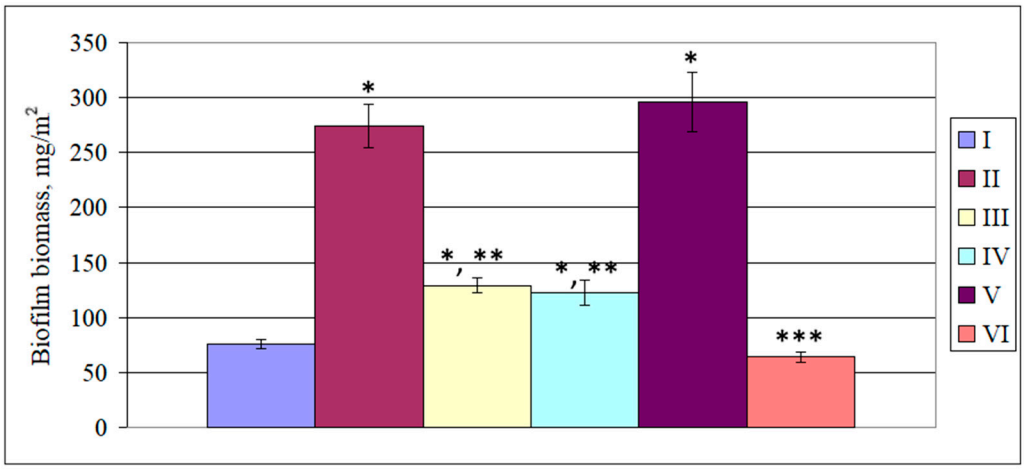

Figure 7. Biofilm biomass of *D. oryzae* on the surface of steel 3: I—steel 3 without bacteria; II—steel 3+SRB; III—steel 3+SRB+DMSO; IV—steel 3+DMSO; V—steel 3+SRB+paracetamol; VI—steel 3+paracetamol; *—the difference was significant compared to option I at $p \leq 0.05$; **—the difference was significant compared to option II at $p \leq 0.05$; ***—the difference was significant compared to option V at $p \leq 0.05$.

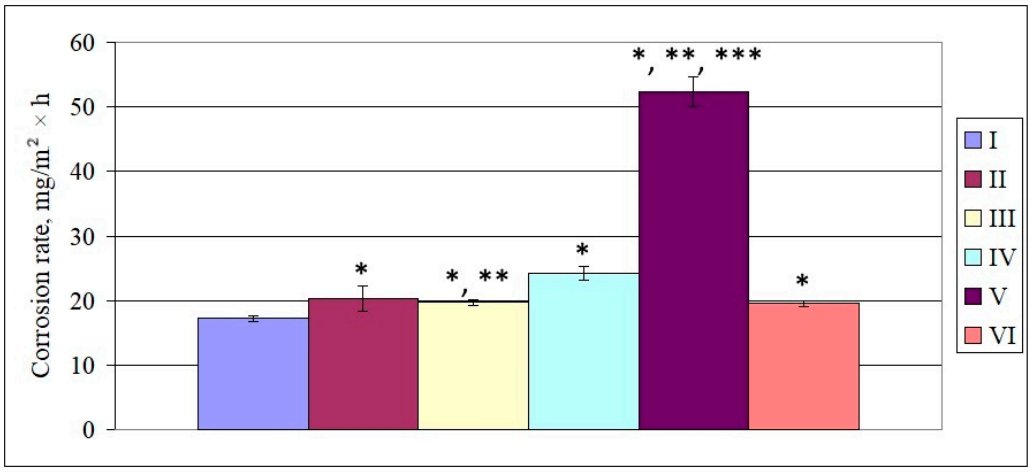

Figure 8. Steel corrosion rate: I—steel 3 without bacteria; II—steel 3+SRB; III—steel 3+SRB+DMSO; IV—steel 3+DMSO; V—steel 3+SRB+paracetamol; VI—steel 3+paracetamol; *—the difference was significant compared to option I at $p \leq 0.05$; **—the difference was significant compared to option IV at $p \leq 0.05$; ***—the difference was significant compared to option II and VI at $p \leq 0.05$.

It was found that the biofilm biomass of *D. oryzae* NUChC SRB1 on steel samples (variant II) was 274.2 ± 20.0 mg/m^2 (Figure 7). In the presence of DMSO, the medium with SRB and steel (variant III) provided a significant reduction in biofilm biomass (by 2.1 times), which was 129.1 ± 7.0 mg/m^2 and on a par with variant IV, with DMSO without bacteria (122.8 ± 11.4 mg/m^2) (Figure 7). In experiments with the addition of paracetamol to the culture of SRB (variant V), neither a stimulating nor an inhibitory effect on biofilm biomass on the surface of the steel samples was observed; the biofilm biomass was 296.1 ± 27.4 mg/m^2, which was on a par with variant II (Figure 7). The mass of the adsorbed crystal violet dye under sterile conditions of variant VI with the addition of paracetamol (64.0 ± 5.0 mg/m^2) did not differ from this indicator for the sterile Postgate's "C" medium (variant I): 75.8 ± 4.4 mg/m^2 (Figure 7).

During the experiment, the corrosion rate of the steel samples of steel 3 in variant II in the presence of *D. oryzae* NUChC SRB1 (22.51 ± 1.43 mg/m^2 × h) was significantly higher, 1.3 times, than in the sterile conditions of variant I (17.20 ± 0.51 mg/m^2 × h) (Figure 8),

which indicates a low corrosion activity of *D. oryzae* NUChC SRB1. It was also found that the presence of DMSO in the medium with SRB (variant III) did not affect the rate of microbial corrosion (19.73 ± 0.45 mg/m^2 × h), which was at the same level as that of variant II without DMSO (Figure 8). Thus, DMSO, despite its antibacterial and antibiofilm properties against SRB (Figures 5–7), does not provide a reduction in the corrosion rate under anaerobic sulfate-reduction conditions (Figure 8). However, an increase in the corrosion rate under these conditions was also not observed, while in the presence of DMSO in sterile conditions (variant IV), a slight (1.4-fold) significant stimulation of the steel corrosion rate was observed (24.24 ± 0.97 mg/m^2 × h) (Figure 8). The corrosion rate of steel 3 when paracetamol was added to the medium with bacterial sulfate reduction (variant V) significantly increased (3.0 times compared to variant I, and 2.6 times compared to variant VI), and amounted to 52.40 ± 2.27 mg/m^2 × h (Figure 8). Therefore, paracetamol showed a stimulating effect on the rate of the microbial corrosion of steel induced by SRB.

4. Discussion

Dimethyl sulfoxide and paracetamol are compounds that exhibit biologically active properties. A number of authors detect the antibiofilm properties of DMSO, which was also shown by us at a concentration of the compound of 45%. In particular, the inhibition of biofilm formation under the influence of DMSO was noted for the following bacteria: *Burkholderia cepacia*, *B. pyrrocinia* (clinical isolate), *P. aeruginosa* [30], *S. aureus* strains 72, 80, 510, ATCC 29213 [29], *P. aeruginosa* (PAO1), *E. coli* [58], *E. coli* UTI89, UTI89csgA, MC4100, MC4100csgA [59], *E. coli* ATCC 1299, *P. aeruginosa* ATCC 10145, and *Salmonella typhimurium* ATCC 14028 [31]. Summer et al. [60] emphasized the scientific rigor of using DMSO as a solvent in antibiofilm assays. The authors demonstrated that DMSO at concentrations of 0.03–25% significantly inhibited biofilm formation by *P. aeruginosa*, but not by *Streptococcus pneumoniae*. In addition, it acts synergistically with standard antibiotics at very low concentrations (<1%). Nevertheless, intermediate concentrations of DMSO (~6%) strongly promoted the growth of *P. aeruginosa* biofilms [60].

The antibacterial properties of DMSO revealed are consistent with the results of other researchers. In particular, the antibacterial properties of DMSO via the serial dilution method were detected against *Paenibacillus larvae*, *Melissococcus pluton*, and *Paenibacillus alvei* [28], isolates of the bacteria *Staphylococcus aureus*, *S. aureus* var. *albus*, β-hemolytic streptococci, *Corynebacterium acnes*, *Corynebacterium species*, *Alcaligenes faecalis*, *Escherichia coli* and *Proteus* [26], *Staphylococcus epidermidis* MTCC 435, *Pseudomonas oleovorans* MTCC 617, *Vibrio cholerae* MTCC 3906, *Shigella flexneri* MTCC 1457 and *Salmonella paratyphi* A [27], and *Pseudomonas aeruginosa* [61]. The increase in cell permeability is one of the effects caused by DMSO [62,63]. According to Basch and Gadebusch [61], the minimum inhibitory concentration of DMSO in vitro for *P. aeruginosa* is 8%. The changes in microbial-community participants in laboratory-scale bioreactors were observed as the DMSO concentration exceeded 2% [64]. According to the authors, DMSO was toxic to bacteria at a high concentration since a large amount of methanesulfenic acid was formed as a result of DMSO degradation, assuming less the harmful effect of DMSO as a solvent at a concentration less than 2% [64]. The repression effect of 1% DMSO on nitrite reductase (nir) gene expression was detected during the partial denitrification (PD) process [65], with an almost complete inhibition of the NIR enzyme activity as the concentration increases to 3.5%. However, the activity of another enzyme of the PD process, nitrate reductase, was not affected by DMSO [65].

Our data on the bactericidal properties of DMSO against SRB *D. oryzae* are consistent with previously published results with other species of bacteria. Given that DMSO provides greater membrane permeability for various ions [63], it is possible that a combination of the

solvent and other bactericides would intensify antimicrobial effect and decrease required active concentration of the latter.

DMSO also exhibits phytotoxic properties against *Oryza sativa* L. plants [37], *Phaseolus vulgaris*, *Pisum sativa*, *Hordeum vulgare*, *Secale cereale* [66], and *Raphanus raphanistrum* subsp. *sativus* (L.) Domin. [39].

Paracetamol is one of the drugs widely used in medical practice [48]. Paracetamol has a high degree of toxicity at concentrations of 500, 400, 300, 200, 100, 50, 25, 5, and 1 mg/L, demonstrating a cytotoxic effect (the inhibition of root growth, the presence of anomalies, and a significant micronuclear index) in an ecotoxicological bioassay with *Lens culinaris* and *Pisum sativum* [38]. Paracetamol is known as a compound that can affect the formation of biofilms by microorganisms, but with different effects. Thus, the stimulating effect of paracetamol on the formation of biofilms of *S. aureus* was noted in the work of Sultan et al. [67]. However, the inhibition of biofilm formation by paracetamol has been demonstrated for the *E. coli* [32] and *P. aeruginosa* [68,69], and *Acinetobacter baumannii* [68] river microbial communities [70]. In our study, paracetamol (0.2%) in the form of the drug "Infulgan" did not affect biofilm formation by SRB.

DMSO and paracetamol are able to affect the corrosion process development. It was reported that DMSO (45%) inhibits corrosion processes in the presence of a soluble inert inorganic salt of a strong base and a weak acid dissolved there in oxygen-free media [33]. In addition, the effectiveness of the corrosion inhibition of the low-carbon steel by dimethyl sulfoxide-treated starch of *Dioescorea hispida* in a sodium chloride medium was demonstrated [34]. It was noted that DMSO has a very low level of corrosivity [71]. In our study, no effect of DMSO (45%) on the corrosion rate of steel 3 under the conditions of microbial corrosion induced by SRB was observed. The slight increase in the corrosion rate of steel 3 under sterile conditions and the presence of DMSO are consistent with the report of a low level of corrosivity of this compound [71], as well as with the data of Rastogi et al. [72] on the corrosion process development in HCl solutions in the presence of DMSO.

Paracetamol is known for its anticorrosion properties under acid corrosion conditions [21]. It was noted that the observed effectiveness of paracetamol (from 0.755×10^{-2}% to 0.15%) in inhibiting the corrosion process on copper (about 96% at the highest concentration 0.15%) was achieved by adsorption on the surface of this metal [36]. The potential of paracetamol (at concentrations of 0.755×10^{-2}–0.0275%) as a corrosion inhibitor was also shown in experiments with low carbon steel in a 1.0 mol/L H_2SO_4 solution [35]. However, in our study, the stimulation of the corrosion process by paracetamol was established, which may be associated with the peculiarities of the experimental conditions (anaerobic bacterial sulfidogenic environment), which may contribute to the anaerobic degradation of this compound [73,74].

Therefore, the presence of DMSO and paracetamol should be taken into account in environments that contain SRB, and are critical from the point of view of corrosion damage. In particular, the active development of sulfate-reducing bacteria and their involvement in microbial corrosion processes occurs in wastewater treatment plants [75,76]. DMSO and paracetamol were detected in wastewater at the concentrations of 0.05–0.08% (DMSO) [37] and 0.7×10^{-8}–0.246×10^{-4}% (paracetamol) [50]. It should be noted that microorganisms have a high ability to reduce DMSO to dimethyl sulfide both in soil [77] and aquatic environments [78]. Of the 144 strains tested (both fungi and bacteria), only 5 strains were not capable of reducing DMSO [78]. It was also reported that 65 bacterial species belonging to 33 genera and over 300 strains are capable of reducing DMSO, while 26 bacterial species are not [79]. Most species that do not reduce DMSO are enteric bacteria belonging to the genera *Salmonella*, *Shigella*, and *Proteus* [79]. There has been some ambiguity in the reduction of DMSO by sulfate-reducing bacteria, with the results being both positive and negative,

depending on the species and strain of bacterium studied [79]. However, there are reports that the representatives of sulfate-reducing bacteria from the genera *Desulfobacterium*, *Desulfobacter*, and *Desulfovibrio* are able to reduce DMSO [80]. The authors suggest that in anoxic marine environments, the reduction of DMSO by sulfate-reducing bacteria may lead to increased dimethyl sulfide emissions [80]. The genes encoding enzymes with DMSO reductase activity have been identified not only in bacterial, but also archaeal genomic sequences [81–84]. Paracetamol is also subject to microbial degradation [74,85–87], including *Pseudomonas*, *Bacillus*, *Acinetobacter*, and *Sphingomonas* genera with acylamidohydrolase, deaminase, and hydroquinone 1,2-dioxygenase activity to transform paracetamol [88] and SRB [87], which have the enzyme aldehyde oxidoreductase (for example, in *Desulfovibrio desulfuricans* ATCC 27774) which is involved in the bioremediation of paracetamol [89]. Archaea have also been associated with the biodegradation process of paracetamol (acetaminophen) [63]. Changes in the structure of bacterial and archaeal communities in the acetaminophen sludges were observed [90]. Therefore, it is important to further investigate the indicators of the microbial corrosion of steel induced by SRB at the concentrations of DMSO and paracetamol found in wastewater.

5. Conclusions

Sulfate-reducing bacteria *Desulfovibrio oryzae* NUChC SRB1 are sensitive to DMSO. DMSO (45%) showed toxic (bactericidal and antibiofilm) properties against the studied sulfate-reducing bacteria, but did not show anticorrosion properties under the conditions of microbial corrosion induced by *D. oryzae* NUChC SRB1. Paracetamol (0.2%) did not show toxic properties against SRB biofilm formation under these conditions, and contributed to the increase in the rate of the microbial corrosion of steel. The obtained results deepen the knowledge in the field of microbiologically influenced corrosion caused by SRB in the presence of compounds with bioactive properties. The prospect of further research is to assess the effect of DMSO and paracetamol on the indicators of microbial corrosion induced by SRB under the influence of the concentrations of these compounds found in wastewater, to clarify the possible additional causes of damage to the equipment of wastewater treatment plants in the form of these polluting compounds. The complexes of DMSO and various antimicrobial compounds should be another field of further research since DMSO demonstrates antimicrobial features and can increase membrane permeability. This would be the grounds for the development of an eco-friendly drug against microbiologically influenced corrosion.

Author Contributions: Conceptualization, N.T. and L.Z.; Methodology, N.T.; Formal Analysis, N.T. and L.Z.; Investigation, N.T. and Y.N.; Resources, N.T. and Y.N.; Writing—Original Draft Preparation, N.T. and L.Z.; Writing—Review and Editing, N.T. and L.Z.; Visualization, N.T.; Supervision, N.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The authors provide a minimal data set.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Beech, I.B.; Gaylarde, C. Recent advances in the study of biocorrosion: An overview. *Rev. Microbiol.* **1999**, *30*, 117–190. [CrossRef]
2. Javaherdashti, R. Editorial: Microbiologically influenced corrosion (MIC): Its mechanisms, technological, economic, and environmental impacts. *Front. Microbiol.* **2023**, *14*, 1249565. [CrossRef] [PubMed]

3. Andreyuk, K.; Kozlova, I.; Kopteva, Z.; Pilyashenko-Novokhatny, A.; Zanina, V.; Purish, L. *Microbial Corrosion of Underground Structures*; Naukova Dumka Publishing House: Kyiv, Ukraine, 2005; 258p. (In Ukrainian)
4. Knisz, J.; Eckert, R.; Gieg, L.M.; Koerdt, A.; Lee, J.S.; Silva, E.R.; Skovhus, T.L.; An Stepec, B.A.; Wade, S.A. Microbiologically influenced corrosion—More than just microorganisms. *FEMS Microbiol. Rev.* **2023**, *47*, fuad041. [CrossRef]
5. Little, B.J.; Lee, J.S. Microbiologically influenced corrosion: An update. *Int. Mater. Rev.* **2014**, *59*, 384–393. [CrossRef]
6. Jin, J.; Li, Y.; Huang, H.; Xiang, Y.; Yan, W. Symbiosis of Sulfate-Reducing Bacteria and Total General Bacteria Affects Microbiologically Influenced Corrosion of Carbon Steel. *Coatings* **2024**, *14*, 788. [CrossRef]
7. Sun, M.; Wang, X.; Cui, W. Corrosion of Sulfate-Reducing Bacteria on L245 Steel under Different Carbon Source Conditions. *Microorganisms* **2024**, *12*, 1826. [CrossRef] [PubMed]
8. Welikala, S.; Al-Saadi, S.; Gates, W.P.; Panter, C.; Singh Raman, R.K. Sulphate reducing bacteria (SRB) biofilm development and its role in microbial corrosion of carbon steel. *Front. Mater.* **2024**, *11*, 1360869. [CrossRef]
9. Blackwood, D.J. An Electrochemist Perspective of Microbiologically Influenced Corrosion. *Corros. Mater. Degrad.* **2020**, *1*, 59–76. [CrossRef]
10. Mah, T.F.; O'Toole, G.A. Mechanisms of biofilm resistance to antimicrobial agents. *Trends Microbiol.* **2001**, *9*, 34–39. [CrossRef] [PubMed]
11. Davies, D. Understanding biofilm resistance to antibacterial agents. *Nat. Rev. Drug. Discov.* **2003**, *2*, 114–122. [CrossRef]
12. Singh, S.; Singh, S.K.; Chowdhury, I.; Singh, R. Understanding the Mechanism of Bacterial Biofilms Resistance to Antimicrobial Agents. *Open Microbiol. J.* **2017**, *11*, 53–62. [CrossRef] [PubMed]
13. Grooters, K.E.; Ku, J.C.; Richter, D.M.; Krinock, M.J.; Minor, A.; Li, P.; Kim, A.; Sawyer, R.; Li, Y. Strategies for combating antibiotic resistance in bacterial biofilms. *Front. Cell. Infect. Microbiol.* **2024**, *14*, 1352273. [CrossRef] [PubMed]
14. Kong, L.; Zhang, B.; Fang, J. Study on the applicability of bactericides to prevent concrete microbial corrosion. *Constr. Build. Mater.* **2017**, *149*, 1–8. [CrossRef]
15. Gurbanov, H.R.; Adigezalova, M.B. New multifunctional corrosion inhibitor of steel in formation water with oil containing hydrogen sulfide and carbon dioxide. *Vopr. Khimii Khimicheskoi Tekhnologii* **2023**, *6*, 68–75. [CrossRef]
16. Shi, X.; Zhang, R.; Sand, W.; Mathivanan, K.; Zhang, Y.; Wang, N.; Duan, J.; Hou, B. Comprehensive Review on the Use of Biocides in Microbiologically Influenced Corrosion. *Microorganisms* **2023**, *11*, 2194. [CrossRef] [PubMed]
17. Dou, W.; Xu, D.; Gu, T. Biocorrosion caused by microbial biofilms is ubiquitous around us. *Microb. Biotechnol.* **2021**, *14*, 803–805. [CrossRef]
18. Tuck, B.; Leinecker, N.; Watkin, E.; Somers, A.; Forsyth, M.; Machuca, L.L. Efficiency of a Novel Multifunctional Corrosion Inhibitor Against Biofilms Developed on Carbon Steel. *Front. Bioeng. Biotechnol.* **2022**, *10*, 803559. [CrossRef]
19. Abdallah, M. Antibacterial drugs as corrosion inhibitors for corrosion of aluminum in hydrochloric solution. *Corros. Sci.* **2004**, *46*, 1981–1996. [CrossRef]
20. Tang, R.; Wang, X.; Chen, Z.; Liu, Y.; Yang, W. An S^{2-} responsive nanocontainer for inhibiting microbial corrosion caused by sulfate-reducing bacteria. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *663*, 131110. [CrossRef]
21. Vaszilcsin, N.; Kellenberger, A.; Dan, M.L.; Duca, D.A.; Ordodi, V.L. Efficiency of Expired Drugs Used as Corrosion Inhibitors: A Review. *Materials* **2023**, *16*, 5555. [CrossRef]
22. Strotmann, U.; Durand, M.J.; Thouand, G.; Eberlein, C.; Heipieper, H.J.; Gartiser, S.; Pagga, U. Microbiological toxicity tests using standardized ISO/OECD methods-current state and outlook. *Appl. Microbiol. Biotechnol.* **2024**, *108*, 454. [CrossRef]
23. Strotmann, U.; Pastor Flores, D.; Konrad, O.; Gendig, C. Bacterial Toxicity Testing: Modification and Evaluation of the Luminescent Bacteria Test and the Respiration Inhibition Test. *Processes* **2020**, *8*, 1349. [CrossRef]
24. Carpenter, D.E.; Anderson, K.; Citron, D.M.; Dzink-Fox, J.A.L.; Hackel, M.; Jenkins, S.G.; Knapp, C.; Koeth, L.; Schuetz, A.N.; Wexler, H. *Methods for Antimicrobial Susceptibility Testing of Anaerobic Bacteria*, 9th ed.; M11; Clinical and Laboratory Standards Institute: Wayne, PA, USA, 2018; 64p, Available online: https://clsi.org/standards/products/microbiology/documents/m11/ (accessed on 9 January 2025).
25. Tkachuk, N.V.; Yanchenko, V.O.; Demchenko, N.R. Minimum inhibitory concentration of some 6,7,8,9-tetrahydro-5H-[1,2,4]triazolo[4,3-a]azepine derivatives against ammonifying bacteria isolated from the soil ferrosphere. *BHT* **2023**, *1*, 24–32. [CrossRef]
26. Kligman, A.M. Dimethyl Sulfoxide—Part 2. *AMA* **1965**, *193*, 923–928. [CrossRef] [PubMed]
27. Wadhwani, T.; Desai, K.; Patel, D.; Lawani, D.; Bahaley, P.; Joshi, P.; Kothari, V. Effect of various solvents on bacterial growth in context of determining MIC of various antimicrobials. *Int. J. Microbiol.* **2009**, *7*, 1–14.
28. Sirenko, O.S.; Desyatnikova, O.V.; Gur'eva, V.B. Effectiveness of the disinfectant "Guanidez" on pathogens of infectious diseases of bees in laboratory conditions. *Vet. Med. Inter-Dep. Subj. Sci. Collect.* **2019**, *105*, 59–62. (In Ukrainian)
29. Gracia, E.; Fernández, A.; Conchello, P.; Alabart, J.L.; Pérez, M.; Amorena, B. In vitro development of Staphylococcus aureus biofilms using slime-producing variants and ATP-bioluminescence for automated bacterial quantification. *Luminescence* **1999**, *14*, 23–31. [CrossRef]

30. Herasimenka, Y.; Cescutti, P.; Sampaio Noguera, C.E.; Ruggiero, J.R.; Urbani, R.; Impallomeni, G.; Zanetti, F.; Campidelli, S.; Prato, M.; Rizzo, R. Macromolecular properties of cepacian in water and in dimethylsulfoxide. *Carbohydr. Res.* **2008**, *343*, 81–89. [CrossRef]
31. Yahya, M.F.Z.R.; Alias, Z.; Karsani, S.A. Antibiofilm activity and mode of action of DMSO alone and its combination with afatinib against Gram-negative pathogens. *Folia Microbiol.* **2018**, *63*, 23–30. [CrossRef]
32. Eltabey, S.M.; Ibrahim, A.H.; Zaky, M.M.; Ibrahim, A.E.; Alrashdi, Y.B.A.; El Deeb, S.; Saleh, M.M. The Promising Effect of Ascorbic Acid and Paracetamol as Anti-Biofilm and Anti-Virulence Agents against Resistant Escherichia coli. *Curr. Issues Mol. Biol.* **2024**, *46*, 6805–6819. [CrossRef]
33. Sullivan, V.A., Jr.; Smedslund, T.H. Corrosion Inhibition of Dimethyl Sulfoxide. U.S. Patent 2948683A, 9 August 1960. United States Patent Office; 1–4. Available online: https://patentimages.storage.googleapis.com/fe/1c/94/0cf01cc472821b/US2948683.pdf (accessed on 9 November 2024).
34. Othman, N.K.; Salleh, E.M.; Dasuki, Z.; Lazim, A.M. Dimethyl Sulfoxide-Treated Starch of *Dioescorea hispida* as a Green Corrosion Inhibitor for Low Carbon Steel in Sodium Chloride Medium. In *Corrosion Inhibitors, Principles and Recent Applications*; Aliofkhazraei, M., Ed.; InTech: London, UK, 2018; pp. 181–199. [CrossRef]
35. Al-Gorair, A.S.; Abdallah, M. Expired Paracetamol as Corrosion Inhibitor for Low Carbon Steel in Sulfuric Acid. Electrochemical, Kinetics and Thermodynamics Investigation. *Int. J. Electrochem. Sci.* **2021**, *16*, 210771. [CrossRef]
36. Tasić, Ž.Z.; Mihajlovic, M.B.; Radovanović, M.B.; Simonović, A.T.; Antonijevic, M.M. Experimental and theoretical studies of paracetamol as a copper corrosion inhibitor. *J. Mol. Liq.* **2021**, *327*, 114817. [CrossRef]
37. Zhang, X.H.; Yu, X.Z.; Yue, D.M. Phytotoxicity of dimethyl sulfoxide (DMSO) to rice seedlings. *Int. J. Environ. Sci. Technol.* **2016**, *13*, 607–614. [CrossRef]
38. Mercado, S.A.S.; Galvis, D.G.V. Paracetamol ecotoxicological bioassay using the bioindicators *Lens culinaris* Med. and *Pisum sativum* L. *Environ. Sci. Pollut. Res. Int.* **2023**, *30*, 61965–61976. [CrossRef] [PubMed]
39. Tkachuk, N.; Zelena, L.; Novikov, Y.; Taranenko, V. Phytotoxicity of dimethyl sulfoxide in the growth test. *BHT* **2024**, *3*, 51–60. [CrossRef]
40. Hatton, A.D.; Malin, G.; McEwan, A.G.; Liss, P.S. Determination of dimethyl sulfoxide in aqueous solution by an enzyme-linked method. *Anal. Chem.* **1994**, *66*, 4093–4096. [CrossRef]
41. Makashova, O.E.; Zubova, O.L.; Zubov, P.M.; Migunova, R.K.; Babiychuk, L.O. Cryopreservation of cord blood hematopoietic progenitor cells in cryoprotective media containing different concentrations of DMSO and antioxidants. *Ukr. J. Med. Biol. Sports* **2017**, *2*, 234–238. (In Ukrainian)
42. Volkova, N.; Yukhta, M.; Chernyschenko, L.; Stepaniuk, L.; Sokil, L.; Goltsev, A. The effectiveness of biopolymers application for cryopreservation of the fragments of convoluted seminiferous tubules of prepubertal rat's testis. *JCOT* **2019**, *7*, 12–17. [CrossRef]
43. Hoang, C.; Nguyen, A.K.; Nguyen, T.Q.; Fang, W.; Han, B.; Hoang, B.X.; Tran, H.D. Application of dimethyl sulfoxide as a therapeutic agent and drug vehicle for eye diseases. *JOPT* **2021**, *37*, 441–451. [CrossRef] [PubMed]
44. Capriotti, K.; Capriotti, J.A. Dimethyl sulfoxide: History, chemistry, and clinical utility in dermatology. *JCAD* **2012**, *5*, 24–26.
45. Cheng, X.; Peterkin, E. A new reliable method for dimethyl sulfoxide analysis in wastewater: Dimethyl sulfoxide in philadelphia's three water pollution control plants. *WER* **2007**, *79*, 571–575. [CrossRef] [PubMed]
46. Dimethyl Sulfoxide (DMSO) Health and Safety Information. Bulletin 106. Gaylord Chemical Company, L.L.C. 2007, pp. 1–16. Available online: https://www.researchgate.net/file.PostFileLoader.html?id=547d95e4d2fd6436518b468c&assetKey=AS:273644578639890@1442253359624 (accessed on 16 December 2024).
47. Dimethyl sulfoxide. Molecule of the Week Archive. Chemistry for Life. *ACS* **2021**. Available online: https://www.acs.org/molecule-of-the-week/archive/d/dimethyl-sulfoxide.html (accessed on 7 January 2025).
48. Freo, U.; Ruocco, C.; Valerio, A.; Scagnol, I.; Nisoli, E. Paracetamol: A review of guideline recommendations. *J. Clin. Med.* **2021**, *10*, 3420. [CrossRef]
49. Acetaminophen. Molecule of the Week Archive. Chemistry for Life. *ACS* **2014**. Available online: https://www.acs.org/molecule-of-the-week/archive/a/acetaminophen.html (accessed on 7 January 2025).
50. Al-Kaf, A.G.; Naji, K.M.; Abdullah, Q.Y.M.; Edrees, W.H.A. Occurrence of Paracetamol in Aquatic Environments and Transformation by Microorganisms: A Review. *COPS* **2017**, *1*, 341–355. Available online: https://www.researchgate.net/publication/322041109_Occurrence_of_Paracetamol_in_Aquatic_Environments_and_Transformation_by_Microorganisms_A_Review (accessed on 5 December 2024).
51. Tkachuk, N.; Zelena, L.; Mazur, P.; Lukash, O. Genotypic, physiological and biochemical features of *Desulfovibrio* strains in a sulfidogenic microbial community isolated from the soil of ferrosphere. *EQ* **2020**, *31*, 79–88. [CrossRef]
52. Tkachuk, N.; Zelena, L.; Lukash, O.; Mazur, P. Microbiological and genetic characteristics of *Bacillus velezensis* bacillibactin-producing strains and their effect on the sulfate-reducing bacteria biofilms on the poly(-ethylene terephthalate) surface. *EQ* **2021**, *32*, 119–129. [CrossRef]

53. Tkachuk, N.; Zelena, L. Bacterial sulfidogenic community from the surface of technogenic materials in vitro: Composition and biofilm formation. *Biofouling* **2023**, *39*, 327–338. [CrossRef] [PubMed]
54. Tkachuk, N.; Zelena, L.; Mazur, P. Properties of anaerobic bacteria from ferrosphere crucial for biofilm development. *EQ* **2021**, *32*, 107–112. [CrossRef]
55. Tkachuk, N.; Zelena, L. Microbiological indicators of the biofilms microparticles of quartz sand and polypropylene after short-term exposure in soil. *Biofouling* **2024**, *40*, 723–734. [CrossRef]
56. Wang, Q.; Wang, R.; Zhang, Q.; Zhao, C.; Zhou, X.; Zheng, H.; Zhang, R.; Sun, Y.; Yan, Z. Application of Biomass Corrosion Inhibitors in Metal Corrosion Control: A Review. *Molecules* **2023**, *28*, 2832. [CrossRef] [PubMed]
57. Hammer, Ø.; Harper, D.A.; Ryan, P.D. PAST: Paleontological statistics software package for education and data analysis. *Palaeont. Electr.* **2001**, *4*, 1–9.
58. Guo, Q.; Wu, Q.; Bai, D.; Liu, Y.; Chen, L.; Jin, S.; Wu, Y.; Duan, K. Potential Use of Dimethyl Sulfoxide in Treatment of Infections Caused by *Pseudomonas aeruginosa*. *Antimicrob. Agents Chemother.* **2016**, *60*, 7159–7169. [CrossRef] [PubMed]
59. Lim, J.Y.; May, J.M.; Cegelski, L. Dimethyl sulfoxide and ethanol elicit increased amyloid biogenesis and amyloid-integrated biofilm formation in *Escherichia coli*. *Appl. Environ. Microbiol.* **2012**, *78*, 3369–3378. [CrossRef]
60. Summer, K.; Browne, J.; Hollanders, M.; Benkendorff, K. Out of control: The need for standardised solvent approaches and data reporting in antibiofilm assays incorporating dimethyl-sulfoxide (DMSO). *Biofilm* **2022**, *4*, 100081. [CrossRef]
61. Basch, H.; Gadebusch, H.H. In vitro antimicrobial activity of dimethylsulfoxide. *Appl. Microbiol.* **1968**, *16*, 1953–1954. [CrossRef] [PubMed]
62. Notman, R.; Noro, M.; O'Malley, B.; Anwar, J. Molecular basis for dimethylsulfoxide (DMSO) action on lipid membranes. *J. Am. Chem. Soc.* **2006**, *128*, 13982–13983. [CrossRef]
63. de Ménorval, M.A.; Mir, L.M.; Fernández, M.L.; Reigada, R. Effects of dimethyl sulfoxide in cholesterol-containing lipid membranes: A comparative study of experiments in silico and with cells. *PLoS ONE* **2012**, *7*, e41733. [CrossRef]
64. Wang, Z.; Zhang, J.; Zhou, J.; Ismail, S.; Ahmad, H.A.; Awad, H.M.; Tawfik, A.; Ni, S.-Q. Dosage-Dependent Toxicity of Universal Solvent Dimethyl Sulfoxide to the Partial Nitrification Wastewater Treatment Process. *ACS ES&T Water* **2023**, *3*, 848–856. [CrossRef]
65. Wang, Z.B.; Zhang, J.; Miao, Q.; Cao, H.Y.; Xiong, F.; Lee, T.; El-Baz, A.; Xie, L.; Ni, S.Q. Achieving Stable Partial Denitrification by Selective Inhibition of Nitrite Reductase with the Biosafe Aprotic Solvent DMSO. *Environ. Sci. Technol.* **2024**, *58*, 21242–21250. [CrossRef]
66. Erdman, H.E.; Hsieh, J.J.S. Dimethylsulfoxide (DMSO) Effects on Four Economically Important Crops. *Agron. J.* **1969**, *61*, 528–530. [CrossRef]
67. Sultan, A.R.; Lattwein, K.R.; Lemmens-den Toom, N.A.; Snijders, S.V.; Kooiman, K.; Verbon, A.; van Wamel, W.J.B. Paracetamol modulates biofilm formation in Staphylococcus aureus clonal complex 8 strains. *Sci. Rep.* **2021**, *11*, 5114. [CrossRef] [PubMed]
68. Seleem, N.M.; Atallah, H.; Abd El Latif, H.K.; Shaldam, M.A.; El-Ganiny, A.M. Could the analgesic drugs, paracetamol and indomethacin, function as quorum sensing inhibitors? *Microb. Pathog.* **2021**, *158*, 105097. [CrossRef]
69. Sihotang, T.S.U.; Widodo, A.D.W.; Arfijanto, M.V. Comparison of doses of paracetamol or ibuprofen to inhibit the formation of biofilms of *Pseudomonas aeruginosa* bacteria. *Int. J. Health Sci.* **2022**, *6*, 361–367. [CrossRef]
70. Lawrence, J.R.; Zhu, B.; Swerhone, G.D.; Roy, J.; Tumber, V.; Waiser, M.J.; Topp, E.; Korber, D.R. Molecular and microscopic assessment of the effects of caffeine, acetaminophen, diclofenac, and their mixtures on river biofilm communities. *Environ. Toxicol. Chem.* **2012**, *31*, 508–517. [CrossRef] [PubMed]
71. Gaylord Chemical Company, L.L.C. Dimethyl Sulfoxide Recovery, Engineering & Environmental. Available online: https://www.gaylordchemical.com/process-safety-and-technology/dmso-recovery-engineering-environmental/ (accessed on 9 November 2024).
72. Rastogi, R.B.; Singh, M.M.; Singh, K.; Maurya, J.L. Electrochemical Behavior of Mild Steel in Dimethyl Sulfoxide Containing Hydrochloric Acid. *Port. Electrochim. Acta* **2010**, *28*, 359–371. [CrossRef]
73. Palma, T.L.; Donaldben, M.N.; Costa, M.C.; Carlier, J.D. Putative role of *Flavobacterium*, *Dokdonella* and *Methylophilus* strains in paracetamol biodegradation. *Water Air Soil Pollut.* **2018**, *229*, 200. [CrossRef]
74. Yang, C.-W.; Chen, Y.-E.; Chang, B.-V. Microbial Communities Associated with Acetaminophen Biodegradation from Mangrove Sediment. *Sustainability* **2020**, *12*, 5410. [CrossRef]
75. Jana, A.; Sarkar, T.K.; Chouhan, A.; Dasgupta, D.; Khatri, O.P.; Ghosh, D. Microbiologically influenced corrosion of wastewater pipeline and its mitigation by phytochemicals: Mechanistic evaluation based on spectroscopic, microscopic and theoretical analyses. *J. Mol. Liq.* **2022**, *364*, 119960. [CrossRef]
76. Zhang, L.; Qiu, Y.Y.; Sharma, K.R.; Shi, T.; Song, Y.; Sun, J.; Liang, Z.; Yuan, Z.; Jiang, F. Hydrogen sulfide control in sewer systems: A critical review of recent progress. *Water Res.* **2023**, *240*, 120046. [CrossRef]
77. Alef, K.; Kleiner, D. Rapid and sensitive determination of microbial activity in soils and in soil aggregates by dimethylsulfoxide reduction. *Biol. Fert. Soils* **1989**, *8*, 349–355. [CrossRef]

78. Griebler, C.; Slezak, D. Microbial activity in aquatic environments measured by dimethyl sulfoxide reduction and intercomparison with commonly used methods. *Appl. Environ. Microbiol.* **2001**, *67*, 100–109. [CrossRef]
79. Griebler, C.; Slezak, D. Microbial DMSO reduction is widespread among microorganisms and is therefore proposed as a reliable activity parameter. *SIL Proceedings 1922–2010* **2000**, *27*, 2492–2497. [CrossRef]
80. Jonkers, H.M.; Van Der Maarel, M.J.E.C.; Van Gemerden, H.; Hansen, T.A. Dimethylsulfoxide reduction by marine sulfate-reducing bacteria. *FEMS Microbiol. Lett.* **1996**, *136*, 283–287. [CrossRef]
81. McCrindle, S.L.; Kappler, U.; McEwan, A.G. Microbial dimethylsulfoxide and trimethylamine-N-oxide respiration. *Adv. Microb. Physiol.* **2005**, *50*, 147–198. [CrossRef]
82. Miralles-Robledillo, J.M.; Torregrosa-Crespo, J.; Martínez-Espinosa, R.M.; Pire, C. DMSO Reductase Family: Phylogenetics and Applications of Extremophiles. *Int. J. Mol. Sci.* **2019**, *20*, 3349. [CrossRef] [PubMed]
83. Tebbe, D.A.; Gruender, C.; Dlugosch, L.; Lõhmus, K.; Rolfes, S.; Könneke, M.; Chen, Y.; Engelen, B.; Schäfer, H. Microbial drivers of DMSO reduction and DMS-dependent methanogenesis in saltmarsh sediments. *ISME J.* **2023**, *17*, 2340–2351. [CrossRef] [PubMed]
84. Wells, M.; Kim, M.; Akob, D.M.; Basu, P.; Stolz, J.F. Impact of the Dimethyl Sulfoxide Reductase Superfamily on the Evolution of Biogeochemical Cycles. *Microbiol. Spectr.* **2023**, *11*, e0414522. [CrossRef]
85. Zhang, L.; Hu, J.; Zhu, R.; Zhou, Q.; Chen, J. Degradation of paracetamol by pure bacterial cultures and their microbial consortium. *Appl. Microbiol. Biotechnol.* **2013**, *97*, 3687–3698. [CrossRef] [PubMed]
86. Waghmode, M.S.; Lende, S.B.; Gaikwad, P.R.; Patil, N.N.; Khisti, U.V. Studies on Biodegradation of Acetaminophen by *Bacillus subtilis* subsp. subtilis NCIB 3610(T). *Curr. World Environ.* **2023**, *18*, 155–163. [CrossRef]
87. Utami, T.S.; Arbianti, R.; Hidayatullah, I.M.; Yusupandi, F.; Hamdan, M.; Putri, N.F.; Riyadi, F.A.; Boopathy, R. Paracetamol degradation in a dual-chamber rectangular membrane bioreactor using a microbial fuel cell system with a microbial consortium from sewage sludge. *CSCEE* **2024**, *9*, 100551. [CrossRef]
88. Żur, J.; Wojcieszyńska, D.; Hupert-Kocurek, K.; Marchlewicz, A.; Guzik, U. Paracetamol—Toxicity and microbial utilization. Pseudomonas moorei KB4 as a case study for exploring degradation pathway. *Chemosphere* **2018**, *206*, 192–202. [CrossRef]
89. George Haikal, N.K.K.; Razali, I.A.; Wan Hanafi, W.N.; Geraldi, A.; Ni'Matuzahroh, F.; Tay, C.C. Sustainable bioremediation of acetaminophen using bacteria: A review. *J. Sustain. Sci. Manag.* **2023**, *18*, 149–160. [CrossRef]
90. Gallardo-Altamirano, M.J.; Maza-Márquez, P.; Montemurro, N.; Pérez, S.; Rodelas, B.; Osorio, F.; Pozo, C. Insights into the removal of pharmaceutically active compounds from sewage sludge by two-stage mesophilic anaerobic digestion. *Sci. Total Environ.* **2021**, *789*, 147869. [CrossRef] [PubMed]