energies

MDPI

Article

The Application of a New Microbial Biosurfactant to Remove Residual Oil from Electric Power Plant and to Inhibit Metal Corrosion in a Salty Environment

Alexandre Augusto P. Selva Filho [1,2,3], Yslla Emanuelly S. Faccioli [1,2,3], Attilio Converti [4], Alessandro Alberto Casazza [4,*], Rita de Cássia F. Soares da Silva [1] and Leonie A. Sarubbo [1,2,3,*]

1 Instituto Avançado de Tecnologia e Inovação (IATI), Rua Potyra, n. 31, Prado, Recife 50751-310, Brazil; alexandre.selvafilho@ufrpe.br (A.A.P.S.F.); ysfaccioli@hotmail.com (Y.E.S.F.); rita.freire@iati.org.br (R.d.C.F.S.d.S.)
2 Escola de Tecnologia e Comunicação, Universidade Católica de Pernambuco (UNICAP), Rua do Príncipe, n. 526, Boa Vista, Recife 50050-900, Brazil
3 Rede Nordeste de Biotecnologia (RENORBIO), Universidade Federal Rural de Pernambuco (UFRPE), Rua Dom Manuel de Medeiros, s/n, Dois Irmãos, Recife 52171-900, Brazil
4 Department of Civil, Chemical and Environmental Engineering, University of Genoa (UNIGE), Pole of Chemical Engineering, Via Opera Pia, n. 15, 16145 Genova, Italy; converti@unige.it
* Correspondence: alessandro.casazza@unige.it (A.A.C.); leonie.sarubbo@unicap.br (L.A.S.)

Abstract

Human development has led to increased production of oil and gas, mainly as energy sources, which, however, are responsible for contamination and metal corrosion in industrial, marine, and terrestrial environments. Lubricating oil, in particular, is widely used in generators and industrial machines in the electric sector and is responsible for contamination not only in industrial environments but also in many terrestrial and aquatic ecosystems. In this context, this study aimed to apply the *Starmerella bombicola* ATCC 222214 biosurfactant to inhibit metal corrosion in seawater and in an Accelerated Corrosion Chamber (ACC). For this purpose, its toxicity against the microcrustacean *Artemia salina*, its dispersion capacity, and its ability to promote oil biodegradation in a saline environment were investigated. The biosurfactant, when applied at twice its Critical Micellar Concentration (CMC), caused low mortality (30.0%) of microcrustaceans in a saline environment, and, in its crude form, the biosurfactant ensured the dispersion of no less than 77.56% of residual engine oil in seawater. Oil biodegradation by autochthonous microorganisms reached 94.39% in the presence of the biosurfactant in seawater. Furthermore, the biosurfactant, when used at twice its CMC, acted satisfactorily as a corrosion inhibitor by reducing the mass loss of galvanized iron specimens (plates) in seawater in a static system to only 0.36%. On the other hand, when the biosurfactant was added at the CMC as an atmospheric corrosion inhibitor, the reduction in mass loss of carbon steel plates treated in the ACC was 17.38% compared to the control containing only a biodegradable matrix based on vegetable resin. When the biosurfactant was incorporated into different paints applied to galvanized iron plates placed in contact with the salt spray produced in the ACC, the best result was obtained using the biomolecule at a concentration of 3% in the satin paint, ensuring a plate mass loss (29.236 g/m^2) that was almost half that obtained without surfactant (52.967 g/m^2). The study indicated the use of yeast biosurfactant as a sustainable alternative in combating the contamination of marine environments and metal corrosion, with the aim of preserving the environment and improving the quality of life in aquatic and terrestrial ecosystems.

check for updates

Academic Editor: Agnieszka Cydzik-Kwiatkowska

Received: 6 February 2025
Revised: 4 June 2025
Accepted: 24 June 2025
Published: 26 June 2025

Citation: Selva Filho, A.A.P.; Faccioli, Y.E.S.; Converti, A.; Casazza, A.A.; Soares da Silva, R.d.C.F.; Sarubbo, L.A. The Application of a New Microbial Biosurfactant to Remove Residual Oil from Electric Power Plant and to Inhibit Metal Corrosion in a Salty Environment. *Energies* **2025**, *18*, 3359. https://doi.org/10.3390/en18133359

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Keywords: oil spill; corrosion; biosurfactant; *Starmerella bombicola*; Accelerated Corrosion Chamber

1. Introduction

The main source of energy comes from oil or oil derivatives; however, the transportation and use of these resources lead to contamination of the atmosphere as well as the aquatic and terrestrial environment by hydrocarbons [1–4]. Other pollutants present in ecosystems are heavy metals, also from industrial activities. Thus, the presence of these contaminants increases toxicity and bioaccumulation processes [5–8].

The transportation of oil in maritime environments, which amounts to 35 million barrels/year, is the main source of contamination in these sites. This causes an imbalance in ecosystems through the phenomena of bioaccumulation and biomagnification. In addition, petroleum derivatives are carcinogenic and recalcitrant compounds, which cause harm to the health of living beings affected by the pollution. Several studies describe the use of chemical surfactants, which are oil derivatives, to treat oil spilled into the environment and in industries themselves. These compounds are, in fact, able to make hydrophobic pollutants bioavailable so that microorganisms can degrade them, consequently increasing their biodegradation rate. On the other hand, the synthetic nature of these surfactants also has a negative impact on the treated environments, since they are toxic and non-biodegradable. The process of obtaining these agents also releases greenhouse gases [9–11].

Thus, in recent decades, several studies have been conducted to develop so-called green surfactants, a category of natural and biodegradable surfactants that primarily include microbial surfactants, also known as biosurfactants, and plant surfactants [12–15]. These compounds are amphipathic and, in the case of biosurfactants produced by bacteria, yeasts, and some fungi, they are able to reduce surface and interfacial tensions between phases with distinct polarities at lower concentrations than chemical surfactants [16–22].

The measurement of a surfactant's functionality is based on the Critical Micellar Concentration (CMC), which is the lowest concentration at which its molecules begin to self-aggregate. The resulting micelles are rounded structures with hydrophilic heads facing outward and hydrophobic tails facing inward, which allow the interactivity of nonpolar liquids, such as oils, with polar liquids, such as water [23,24]. The most extensively studied chemical structures of the biosurfactant class are glycolipids and lipopeptides [25,26].

Micelle formation occurs when the water surface becomes saturated with biosurfactant molecules. However, this process is not directly related to the optimal concentration for inhibiting metal corrosion, as certain surfactants exhibit maximum inhibition efficiency at concentrations superior to the critical micelle concentration (CMC). It is known that the polar portion of biosurfactant molecules has a strong affinity for metal surfaces, promoting adsorption onto the metallic substrate. As more biosurfactant is added, a continuous protective layer is formed until the surface is completely covered and adsorption reaches equilibrium [27]. However, micelle formation plays a crucial role in aqueous systems, resulting in anisotropic distribution that alters the physical and mechanical properties of water, such as the flow direction and surface tension. These spherical structures are also essential for solubilizing nonpolar compounds, encapsulating oil droplets within their hydrophobic cores, thereby facilitating the dispersion and removal of contaminants [28]. Thus, the biosurfactant serves not only as a corrosion inhibitor but also as a highly efficient multifunctional agent in both chemical and environmental processes.

Energy industries, such as thermoelectric and oil plants, can apply biosurfactants as corrosion inhibitors in their metal equipment, since, through adsorption, their molecules form a protective layer on the metal surface against these corrosive processes [5,29–31].

Corrosion is also responsible for damage to equipment used in the transportation of oil and gases. Paints are usually applied, which form a barrier to the corrosion process in metal equipment [32–34]. The transportation of gas and oil presents problems of corrosion and formation of hydrated gas agglomerates in the pipelines, which are commonly treated with anti-agglomerants and corrosion inhibitors [35–37]. In recent years, the study of corrosion has gained increasing prominence in the environmental field, where biosurfactants are being explored as inhibitors of atmospheric oxidation [38–40]. Unlike their chemical counterparts, biosurfactants have the advantage of being biodegradable and environmentally compatible, in addition to exhibiting high specificity and stability in different temperature, salinity, and pH ranges. An advance in the area of these biomolecules is the use of low-cost substrate sources such as industrial waste, which makes the production of natural surfactants economically viable [41–43].

In the energy industry, such as the oil industry, biosurfactants, such as glycolipids or lipopeptides, are injected into oil reservoirs, contributing to the reduction in interfacial tensions between oil and water and the breaking of capillary forces that prevent oil from escaping through rock pores in Microbial Enhanced Oil Recovery (MEOR) processes. Biosurfactants such as Emulsan, Liposan, or Alasan are described in the literature for their ability to form stable emulsions with oils, reducing their viscosity and enabling their transportation in pipelines [5,44,45].

The specificity and sustainable nature of biosurfactants have driven research in the environmental field, especially in marine environments [41,46,47]. Seawater is widely used in desalination plants and for cooling equipment, and is often in contact with equipment, commonly causing corrosion. Studies have shown that increasing the concentration of biosurfactants in contact with steel structures reduces the mass loss of these materials submerged in saline water [48–52]. In this context, *Starmerella bombica* is one of the most studied yeast species in the world and is known for producing large amounts of sophorolipids, a type of biosurfactant, as secondary metabolites. This molecule, a glycolipid, contains sophorose and a fatty acid in its structure and is widely used in various industrial fields [53].

In light of this background, the present work aimed to produce a biosurfactant from the yeast strain *Starmerella bombicola* ATCC 222214, evaluate its capacity to decontaminate marine environments polluted by oil, and investigate its application as an inhibitor of metal corrosion caused by physical (air and marine) factors.

2. Materials and Methods

2.1. Microorganism

Starmerella bombicola ATCC 222214 yeast cells from the American Type Culture Collection (ATCC®) were activated at 28 °C for 48 h in an incubator in Yeast Mold Agar (YMA) medium containing 2% agar, 1% D-glucose, 0.5% peptone, and 0.3% yeast extract. The microorganism was then transferred to Erlenmeyer flasks previously autoclaved at 121 °C for 20 min containing Yeast Mold Broth (YMB) medium, pH 7.0, which had the same composition as YMA but without agar. Yeast growth occurred for 24 h at 28 °C under orbital shaking at 150 rpm. Then, dilutions of the culture medium were made until reaching a pre-inoculum of 5% with 10^6 cells/mL to be transferred to the biosurfactant production medium.

2.2. Biosurfactant Production

For biosurfactant production, yeast was grown in mineral medium containing 0.3% $NaNO_3$, 0.05% KH_2PO_3, 0.005% $CaCl_2 \cdot H_2O$, 0.04% $MgSO_4 \cdot 7H_2O$, and 0.005% $FeCl_3$ and supplemented with 5% residual canola oil from frying. This oil, used as an insoluble substrate, was obtained from a commercial establishment in the city of Recife, Brazil. Peel flour of potato (*Solanum tuberosum* L.) acquired from local commercial waste was added as a soluble substrate to the production medium at concentration of 2%. The peels were dried and ground until a powder was obtained. Urea at concentration of 0.2% was used as the nitrogen source. Following the methodology described by Selva Filho et al. [54], fermentations were carried out at 28 °C and pH 6.0 in 1000 mL Erlenmeyer flasks containing 500 mL of the medium, under agitation at 200 rpm, for 180 h, with 5% inoculum.

2.3. Biosurfactant Extraction

Biosurfactant extraction was performed according to Farias et al. [55]. After centrifugation of the metabolic liquid resulting from microbial fermentation at 4400 rpm and 4 °C for 15 min, filtration was performed on Whatmann No. 1 filter paper. Then, the cell-free metabolic liquid was transferred to a separatory funnel, ethyl acetate was added up to a 1:1 (v/v) ratio, the mixture was stirred for 15 min, and the organic phase was extracted. The residue was subjected to extraction with the solvent again. Then, the solvent was evaporated at 40 °C, and the retained portion was washed twice with hexane, which in turn was evaporated. The resulting isolated biosurfactant was quantified by gravimetric analysis to determine the surfactant production yield.

2.4. Toxicity Test with Artemia Salina

Larvae of the microcrustacean *Artemia salina* were acquired from a commercial fishing establishment and incubated for 24 h. Then, 10 larvae were transferred to 10 mL of seawater placed in 15 mL vials containing 1% and 2% solutions of the isolated biosurfactant at half the CMC, the CMC, and twice the CMC [56]. Distilled water was used as a control. After 24 h, the mortality of the microcrustaceans was checked. The toxic concentration was assumed to be the lowest concentration capable of causing the death of the larvae. The CMC of the biosurfactant (2.0 g/L) was previously established by Selva Filho et al. [54].

2.5. Dispersion of Engine Oil in Seawater

The dispersion test was performed by contaminating 5% of the seawater in a Petri dish with engine oil collected from an electric power plant. Biosurfactant solutions were then added in volumetric ratios of 1:2, 1:8, and 1:25 (v/v) of biosurfactant to oil. These biosurfactant solutions were previously prepared in deionized water at concentrations corresponding to half the critical micelle concentration (½ CMC), the CMC, and twice the CMC (2× CMC), as well as biosurfactant at crude form. After preparation, these solutions were applied to the system at final proportions of 1% and 2% (v/v). The effectiveness of dispersion was visually evaluated by measuring the diameter of the clear zone formed in the oil droplet [57].

2.6. Tests of Bioremediation of Oil Spill in Seawater

Microbiological determinations to evaluate the potential of the biosurfactant as a bioremediation agent were performed according to the official Standard Methods for the Examination of Water and Wastewater [58]. Initially, seawater samples (100 mL) were collected. Then, 1% motor oil was added to the flasks together with solutions of the solated biosurfactant at half the CMC, the CMC and twice the CMC. The solutions were incubated at 27 °C and 150 rpm for 30 days, and samples were taken after 1, 7, 14, 21 and 30 days

to count microorganisms using the Most Probable Number (MPN) technique. Decimal dilutions of samples (1/10, 1/1000, and 1/10,000,000) were performed using sterile saline solution (0.85% NaCl, pH 7.2). In parallel, the residual oil was also quantified through gravimetric analysis.

Standard bacterial counts were performed using the pour plate technique. For this purpose, decimal dilutions were performed with buffered water by adding 1 mL of each dilution in duplicate in Petri dishes to the Nutrient Agar culture medium. Colonies were enumerated after 2 days of incubation at 35 °C, and the results were expressed in CFU/mL.

Filamentous fungi and yeasts were counted using Sabouraud Agar culture medium with chloramphenicol distributed in Petri dishes. Dilutions of the samples were added (1 mL) to the culture medium and dispersed with a glass loop (Drigalski). The results obtained after incubation at 25 °C for 5 to 7 days were expressed in CFU/mL of filamentous colonies (filamentous fungi) or milky colonies (yeasts) [59].

2.7. Inhibition of Metal Corrosion in Seawater Using the Isolated Biosurfactant

To test the ability of the biosurfactant to inhibit metal corrosion, the method described by Faccioli et al. [60] was used. Briefly, seawater from Boa Viagem Beach (Recife, Brazil) (1 L); deionized water; and solutions of the isolated biosurfactant at half the CMC, the CMC, and twice the CMC were added to plastic bottles made from PET (polyethylene terephthalate). Distilled water was used as a control instead of seawater.

Metal specimens (plates) made of galvanized iron and carbon steel were initially weighed, tied, and submerged in the fluid. After 90 days, they were removed from the fluid, cleaned, and weighed again. The dynamic process followed the static method, but with the addition of aeration pumps in each fluid contained in each bottle.

The percentage of inhibition of metal corrosion (I_c) was calculated according to the equation

$$I_c = \frac{M_d}{M_a} \times 100\% \quad (1)$$

where M_d and M_a are the masses of specimens after and before the corrosion process, respectively, both expressed in grams.

Furthermore, the corrosion rate (T_c) was calculated as the mass loss of each specimen per unit of time, according to the formula

$$\boldsymbol{T_C = \frac{\Delta M}{\Delta t}} \quad (2)$$

where ΔM and Δt are the changes in mass and time, expressed in grams and days, respectively.

2.8. Evaluation of Biosurfactant Incorporated into Biodegradable Matrix as an Inhibitor of Corrosion Due to Atmospheric Physical Factors on Metal Surfaces

Carbon steel test specimens (Ts) were manufactured with size of 100.0 × 70.0 × 1.0 mm for mass loss tests in the Accelerated Corrosion Chamber (ACC) (Figure 1) developed by Soares da Silva et al. [61]. The Ts were previously cleaned and weighed to determine the initial mass before the test [62]. The test consisted of exposing the Ts for 30 days to a mixture of 5.0% (w/v) sodium chloride in water at a constant temperature of 40 °C and relative humidity close to 100% (simulating the reality of a maritime atmosphere). It was decided to reproduce these atmospheric conditions in an ACC because it allows for (a) obtaining results in much shorter periods of time compared to tests performed in the field, (b) controlling the factors responsible for corrosion attacks, and (c) separately studying these agents with satisfactory repeatability.

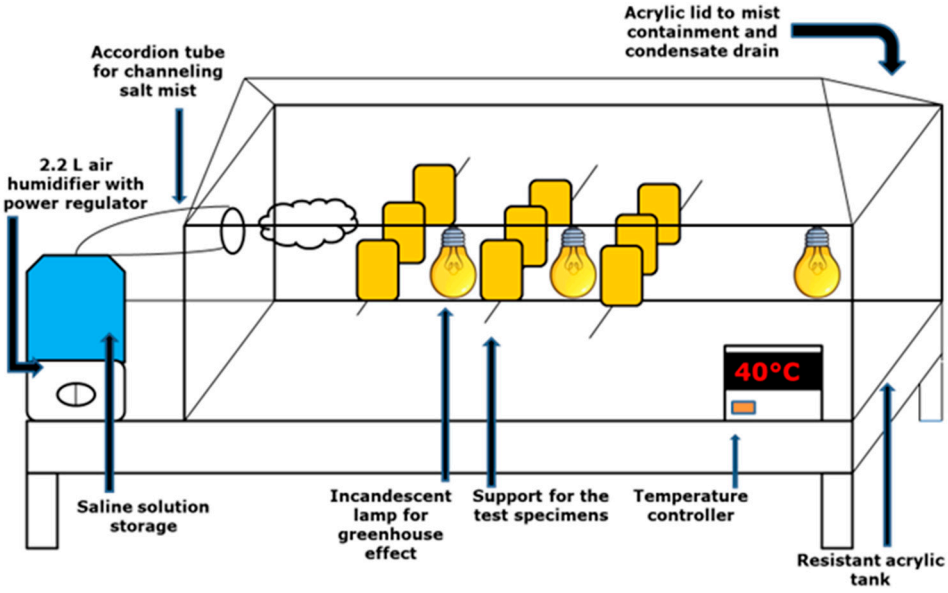

Figure 1. Schematic of the Accelerated Corrosion Chamber containing the test specimens of biodegradable matrix incorporating the isolated *Starmerella bombicola* ATCC °C biosurfactant.

The samples were prepared as described below. The Ts were subjected to the application of a biodegradable matrix, described by Soares da Silva et al. [61], containing rosin resin, oleic acid, ethanol, calcium carbonate ($CaCO_3$), and the isolated biosurfactant at concentrations of half the CMC, the CMC, and twice the CMC. The biosurfactant under study was incorporated into the matrix to act as an adhesion element on the surface of the Ts (Figure 2). The Ts were cleaned and dried to perform a careful evaluation of the extent of corrosion and other visible effects.



Figure 2. Carbon steel plates placed in the Accelerated Corrosion Chamber and coated with a biodegradable matrix containing rosin resin, oleic acid, ethanol, and calcium carbonate and incorporating the biosurfactant from *Starmerella bombicola* ATCC 222214.

The Ts were then subjected to the following chemical cleaning process: immersion in 26% HCl, washing in running water, neutralization with 10% NaOH solution, washing again in running water, drying, sanding, immersion in isopropyl alcohol and acetone, drying with hot air and, finally, cooling to room temperature, as described by Dantas [63]

and Oliveira [64]. The objective of this treatment was to remove corrosion products. The mass loss (L), expressed in g/m^2, was obtained by the equation

$$L = \frac{M_0 - M_f}{A} \quad (3)$$

where M_f and M_0 are the final and initial masses after and before the corrosion process, respectively, both expressed in grams, and A is the area of the plates in m^2. An analytical balance was used to determine the Ts final mass, after the test, to calculate the mass loss.

2.9. Biosurfactant's Incorporation into Synthetic Enamels

Synthetic enamels, obtained from three different companies, were applied as coating matrix incorporating the biosurfactant from *S. bombicola* ATCC 222214. The Ts used in this kind of test were plates (61.0 × 31.0 × 5.0 mm) made of galvanized iron, a material commonly subjected to paint applications in everyday life (Figure 3). These paints, which followed their respective Material Safety Data Sheets, presented the characteristics and compositions listed in Table 1.

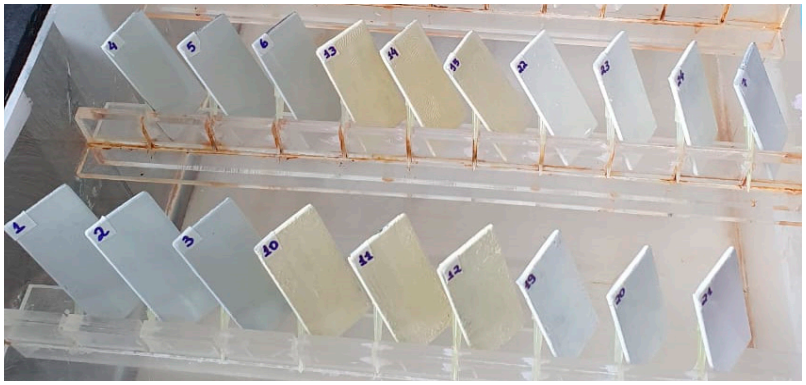

Figure 3. Illustration of galvanized iron plates coated with satin paints based on quick-drying alkyd and synthetic resin, with and without the incorporation of the isolated *Starmerella bombicola* ATCC 222214 biosurfactant.

Table 1. Characteristics and compositions of the paints used to coat the test specimens.

Paint	Characteristics	Composition	Color	Application
Type A	Easy-to-apply alkyd resin-based enamel with quick drying and good coverage, 900 mL	Resin consisting of polyalcohols, polyacids, aliphatic solvent, active pigments, additives, drying oils, and turpentine	Ice white	Covering of external and internal surfaces of wood, metal, and masonry
Type B	Quick-drying satin synthetic enamel, 900 mL	Resin containing polyacids, polyalcohols, pigments, solvents, additives, and oils	Bright ivory	External covering of wood, metal, galvanized steel, and aluminum
Type C	Premium quick-drying synthetic enamel, 900 mL	Hydrated light petroleum distillates, xylene, toluene, cobalt octoate, manganese octoate, and methyl ethyl ketoxime	Snow white	Covering of wood, aluminum, ferrous metals, galvanized steel, and masonry surfaces

2.10. Application of Biosurfactant as an Additive in Synthetic Enamels to Inhibit Metal Corrosion Due to Atmospheric Physical Factors

The *S. bombicola* ATCC 222214 biosurfactant was added at a concentration of 3% to each type of selected synthetic enamel in order to (a) reduce its toxicity, being a natural

component, and (b) inhibit metal corrosion in ACC simulating a critical marine atmosphere. Particularly, the paints were applied, as described by Pontes et al. [65], by covering the galvanized iron plates with two thin and homogeneous layers, waiting 24 h for drying, and working in ACC for 15 days.

At the end of the process, the Ts, which had been sanded and weighed before the paint was applied, were subjected to chemical cleaning, as described by Dantas [63] and Oliveira [64]. The plates were then weighed again to quantify the corrosion extent using the mass loss formula (Equation (2)). Therefore, the tested Ts plus the plates coated with paints without biosurfactant (controls) included 6 systems.

2.11. Statistical Analysis of Results

The results of experiments were obtained in quintuplicate and expressed as mean ± standard deviation. In addition, Analysis of Variance (ANOVA) was performed in order to determine the significance levels at which p-values < 0.05 were considered statistically significant.

3. Results and Discussion

3.1. Toxicity of the Biosurfactant to Artemia Salina

The test of *Starmerella bombicola* ATCC 222214 biosurfactant toxicity to larvae of the microcrustacean *Artemia salina* revealed a slightly progressive mortality rate of the bioindicator with an increasing surfactant concentration. The highest mortality rate (30%) was observed using the biosurfactant at twice the CMC (Table 2), which indicates its low toxicity for the microcrustacean, enabling its application in the environment (Table 2).

Table 2. Mortality rate of *Artemia salina*, expressed as a percentage, caused by the *Starmerella bombicola* ATCC 222214 biosurfactant.

Biosurfactant Concentration with Deionized Water as Solvent	*Artemia salina* Mortality Rate	
	1% Biosurfactant Solution in Sea Water	2% Biosurfactant Solution in Sea Water
½ × CMC	3.0% ± 0.8	10.0% ± 0.3
CMC	13.0% ± 0.2	17.0% ± 0.2
2 × CMC	17.0% ± 0.2	30.0% ± 0.4

The corresponding percentage of live microcrustaceans (70%) can be considered satisfactory when compared to the 100% value observed in the presence of the lipopeptide produced by the bacterium *Bacillus cereus* [66] and the glycolipid produced by the fungus *Trichoderma* sp. MK116452 [67], both at a concentration of 1.0 g/L.

Furthermore, when comparing the 70% microcrustacean survival rate observed in the present study using 0.08 g/L *S. bombicola* ATCC 222214 biosurfactant with the value obtained by Deivakumari et al. (80%) for the same target organism using 0.10 g/L *Pseudomonas aeruginosa* DKB1 surfactant [68], it is evident that the efficiency of these biosurfactants is similar.

This type of toxicity test is crucial to prove that biosurfactants are less toxic and sustainable when compared to chemical surfactants. In fact, the work of Deivakumari et al. [68] demonstrated that the chemical surfactant sodium dodecyl sulfate was capable of causing 100% mortality in this marine organism at a concentration of only 0.05 g/L. Furthermore, it should be taken into account that the concentrations tested in this study for the *S. bombicola* ATCC 222214 biosurfactant led to mortality values always well below 50%, that is, below the median lethal concentration (LC50), thereby exhibiting no acute toxicity.

3.2. Dispersion of Engine Oil in Seawater

The dispersion experiment demonstrated that the metabolic liquid of *S. bombicola* ATCC 222214 containing the crude biosurfactant dispersed the engine oil more than the isolated biosurfactant at half the CMC, the CMC, and twice the CMC (Figure 4). In the case of the isolated biosurfactant, the higher its concentration, the greater its dispersion in engine oil (Table 3). It is likely, therefore, that other residual metabolites present in the metabolic liquid contributed to the dispersion. This result can be considered satisfactory if we consider that there will be no costs involved in the extraction process when using the crude preparation. Another important fact is the use of all the metabolic liquid, avoiding medium disposal, in addition to increasing the feasibility of biosurfactant application, considering the volume necessary for treatment in the event of a spill at sea.

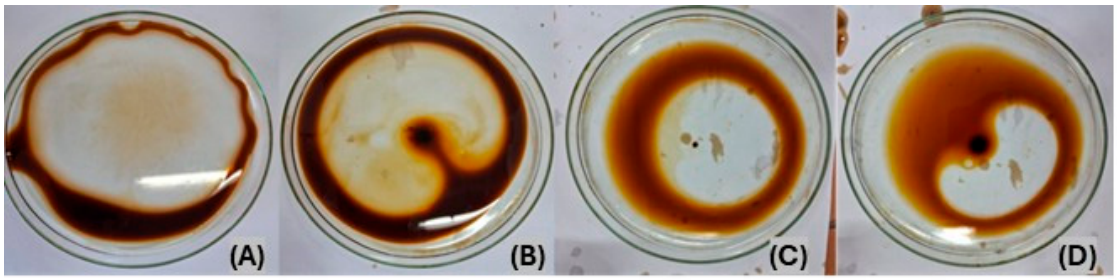

Figure 4. Halos formed in engine oil droplets in seawater after the addition of crude biosurfactant (**A**) and isolated biosurfactant at twice the CMC (**B**), at the CMC (**C**), and at half the CMC (**D**).

Table 3. Results of the test of engine oil dispersion in seawater due to the action of the biosurfactant from *Starmerella bombicola* ATCC 222214.

Biosurfactant/Oil Ratio (*v*/*v*)	Oil Dispersion Rate (%)			
	1/2 × CMC	CMC	2 × CMC	Crude Biosurfactant
1:2	23.3 ± 0.9	25.6 ± 0.6	28.9 ± 0.8	73.0 ± 0.7
1:8	25.6 ± 0.9	45.0 ± 0.7	52.3 ± 0.8	77.6 ± 0.5
1:25	22.2 ± 0.6	37.5 ± 0.6	46.7 ± 0.6	70.1 ± 0.9

The best ratio using the metabolic liquid was 1:8 (*v*/*v*) biosurfactant:oil, at which the engine oil dispersion reached 77.6% (Table 3). This result is not so far from that observed by Santos et al. [69] (90%) using the biosurfactant from the yeast *Candida sphaerica* in the same biosurfactant:oil ratio. Continuing the comparison with values reported in the literature, the crude biosurfactant from the bacterium *Serratia marcescens* UCP 1549, later investigated by the same authors [70], was able to disperse 88.9% of engine oil in distilled water at a ratio of 1:2 (*v*/*v*) surfactant:oil, a value very close to that obtained in this study (73.0%) in the same oil proportion but in seawater.

In conclusion, it is worth remembering that the dispersion of hydrocarbons by biosurfactants is very important, as it aids in the microbial degradation of oil spilled in seawater [71]. The greater dispersion presented by the metabolic broth and the isolated biosurfactant at twice the critical micelle concentration (CMC) demonstrates enhanced hydrophobicity and, consequently, greater dispersion of the engine oil [72]. Similarly, a mixture of the lactonic sophorolipid produced from the same yeast with a synthetic surfactant, choline oleate, achieved 81.15% dispersion in a 1:25 proportion with petroleum oil in synthetic seawater [72]. In this case, the same proportion of the metabolic liquid containing the nonanedioic biosurfactant of *Starmerella bombicola* reached 70.1% with the engine oil in seawater [54].

3.3. Bioremediation of Oil Spills in Seawater

The potential of the biosurfactant as an adjuvant in degradation processes was evaluated in experiments simulating an oil spill in seawater. The behavior of the autochthonous microorganisms in seawater revealed that the bacteria grew until the 21st day, reaching a count of 1.0×10^7 CFU/mL, before decreasing, while the yeasts grew until reaching 2.7×10^2 CFU/mL on the 14th day. Therefore, in this sample, the bacterial population was much greater than that of the other microorganisms (Figure 5A).

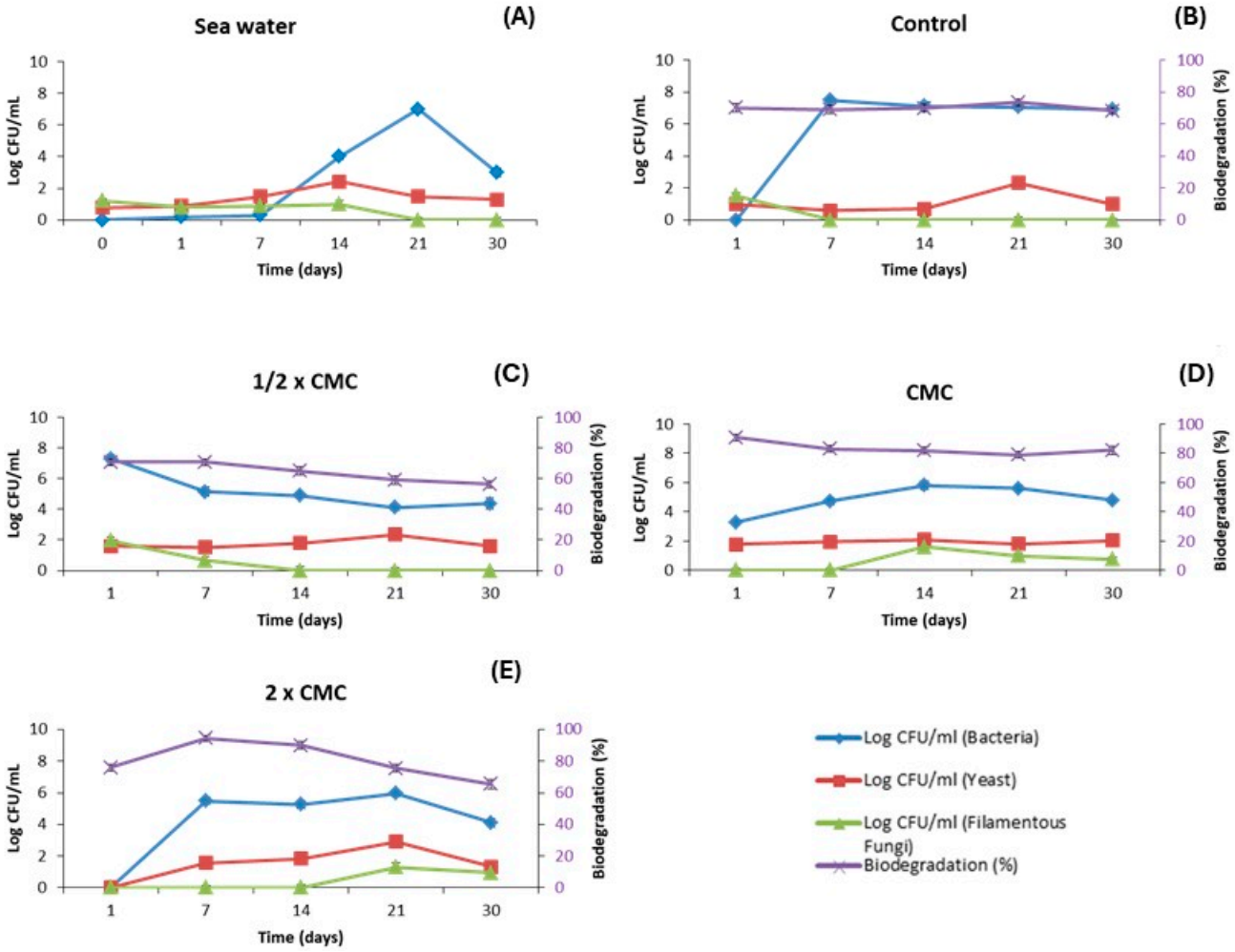

Figure 5. Influence of *Starmerella bombicola* ATCC 222214 biosurfactant on the growth of microorganisms and biodegradation of motor oil in seawater. (**A**) Seawater without oil and without biosurfactant; (**B**) seawater with oil and without biosurfactant; (**C**) seawater with oil and with biosurfactant at half the CMC; (**D**) seawater with oil and with biosurfactant at the CMC; (**E**) seawater with oil and with biosurfactant at twice the CMC.

In the case of seawater contaminated with engine oil, the bacteria grew up to 3.0×10^7 CFU/mL on the 7th day and maintained their count stable until the end of the test (30th day). The yeasts remained stable until the 14th day; grew until the 21st day, reaching 2.1×10^2 CFU/mL; and then their population began to decline. The filamentous fungi peaked on the 1st day with a count of 3.2×10^1 CFU/mL, from which point onwards there was a decline. The oil biodegradation rate reached its highest value (73.57%) at the peak of yeast growth (Figure 5B).

On the other hand, when the biosurfactant was added at half the CMC, the bacterial population, which initially totaled 2.0×10^7 CFU/mL, progressively decreased until the end of the test. Unlike the bacteria, the yeasts grew until the 21st day, reach-

ing 2.1 × 10^2 CFU/mL, and then started to decline, while the filamentous fungi, initially totaling 8.9 × 10^1 CFU/mL, showed a progressive decrease until the 14th day. The biodegradation accompanied the bacterial growth, starting with a 70.64% engine oil removal yield, followed by a slight decrease to 68.25% on the 30th day (Figure 5C).

The addition of the biosurfactant at the CMC caused the bacteria to grow exponentially up to 6.5 × 10^5 CFU/mL on the 14th day, reaching the stationary phase on the 21st day and then declining until the end of the run. The yeast population remained approximately stable throughout the run, with the highest count (1.3 × 10^2 CFU/mL) occurring on the 14th day. Filamentous fungi grew from the 7th to the 14th day, reaching 4.0 × 10^1 CFU/mL, and then their population began to decline until the end of the run. Biodegradation was stable in a similar way to yeast growth, reaching an engine oil removal yield as high as 90.76% on the 1st day (Figure 5D).

The last run was carried out using the biosurfactant at twice the CMC. The bacteria and yeasts showed qualitatively the same behavior, growing sharply until the 7th day and progressively until the 21st day, when both populations began to decrease. The largest yeast population (7.8 × 10^2 CFU/mL) was found precisely in this system, while the bacteria reached only 9.1 × 10^5 CFU/mL. The filamentous fungi began to grow on the 14th day, reached a count of 2.0 × 10^1 CFU/mL on the 21st day, and then began to decline. Biodegradation increased until the 7th day and then decreased progressively. It was precisely in this system that the highest oil removal yield (94.39%) was obtained (Figure 5E).

In summary, the experiment of petroleum derivative bioremediation demonstrated that bacteria grew the most in the control, reaching 3.0 × 10^7 CFU/mL on the 7th day, while the highest counts of yeasts (7.8 × 10^2 CFU/mL) and filamentous fungi (8.9 × 10^1 CFU/mL) were observed using the biosurfactant at twice the CMC on the 21st day and at half the CMC on the 1st day, respectively. The highest biodegradation yield was obtained using the highest biosurfactant concentration after 7 days (Figure 5E). Furthermore, the pH in all systems remained between 6.0 and 7.7 throughout the process, a range that is commonly found in the presence of microorganisms, being ideal for microbial growth (Figure 6).

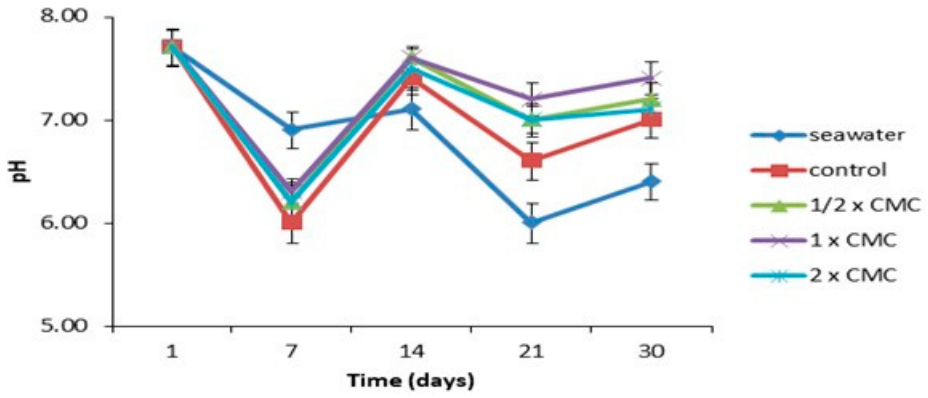

Figure 6. pH evolution over time during engine oil degradation runs carried out in seawater in the presence of *Starmerella bombicola* ATCC 222214 biosurfactant at different concentrations. Seawater without oil and without biosurfactant (◆); seawater with oil and without biosurfactant (■); seawater with oil and with biosurfactant at half the CMC (▲); seawater with oil and with biosurfactant at the CMC (×); and seawater with oil and with biosurfactant at twice the CMC (✳).

The present study identified an optimal pH of approximately 6.0 for bacterial growth, around 7.0 for yeasts, and near 7.5 for filamentous fungi. The highest rate of oil biodegradation was observed at a pH of approximately 6.5, aligning with the findings reported by Kebede et al. [73], who previously reported and reinforced that slightly acidic to neutral conditions are optimal for enhanced microbial activity in hydrocarbon degradation.

Residual products of microorganisms alter the pH, which consequently influences the availability of nutrients and the solubility of the contaminant [73]. In a study carried out by Soares da Silva et al. [74], bacteria showed greater growth up to the 14th day and fungi after the 14th day, while the highest biodegradation rate (75%) was observed using the *Pseudomonas cepacia* biosurfactant at concentrations equal to three and five times the CMC. As in the study carried out by Almeida et al. [75] with the biosurfactant from *Candida tropicalis* UCP0996, the surfactant tested in the present study provided greater growth of autochthonous microorganisms and consequently greater degradation of engine oil in seawater when compared to the control, demonstrating its ability as a bioremediation additive. The yield of petroleum-derived hydrocarbon degradation in the presence of the bacterial biosurfactant produced in situ by *Enterobacter hormaechei* STP-3 reached a value close to 80% in seawater within 7 days [76]. Finally, the engine oil removal yield (94.39%) obtained using the *S. bombicola* ATCC 222214 biosurfactant ex situ was higher than that (85%) reported for the bacterial biosurfactant from *Enterobacter hormaechei* by Muneeswari et al. [76].

3.4. Inhibition of Metal Corrosion by the Isolated Biosurfactant in Seawater

The experiment on metal corrosion inhibition in seawater demonstrated that in the dynamic system, greater mass loss was observed when compared to the static system, due to aeration, which made the Ts more susceptible to oxidation (Figure 7). This was verified by the values of mass loss over time illustrated in Figure 8. In addition, the biosurfactant at a concentration equal to half the CMC reduced the metal corrosion of the carbon steel specimens by no less than 99.75%. In general, there was greater inhibition in the carbon steel Ts than in the galvanized iron ones (Figure 8).



Figure 7. Galvanized iron and carbon steel metal specimens after corrosion in seawater in the dynamic system (**A**) without and (**B**) with *Starmerella bombicola* ATCC 222214 biosurfactant. Metal specimens after the chemical cleaning process (**C**) without and (**D**) with biosurfactant.

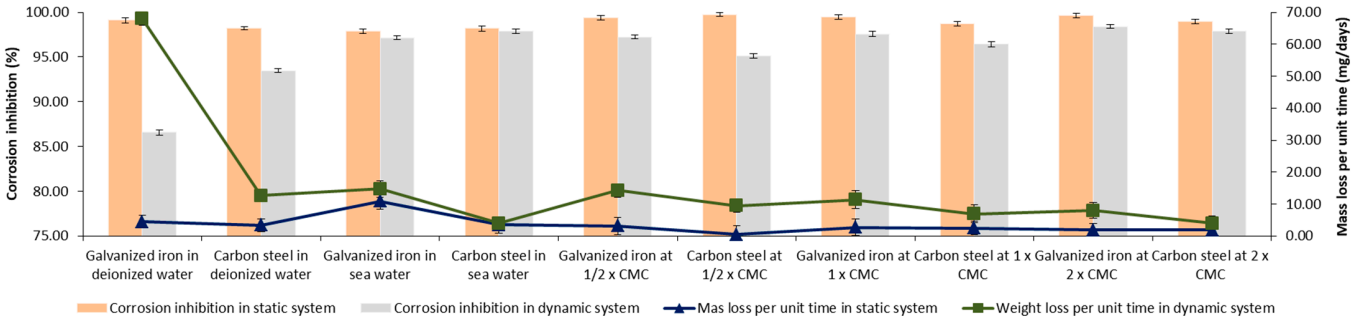

Figure 8. Inhibition of metal corrosion and mass loss as functions of time in galvanized iron and carbon steel specimens when using deionized water, seawater, and *Starmerella bombicola* ATCC 222214 biosurfactant in seawater at concentrations of ½ × CMC, 1 × CMC, and 2 × CMC in static and dynamic systems.

The mass loss in galvanized iron Ts using deionized water as a control reached 13.41% in the dynamic system, a value close to that reported by Faccioli et al. [60] (18%) in a similar system. Furthermore, in that study, the isolated biosurfactant from *P. cepacia* led to a nearly 2% mass loss decrease in galvanized iron specimens in the static system, while in the present study, the addition of *S. bombicola* ATCC 222214 biosurfactant at twice the CMC in a similar system ensured a mass loss as low as 0.36% (Figure 9).

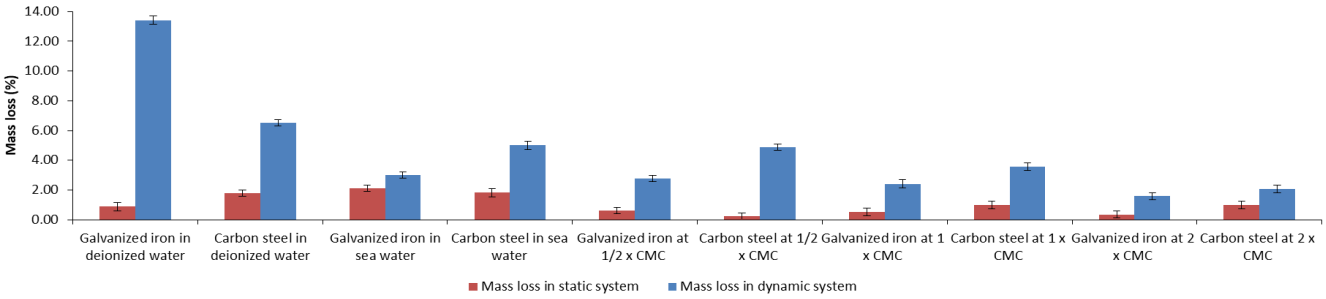

Figure 9. Mass loss in galvanized iron and carbon steel specimens when using deionized water, seawater, and *Starmerella bombicola* ATCC 222214 biosurfactant in seawater at concentrations of ½ × CMC, 1 × CMC, and 2 × CMC in static and dynamic systems.

In the study performed by Li et al. [77] simulating seawater conditions, the *P. aeruginosa* biosurfactant reduced the mass loss in carbon steel Ts by 1.96 and 0.79 mg/cm^2 compared to the control and the initial mass, respectively. In the present study, the *S. bombicola* ATCC 222214 biosurfactant at twice the CMC in a static system had a reduction that was an order of magnitude higher (16.44 mg/cm^2) for galvanized iron Ts in seawater compared to the control, thereby demonstrating its great effectiveness in this regard.

In the study developed by Tang et al. [36], oleic acid-based biosurfactants were physically and chemically adsorbed on the surface of solid steel in an almost parallel direction, effectively protecting the surface, leading to a surface exposed to corrosion of only 1%. Similarly, the yeast biosurfactant resulted in a minimal mass loss of 1.01% in carbon steel in a static system in seawater. It is essential to note that the salts present in seawater render the medium highly corrosive due to electrochemical reactions, similar to the water simulated to contain H_2S and CO_2 in an oil field, which was also highly corrosive due to electrochemical reactions.

3.5. Biosurfactant in Biodegradable Matrix as an Inhibitor of Corrosion Due to Atmospheric Physical Factors

It can be seen in Figure 10 that, in the biodegradable matrix, the isolated *S. bombicola* ATCC 222214 biosurfactant significantly reduced corrosion by atmospheric physical factors.

Particularly, the Ts mass losses per unit area in the control and in the presence of the biosurfactant at half the CMC, the CMC, and twice the CMC were, at the end of the 30-day experiment in the ACC (30 days), 123.60, 25.22, 18.93, and 22.12 g/m^2, respectively.

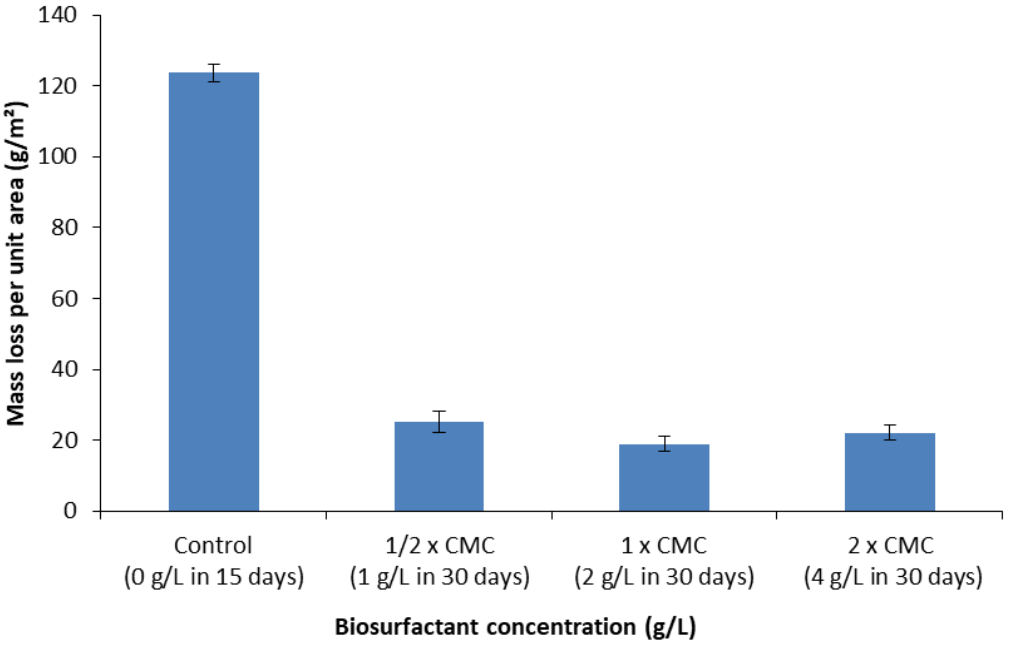

Figure 10. Mass loss per unit area in carbon steel specimens containing the biodegradable matrix subjected to salt spray in the Accelerated Corrosion Chamber at 40 °C with and without the *Starmerella bombicola* ATCC 222214 biosurfactant at concentrations of half the CMC, the CMC, and twice the CMC.

The treatment with the biosurfactant, compared to the control, led to a mass loss due to corrosion by atmospheric physical factors (17.38%) close to that due to biological factors (15.7%) reported by Faccioli et al. [60] using the *P. cepacia* biosurfactant. Furthermore, Soares da Silva et al. [61] reported a mass loss per unit area of 90.1 g/m^2 using the same biodegradable matrix under the same conditions, but incorporating the *P. cepacia* surfactant at half of the CMC. This proves that biosurfactants are promising in reducing mass loss on metal surfaces.

When carbon steel specimens containing the biodegradable matrix incorporating the *S. bombicola* ATCC 222214 biosurfactant at the CMC were exposed to salt spray in ACC at 40 °C, the mass loss (18.93 g/m^2) was much lower than that extrapolated to 30 days for copper foils submerged in 1.0 M HNO_3 at 24.85 °C (10,800 g/m^2) using the biosurfactant sodium N-hexadecyl valine [78] at a concentration of 80 mg/L.

3.6. Use of Synthetic Enamels with Biosurfactant to Inhibit Corrosion Due to Atmospheric Physical Factors

The galvanized iron Ts, after being subjected to the corrosion process in ACC for 15 days, were cleaned and weighed in order to measure the mass loss per unit area. This time was selected so that the corrosion process would become visually evident in specimens coated with the three selected enamels from different brands, as well as in the controls without biosurfactant.

The control specimens suffered a higher level of corrosion than those coated with paints containing the *S. bombicola* ATCC 222214 biosurfactant. This was confirmed by the higher values of mass loss per unit area in the control specimens coated with ice white (type A) (58.032 g/m^2), bright ivory (type B) (52.967 g/m^2), and snow white (type C) (82.208 g/m^2) paints compared to those coated with biosurfactant-incorporating paints (36.595, 29.236 and 41.099 g/m^2, respectively) (Figure 11).

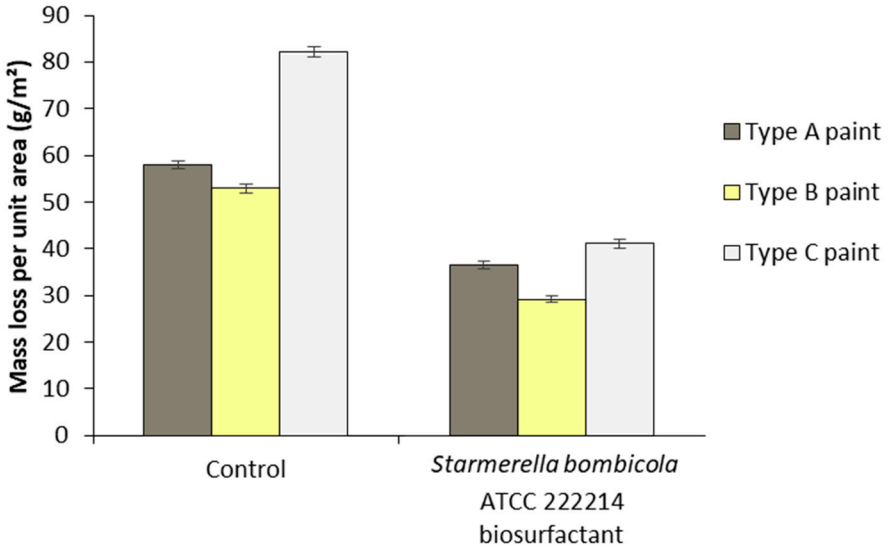

Figure 11. Mass loss in galvanized iron plates treated in an Accelerated Corrosion Chamber after coating with synthetic paints with and without *Starmerella bombicola* ATCC 222214 biosurfactant. Paint A—formulated with resin based on polyacids, polyalcohols, drying oils, active pigments, additives, aliphatic solvent, and turpentine. Paint B—formulated with light hydrated petroleum distillates, xylene, toluene, cobalt octoate, manganese octoate, and methyl ethyl ketoxime. Paint C—formulated with resin based on oils, polyacids and polyalcohols, solvents, additives, and pigments.

In the work carried out by Soares da Silva et al. [61], the same enamels were used on galvanized iron plates treated in the same ACC, but incorporating the *P. cepacia* biosurfactant. The loss of mass per unit area in the Ts coated with paint type A (46.010 g/m^2) was approximately 25% higher than that obtained in the present study using the biosurfactant from *S. bombicola* ATCC 222214. The mass loss values for the coating with type B paint, in turn, were similar for both biosurfactants.

Nao-ionic gemini surfactants synthesized by Deyab et al. [79] using natural sources, including polyethenoxy di-dodecanoate, led to much higher mass loss (2916 g/m^2 corresponding to 0.81 mg/cm^2·h) in carbon steel Ts after 15 days of exposure to 1.0 M HCl solution at 54.85 °C than the maximum value detected in this study using the biosurfactant from *S. bombicola* ATCC 222214 (41.099 g/m^2).

On the other hand, the study developed by Semeniuk et al. [32], who worked with rhamnolipid-incorporated paint to coat steel plates in a 0.1% NaCl solution environment at 20 °C, indicated values for corrosion rate and degree of protection of the plates against corrosion of 1.85 10^{-6} g/cm^2·h and 55%, respectively. Thus, the corrosion rate obtained by Semeniuk et al. [32] was lower than that of the present study, incorporating the yeast biosurfactant, which was estimated to be 8.1211·10^{-6} g/cm^2·h. However, the degree of protection of the plates was similar, being 45% for the yeast biomolecule added to type B paint, even in a more critical environment (5% NaCl at 30 °C), than the rhamnolipid.

In summary, the present mass loss results demonstrated that the addition of the biosurfactant from *S. bombicola* ATCC 222214 to enamels improved their deposition on the metal surface of galvanized iron plates and increased the Ts resistance against corrosion resulting from the simulation of a maritime atmosphere. Thus, the biomolecule acted effectively in inhibiting metal corrosion.

As is known, the mechanism by which a biosurfactant acts to protect a metal surface against electrochemical corrosion reactions occurs through its physical adsorption on a metal surface. Furthermore, the presence of an oxygen atom in the polar moiety of a biosurfactant molecule provides a pair of electrons to the metal surface, strengthening the intermolecular bond, in addition to its nonpolar moiety forming a barrier capable of re-

pelling the electrochemical reactions responsible for corrosion [32]. The presence of oxygen in the hydrophilic portion and of hydrocarbons in the hydrophobic portion of the biosurfactant investigated in this study was previously proven through chemical characterization by gas chromatography with mass spectrometry, Fourier transform infrared spectroscopy, and nuclear magnetic resonance, which allowed the entify of 6,6-dimethoxyoctanoic acid and nonanedioic acid [54].

4. Conclusions

The biosurfactant from the yeast *Starmerella bombicola* ATCC 222214 was shown to be harmless to larvae of the microcrustacean *Artemia salina* and demonstrated dispersion power in seawater. The biomolecule acted as a stimulant of the growth of autochthonous microorganisms in seawater, which suggests its use as an agent to promote bioremediation processes in marine environments contaminated by oil and derivatives.

Corrosion tests in an Accelerated Corrosion Chamber also demonstrated the ability of the yeast biosurfactant to protect metal surfaces subjected to atmospheric oxidation and in seawater. This study also revealed that the biosurfactant can act incorporated into a biodegradable coating matrix and as a paint additive, contributing to the better protection of metal surfaces against corrosion. This was proven by low values of mass loss in carbon steel and galvanized iron specimens.

In conclusion, the microbial surfactant investigated in this study can be considered promising since bioremediation and corrosion processes are quite common in tropical regions with high temperatures and salinities, especially in Brazil, causing damage to both the environment and industries. Visionary developed countries are already investing in ecological corrosion inhibitors, which, in turn, are biodegradable and do not cause environmental damage. As a result, ecological products are gaining ground in the market.

Author Contributions: Conceptualization: L.A.S. and R.d.C.F.S.d.S.; methodology: L.A.S. and R.d.C.F.S.d.S.; validation: L.A.S., R.d.C.F.S.d.S., A.A.C. and A.C.; formal analysis: A.A.P.S.F. and Y.E.S.F.; investigation: A.A.P.S.F. and Y.E.S.F.; resources: L.A.S.; writing—original draft preparation: A.A.P.S.F., R.d.C.F.S.d.S. and Y.E.S.F.; writing—review and editing: L.A.S., A.A.C. and A.C.; visualization: L.A.S. and A.C.; supervision: L.A.S. and R.d.C.F.S.d.S.; project administration: L.A.S.; funding acquisition: L.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Fundação de Apoio à Ciência e Tecnologia do Estado de Pernambuco (FACEPE [State of Pernambuco Science Assistance Foundation]), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq [National Council of Scientific and Technological Development]), and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES [Coordination for the Advancement of Higher Education Personnel]; Finance Code-001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors are grateful for the assistance provided by the Catholic University of Pernambuco (UNICAP) and the Advanced Institute of Technology and Innovation (IATI), Brazil.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could constitute a potential conflict of interest.

References

1. Singh, R.; Rathore, D. Effects of fertilization with textile effluent on germination, growth and metabolites of chilli (*Capsicum annum* L.) cultivars. *Environ. Process.* **2021**, *8*, 1249–1266. [CrossRef]
2. Ossai, I.C.; Ahmed, A.; Hassan, A.; Hamid, F.S. Remediation of soil and water contaminated with petroleum hydrocarbon: A review. *Environ. Technol. Innov.* **2020**, *17*, 100526. [CrossRef]
3. Elijah, A.A. A review of the petroleum hydrocarbons contamination of soil, water and air and the available remediation techniques, taking into consideration the sustainable development goals. *Earthline J. Chem. Sci.* **2022**, *7*, 97–113. [CrossRef]
4. Kuppusamy, S.; Maddela, N.R.; Megharaj, M.; Venkateswarlu, K. Fate of total petroleum hydrocarbons in the environment. In *Total Petroleum Hydrocarbons: Environmental Fate, Toxicity, and Remediation*; Kuppusamy, S., Maddela, N.R., Megharaj, M., Venkateswarlu, K., Eds.; Springer: Cham, Switzerland, 2020; pp. 57–77. [CrossRef]
5. Faccioli, Y.E.S.; Oliveira, K.W.; Campos-Guerra, J.M.; Converti, A.; Soares da Silva, R.C.F.; Sarubbo, L.A. Biosurfactants: Chemical properties, ecofriendly environmental applications, and uses in the industrial energy sector. *Energies* **2024**, *17*, 5042. [CrossRef]
6. Chormare, R.; Kumar, M.A. Environmental health and risk assessment metrics with special mention to biotransfer, bioaccumulation and biomagnification of environmental pollutants. *Chemosphere* **2020**, *302*, 134836. [CrossRef]
7. Souza, P.F.; Vieira, K.S.; Gaylarde, C.C.; Lima, L.S.; Azevedo-Netto, A.; Delgado, J.F.; Corrêa, T.R.; Baptista Neto, J.A.; Fonseca, E.M. Heavy metal and hydrocarbons bioaccumulation by two bivalve's species from Santos Bay, Brazil. *Stud. Neotrop. Fauna Environ.* **2024**, *59*, 123–131. [CrossRef]
8. Long, Z.; Huang, Y.; Zhang, W.; Shi, Z.; Yu, D.; Chen, Y.; Liu, C.; Wang, R. Effect of different industrial activities on soil heavy metal pollution, ecological risk, and health risk. *Environ. Monit. Assess.* **2021**, *193*, 20. [CrossRef] [PubMed]
9. Vigil, T.N.; Felton, S.M.; Fahy, W.E.; Kinkeade, M.A.; Visek, A.M.; Janiga, A.R.; Jacob, S.G.; Berger, B.W. Biosurfactants as templates to inspire new environmental and health applications. *Front. Synth. Biol.* **2024**, *2*, 1303423. [CrossRef]
10. Stubbs, S.; Yousaf, S.; Khan, I. A review on the synthesis of bio-based surfactants using green chemistry principles. *DARU J. Pharm. Sci.* **2022**, *30*, 407–426. [CrossRef]
11. Nagtode, V.S.; Cardoza, C.; Yasin, H.K.A.; Mali, S.N.; Tambe, S.M.; Roy, P.; Singh, K.; Goel, A.; Amin, P.D.; Thorat, B.R.; et al. Green surfactants (biosurfactants): A petroleum-free substitute for sustainability– Comparison, applications, market, and future prospects. *ACS Omega* **2023**, *8*, 11674–11699. [CrossRef]
12. Zahed, M.A.; Matinvafa, M.A.; Azari, A.; Mohajeri, L. Biosurfactant, a green and effective solution for bioremediation of petroleum hydrocarbons in the aquatic environment. *Discov. Water* **2022**, *2*, 5. [CrossRef]
13. Rizvi, H.; Verma, J.S.; Ashish. Biosurfactants for oil pollution remediation. In *Microbial Biosurfactants: Preparation, Properties and Applications*; Inamuddin, Ahamed, M.I., Prasad, R., Eds.; Springer: Singapore, 2021; pp. 197–212. [CrossRef]
14. Siddiqui, Z.; Anas, M.; Khatoon, K.; Malik, A. Biosurfactant-producing bacteria as potent scavengers of petroleum hydrocarbons. In *Microbiomes and the Global Climate Change*; Lone, S.A., Malik, A., Eds.; Springer: Singapore, 2021; pp. 321–348. [CrossRef]
15. Gaur, V.K.; Gupta, S.; Pandey, A. Evolution in mitigation approaches for petroleum oil-polluted environment: Recent advances and future directions. *Environ. Sci. Pollut. Res.* **2022**, *29*, 61821–61837. [CrossRef] [PubMed]
16. Arumanatharayil, J.J. Exploring the Effectiveness of Biosurfactant in Enhancing Oil Recovery and Reducing Environmental Impact in Oil and Gas Industry. Master's degree dissertation, Technische Universität Wien, Vienna, Austria, 2024.
17. Jahan, R.; Bodratti, A.M.; Tsianou, M.T.; Alexandridis, P. Biosurfactants, natural alternatives to synthetic surfactants: Physicochemical properties and applications. *Adv. Colloid Interface Sci.* **2020**, *275*, 102061. [CrossRef]
18. Drakontis, C.E.; Amin, S. Biosurfactants: Formulations, properties, and applications. *Curr. Opin. Colloid Interface Sci.* **2020**, *48*, 77–90. [CrossRef]
19. Hausmann, R.; Déziel, E.; Soberón-Chávez, G. Microbial biosurfactants: Updates on their biosynthesis, production and applications. *Front. Bioeng. Biotechnol.* **2024**, *12*, 1433035. [CrossRef]
20. Adu, S.A.; Naughton, P.J.; Marchant, R.; Banat, I.M. Microbial biosurfactants in cosmetic and personal skincare pharmaceutical formulations. *Pharmaceutics* **2020**, *12*, 1099. [CrossRef]
21. Johnson, P.; Trybala, A.; Starov, V.; Pinfield, V.J. Effect of synthetic surfactants on the environment and the potential for substitution by biosurfactants. *Adv. Colloid Interface Sci.* **2021**, *288*, 102340. [CrossRef]
22. Markande, A.R.; Patel, D.; Varjani, S. A review on biosurfactants: Properties, applications and current developments. *Bioresour. Technol.* **2021**, *330*, 124963. [CrossRef]
23. Perinelli, D.R.; Cespi, M.; Lorusso, N.; Palmieri, G.F.; Bonacucina, G.; Blasi, P. Surfactant self-assembling and critical micelle concentration: One approach fits all? *Langmuir* **2020**, *36*, 5745–5753. [CrossRef]
24. Zhang, X.; Li, F.; Zhao, X. Treatment of surfactants with concentrations below critical micelle concentration by ultrafiltration: A mini-review. *Water Cycle* **2022**, *3*, 50–55. [CrossRef]
25. Moldes, A.B.; Álvarez-Chaver, P.; Vecino, X.; Cruz, J.M. Purification of lipopeptide biosurfactant extracts obtained from a complex residual food stream using Tricine-SDS-PAGE electrophoresis. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1199103. [CrossRef]

26. Venkataraman, S.; Rajendran, D.S.; Kumar, P.S.; Vo, D.N.; Vaidyanathan, V.K. Extraction, purification and applications of biosurfactants based on microbial-derived glycolipids and lipopeptides: A review. *Environ. Chem. Lett.* **2022**, *20*, 949–970. [CrossRef]
27. Moradighadi, N.; Lewis, S.; Olivo, J.D.; Young, D.; Brown, B.; Nešić, S. Determining critical micelle concentration of organic corrosion inhibitors and its effectiveness in corrosion mitigation. *Corrosion* **2021**, *77*, 266–275. [CrossRef] [PubMed]
28. Gong, L.; Liao, G.; Luan, H.; Chen, Q.; Nie, X.; Liu, D.; Feng, Y. Oil solubilization in sodium dodecylbenzenesulfonate micelles: New insights into surfactant enhanced oil recovery. *J. Colloid Interface Sci.* **2020**, *569*, 219–228. [CrossRef] [PubMed]
29. Nehal, N.; Sonal; Jaiswar, S.; Singh, P. Extensive studies on fermentative production of biosurfactants from extremophilic marine microbes. In *Marine Surfactants: Preparations and Applications*; Kim, S., Shin, K., Eds.; Taylor & Francis Group: Boca Raton, FL, USA, 2023; pp. 375–404. [CrossRef]
30. Sivakumar, D.; Ramasamy, R.; Thiagarajan, Y.R.; Thirumalairaj, B.; Krishnamoorthy, U.; Siddiqui, M.I.H.; Lakshmaiya, N.; Kumar, A.; Shah, M.A. Biosurfactants in biocorrosion and corrosion mitigation of metals: An overview. *Open Chem.* **2024**, *22*, 20240036. [CrossRef]
31. Parthipan, P.; Cheng, L.; Rajasekar, A.; Karthikeyan, O.P.; Rahman, P.K.S.M. Editorial: Biosurfactants-next-generation biomolecules for enhanced biodegradation of organic pollutants, volume II. *Front. Microbiol.* **2024**, *15*, 1513087. [CrossRef]
32. Semeniuk, I.; Karpenko, O.; Banya, A.; Lubenets, V.; Shapovalenko, S.; Pengxiang, G. New environmentally friendly compositions as inhibitors of metal corrosion. *Sci. Stud. Res. Chem. Chem.* **2023**, *24*, 41–48.
33. Barxanadjyan, A.; Hakimov, R.; Ibragimov, B. Research of the possibility of using waste of paint and varnish materials for anti-corrosion protection of metal parts of transport equipment. *J. Tashkent Inst. Railw. Eng.* **2020**, *16*, 54–60.
34. Silva, M.N.; Kassab, E.; Pandoli, O.G.; Oliveira, J.L.; Quintela, J.P.; Bott, I.S. Corrosion behaviour of an epoxy paint reinforced with carbon nanoparticles. *Corros. Eng. Sci. Technol.* **2020**, *55*, 603–608. [CrossRef]
35. Hegazy, M.A.; Hegazy, M.M.; Awad, M.K.; Shawky, M. Chemical, electrochemical, theoretical (DFT & MEP), thermodynamics and surface morphology studies of carbon steel during gas and oil production using three novel di-cationic amphiphiles as corrosion inhibitors in acidic medium. *J. Mol. Liq.* **2021**, *337*, 116541. [CrossRef]
36. Tang, C.; Farhadian, A.; Berisha, A.; Deyab, M.A.; Chen, J.; Iravani, D.; Rahimi, A.; Zhang, Z.; Liang, D. Novel biosurfactants for effective inhibition of gas hydrate agglomeration and corrosion in offshore oil and gas pipelines. *ACS Sustain. Chem. Eng.* **2022**, *11*, 353–367. [CrossRef]
37. Farhadian, A.; Varfolomeev, M.A.; Kudbanov, A.; Rezaeisadat, M.; Nurgaliev, D.K. Waterborne polymers as kinetic/anti-agglomerant methane hydrate and corrosion inhibitors: A new and promising strategy for flow assurance. *J. Nat. Gas Sci. Eng.* **2020**, *77*, 103235. [CrossRef]
38. Płaza, G.; Achal, V. Biosurfactants: Eco-friendly and innovative biocides against biocorrosion. *Int. J. Mol. Sci.* **2020**, *21*, 2152. [CrossRef] [PubMed]
39. Oshin, T.A.; Fakinle, B.S.; Oyewole, O. The role of microbes in the inhibition of the atmospheric corrosion of steel caused by air pollutants. *Corros. Rev.* **2023**, *41*, 635–647. [CrossRef]
40. Xiong, Y.; Cao, M. Application of surfactants in corrosion inhibition of metals. *Curr. Opin. Colloid Interface Sci.* **2024**, *73*, 101830. [CrossRef]
41. Ambaye, T.G.; Vaccari, M.; Prasad, S.; Rtimi, S. Preparation, characterization and application of biosurfactant in various industries: A critical review on progress, challenges and perspectives. *Environ. Technol. Innov.* **2021**, *24*, 102090. [CrossRef]
42. Kashif, A.; Rehman, R.; Fuwad, A.; Shahid, M.K.; Dayarathne, H.N.P.; Jamal, A.; Aftab, M.N.; Mainali, B.; Choi, Y. Current advances in the classification, production, properties and applications of microbial biosurfactants–A critical review. *Adv. Colloid Interface Sci.* **2022**, *306*, 102718. [CrossRef]
43. Mohanty, S.S.; Koul, Y.; Varjani, S.; Pandey, A.; Ngo, H.H.; Chang, J.; Wong, J.W.C.; Bui, X. A critical review on various feedstocks as sustainable substrates for biosurfactants production: A way towards cleaner production. *Microb. Cell Fact.* **2021**, *20*, 120. [CrossRef]
44. Andrade, A.; Mehl, A.; Mach, E.; Couto, P.; Mansur, C.R.E. Application of biosurfactants in enhanced oil recovery ex-situ: A review. *Braz. J. Microbiol.* **2024**, *55*, 3117–3139. [CrossRef]
45. Xi, W.; Ping, Y.; Alikhani, M.A. A review on biosurfactant applications in the petroleum industry. *Int. J. Chem. Eng.* **2021**, *2021*, 5477185. [CrossRef]
46. Gayathiri, E.; Prakash, P.; Karmegam, N.; Varjani, S.; Awasthi, M.K.; Ravindran, B. Biosurfactants: Potential and eco-friendly material for sustainable agriculture and environmental safety—A review. *Agronomy* **2022**, *12*, 662. [CrossRef]
47. Manga, E.B.; Celik, P.A.; Cabuk, A.; Banat, I.M. Biosurfactants: Opportunities for the development of a sustainable future. *Curr. Opin. Colloid Interface Sci.* **2021**, *56*, 101514. [CrossRef]
48. Fawzy, A.; Abdallah, M.; Alfakeer, M.; Altass, H.M.; Althagafi, I.I.; El-Ossaily, Y.A. Performance of unprecedented synthesized biosurfactants as green inhibitors for the corrosion of mild steel-37-2 in neutral solutions: A mechanistic approach. *Green Chem. Lett. Rev.* **2021**, *14*, 488–499. [CrossRef]

49. Wang, Q.; Yan, Z. Potential of biosurfactants in corrosion inhibition. In *Industrial Applications of Biosurfactants and Microorganisms: Green Technology Avenues from Lab to Commercialization*; Aslam, R., Aslam, J., Hussain, C.M., Eds.; Academic Press: Cambridge, MA, USA, 2024; pp. 277–305. [CrossRef]
50. Verma, C.; Hussain, C.M.; Quraishi, M.A.; Alfantazi, A. Green surfactants for corrosion control: Design, performance and applications. *Adv. Colloid Interface Sci.* **2023**, *311*, 102822. [CrossRef]
51. Zehra, S.; Mobin, M.; Aslam, R. Application of biosurfactants as anti-corrosive agents. In *Advancements in Biosurfactants Research*; Aslam, R., Mobin, M., Aslam, J., Zehra, S., Eds.; Springer: Cham, Switzerland, 2023; pp. 171–189.
52. 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]
53. Graeve, M.D.; Maeseneire, S.L.D.; Roelants, S.L.K.W.; Soetaert, W. *Starmerella bombicola*, an industrially relevant, yet fundamentally underexplored yeast. *FEMS Yeast Res.* **2018**, *18*, foy072. [CrossRef] [PubMed]
54. Selva Filho, A.A.P.; Faccioli, Y.E.S.; Converti, A.; Soares da Silva, R.C.F.; Sarubbo, L.A. Maximization of the production of a low-cost biosurfactant for application in the treatment of soils contaminated with hydrocarbons. *Sustainability* **2024**, *16*, 7970. [CrossRef]
55. Farias, C.B.B.; Soares da Silva, R.D.C.F.; Almeida, F.C.G.; Santos, V.A.; Sarubbo, L.A. Removal of heavy oil from contaminated surfaces with a detergent formulation containing biosurfactants produced by *Pseudomonas* spp. *PeerJ* **2021**, *9*, e12518. [CrossRef]
56. Silva, S.N.R.L.; Farias, C.B.B.; Rufino, R.D.; Luna, J.M.; Sarubbo, L.A. Glycerol as substrate for the production of biosurfactant by *Pseudomonas aeruginosa* UCP0992. *Colloids Surf. B Biointerfaces* **2010**, *79*, 174–183. [CrossRef]
57. Saeki, H.; Sasaki, M.; Komatsu, K.; Miura, A.; Matsuda, H. Oil spill remediation by using the remediation agent JE1058BS that contains a biosurfactant produced by *Gordonia* sp. strain JE-1058. *Bioresour. Technol.* **2009**, *100*, 572–577. [CrossRef]
58. APHA. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association, American Walter Works Association, Walter Environmental Federation (S.I.): Washington, DC, USA, 1998.
59. Santos, D.K.F.; Meira, H.M.; Rufino, R.D.; Luna, J.M.; Sarubbo, L.A. Biosurfactant production from *Candida lipolytica* in bioreactor and evaluation of its toxicity for application as a bioremediation agent. *Process Biochem.* **2017**, *54*, 20–27. [CrossRef]
60. Faccioli, Y.E.S.; Oliveira da Silva, G.; Soares da Silva, R.C.F.; Sarubbo, L.A. Application of a biosurfactant from *Pseudomonas cepacia* CCT 6659 in bioremediation and metallic corrosion inhibition processes. *J. Biotechnol.* **2022**, *351*, 109–121. [CrossRef]
61. Soares da Silva, R.C.F.; Selva Filho, A.A.P.; Faccioli, Y.E.S.; Silva, Y.K.; Oliveira, K.W.; Araujo, G.P.; Rocha e Silva, N.M.P.; Converti, A.; Sarubbo, L.A. Application of *Pseudomonas cepacia* CCT 6659 biosurfactant as a metal corrosion inhibitor in a constructed Accelerated Corrosion Chamber (ACC). *Fermentation* **2024**, *10*, 602. [CrossRef]
62. Associação Brasileira de Normas Técnicas. *Material Metálico Revestido e Não Revestido: Corrosão Por Exposição à Névoa Salina*; NBR 8094; ABNT: Rio de Janeiro, Brazil, 1983.
63. Dantas, E. *Geração de Vapor e Água de Refrigeração*, 2nd ed.; Ecolab Química Ltda: Rio de Janeiro, Brazil, 1988; pp. 1–305.
64. Oliveira, S.H. Estudo da Utilização da Xantana e Hipoclorito de Sódio Como Estratégia Para Controle da Biocorrosão. Ph.D. Thesis, Universidade Federal de Pernambuco, Recife, Brazil, 2010.
65. Pontes, J.F.R.; Bendinelli, E.V.; Amorim, C.C.; Sá, M.M.; Ordine, A.P. Effect of corrosion inhibitor used in surface treatment on the anticorrosive performance of an epoxy paint system. *Mater. Sci. Appl.* **2016**, *7*, 593–609. [CrossRef]
66. Durval, I.; Rufino, R.; Sarubbo, L. Biosurfactant as an environmental remediation agente: Toxicity, formulation, and application in the removal of petroderivate in sand and rock walls. *Biointerface Res. Appl. Chem.* **2022**, *12*, 34–48. [CrossRef]
67. Matussin, N.B.A.; Shivanand, P.; Lim, L.H. Biosurfactant production by *Trichoderma* sp. MK116452 and its possible application in oil recovery. *Res. Sq.* **2020**, 1–23. [CrossRef]
68. Deivakumari, M.; Sanjivkumar, M.; Suganya, A.M.; Prabakaran, J.R.; Palavesam, A.; Immanuel, G. Studies on reclamation of crude oil polluted soil by biosurfactant producing *Pseudomonas aeruginosa* (DKB1). *Biocatal. Agric. Biotechnol.* **2020**, *29*, 101773. [CrossRef]
69. Santos, E.M.S.; Lira, I.R.A.S.; Pinto, M.I.S.; Almeida, F.C.; Almeida, D.G.; Rufino, R.D.; Sarubbo, L.A.; Luna, J.M. Formulation of the biosurfactant produced by *Candida sphaerica* for application as a bioremediation agent. *Chem. Eng. Trans.* **2019**, *74*, 307–312. [CrossRef]
70. Santos, R.A.; Rodríguez, D.M.; Ferreira, I.N.S.; Almeida, S.M.; Takaki, G.M.C.; Lima, M.A.B. Novel production of biodispersant by *Serratia marcescens* UCP 1549 in solid-state fermentation and application for oil spill bioremediation. *Environ. Technol.* **2022**, *43*, 2956–2967. [CrossRef]
71. Shah, M.U.H.; Moniruzzaman, M.; Sivapragasam, M.; Talukder, M.M.R.; Yusup, S.B.; Goto, M. A binary mixture of a biosurfactant and an ionic liquid surfactant as a green dispersant for oil spill remediation. *J. Mol. Liq.* **2019**, *280*, 111–119. [CrossRef]
72. Shah, M.U.H.; Reddy, A.V.B.; Yusup, S.; Goto, M.; Moniruzzaman, M. Ionic liquid-biosurfactant blends as effective dispersants for oil spills: Effect of carbon chain length and degree of saturation. *Environ. Pollut.* **2021**, *284*, 117119. [CrossRef] [PubMed]
73. Kebede, G.; Tafese, T.; Abda, E.M.; Kamaraj, M.; Assefa, F. Factors influencing the bacterial bioremediation of hydrocarbon contaminants in the soil: Mechanisms and impacts. *J. Chem.* **2021**, *2021*, 9823362. [CrossRef]

74. Soares da Silva, R.C.F.; Luna, J.M.; Rufino, R.D.; Sarubbo, L.A. Ecotoxicity of the formulated biosurfactant from *Pseudomonas cepacia* CCT 6659 and application in the bioremediation of terrestrial andaquatic environments impacted by oil spills. *Process Saf. Environ. Prot.* **2021**, *154*, 338–347. [CrossRef]
75. Almeida, D.G.; Soares da Silva, R.C.F.; Meira, H.M.; Brasileiro, P.P.F.; Silva, E.J.; Luna, J.M.; Rufino, R.D.; Sarubbo, L.A. Production, characterization and commercial formulation of a biosurfactant from *Candida tropicalis* UCP 0996 and its application in decontamination of petroleum pollutants. *Process* **2021**, *9*, 885. [CrossRef]
76. Muneeswari, R.; Swathi, K.V.; Sekaran, G.; Ramani, K. Microbial-induced biosurfactant-mediated biocatalytic approach for the bioremediation of simulated marine oil spill. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 341–354. [CrossRef]
77. Li, Z.; Yuan, X.; Sun, M.; Li, Z.; Fan, Y.; Lei, Y.; Zhang, M.; Xu, D.; Wang, F. Rhamnolipid as an eco-friendly corrosion inhibitor for microbiologically influenced corrosion. *Corros. Sci.* **2022**, *204*, 110390. [CrossRef]
78. Alqarni, N.; El-Gammal, B.; Fargaly, T.A.; Mohammed, A.A.K.; Fawzy, A. Experimental and computational explorations for the inhibitive performances of synthesized green surfactants against the corrosion of copper in nitric acid. *J. Mol. Struct.* **2025**, *1319*, 139439. [CrossRef]
79. Deyab, M.A.; Ibrahim, I.Z.; El-Shamy, O.A.A.; Khalil, K.A.; Awad, A.F.; Alghamdi, M.M.; El-Zahhar, A.A.; Abo-Riya, M.A. Synthesis, surface activity, and corrosion inhibition capabilities of new non-ionic gemini surfactants. *Sci. Rep.* **2024**, *14*, 8040. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.