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Assessing the Toxic Effects of Brine Discharge from the World's Largest Desalination Plant, Gulf Coast of Saudi Arabia

Mohamed O. Saeed[1], M. I. Mohamed Ershath[1,*], Anwar M. Barnawi[1]

[1]*Desalination Technologies Research Institute, Saline Water Conversion Corporation, PO Box 8328, Jubail 31951, Saudi Arabia*

[*]Author to whom any correspondence should be addressed; e-mail: mmohamedidris@swcc.gov.sa, Tel.: +966 13 3430333. Fax: +966 13 3431615

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Abstract

The Jubail desalination and power plants of the Saline Water Conversion Corporation in Saudi Arabia withdraw ≈ 500 × 10^3 m^3/h and discharge ≈ 470 × 10^3 m^3/h of brine and cooling water. In return, the plants produce ≈ 1.4 × 10^6 m^3/d of desalted water. The shallow depths of the Arabian Gulf render it prone to environmental degradation. Brine discharge could potentially result in the loss of marine life, affect biodiversity, and negatively affect the distribution of marine production and food chains. This study presents the results of *in vitro* and *in vivo* toxicity of water samples and sediments from the brine discharge site using rotifer cysts, a bioluminescent bacterium, and biofilm formation. Results of *in vitro* tests showed no difference in the hatching and survival of larval rotifer between discharged brine and pristine seawater. However, there was significant inhibition of light emitted by the bioluminescent bacterium in brine samples, and this was attributed to the effects of chlorination. Attachment slides used *in vivo* showed the development of algae and bacteria in the brine, indicating a biofilm formation.

Keywords

Gulf; desalination; brine discharge; chlorination; toxic effects

1. Introduction

The Arabian Gulf is a water basin with extremely low turnover. Coastal waters of the Gulf are very shallow (≈ 3-4 m) rendering it more prone to environmental degradation. Brine discharge from desalination plant operation is one of many pollutant streams of concern for the environmental health of the Gulf. The International Desalination Association (IDA) recognized the sensitive environment of the Gulf and urged efforts to safeguard its environmental well-being [1]. The Gulf is characterized by high levels of industrial and civil activities that cause environmental disturbance [2]. Such activities include oil and gas extraction, petrochemical and other industries, shipping transport and ports, desalination and water treatment plants, power plants, agriculture, fishing, dredging for land reclamation and channel/port maintenance, and water recreation activities. In addition, the Gulf receives a large volume of pollutants from the Shatt-al-Arab because of activities in the Tigris-Euphrates-Karun basin [3], such as oil and gas extraction, petrochemical and other industries, shipping transport and ports, desalination and water treatment plants, power plants, agriculture, fishing, dredging for land reclamation and channel/port maintenance, and water recreation activities. Consequently, the IDA environmental task force and regional and national environmental regulatory authorities are concerned about the health of the Gulf environment and encourage research efforts to track and document environmental changes and correct any deviation from the norm.

The Saline Water Conversion Corporation (SWCC) of Saudi Arabia owns and operates a total of 33 desalination and power plants around the Red Sea and Gulf coasts. All plants use coastal water from intake systems and discharge the resulting brine into the sea. The largest SWCC plant, in Jubail **(Figure 1)**, comprises Multi-Stage Flash (MSF) and Seawater Reverse Osmosis (SWRO) plants and produces 1.4 Mm^3 of potable water per day (93% from MSF plants and 7% from an SWRO plant). Approximately 12.5 Mm^3/d is pumped from an intake bay, with free water exchange with the open sea; Where ≈11.2 Mm^3/d is reverted to the sea as brine and cooling discharge water (the proportion of brine to cooling water is 1:4.5; giving a proportion of brine to the total discharge of 1:5.5). The physical attributes of discharges from desalination and power plants include elevated temperatures (ΔT 1°C) and ΔS 1ppt or psu [2]. In addition, chemicals that can be released into the Gulf from desalination and power plants include biofouling-control additives and by-products, coagulant/coagulant aids, scale-control additives, foam-control additives, contaminants due to corrosion (e.g. heavy metals), and cleaning chemicals [3].

Not much research is carried out on the effect or no effect of desalination discharges on the Arabian Gulf coastal environment and the counter-effect of source water on desalination plants even though these are matters of great importance. Many approaches exist for studying such interactions. One approach is presented in this study, namely, to assess the effect of a desalination plant's discharge on marine coastal organisms by exposing selected organisms to brine discharge and measuring the toxic effect on these organisms. Marine organisms can serve as ecological indicators of the impact of brine discharges and the need to manage desalination discharges [4]. Certain animal groups are found to be more sensitive to elevated temperature and salinity levels in coastal zones adjacent to discharge sites. For example, echinoderms are found to be especially sensitive to brine discharges, where complete disappearance from the coastal fauna community has been evidenced [4]. Mussels (bivalve mollusks) were not found at the brine outlet of the Jubail desalination and power plants, although they are common in the area [5]. Their conspicuous absence was thought to reflect their sensitivity to high temperature and salinity thereby favoring them as biological indicators for establishing an authorized discharge zone [5]. However, animals in coastal regions, especially in shallow coastal zones similar to those where Jubail's plants discharge their brine, are hypersaline tolerant having a degree of tolerance to a wide salinity range. On the Jubail coast, marine organisms also tolerate wide natural fluctuations in water temperature, from ≈14 °C in winter to ≈36 °C in summer, while at the point of discharge into the coastal water the brine temperature is only ≈5 °C above ambient in winter and ≈10 °C above ambient in summer [2]. The temperature stabilizes within a short distance (500-1000 m) from the discharge point depending on the wave, wind, and current condition [5]. Such factors may include competition for space with other less sensitive organisms, the inability of larvae to attach due to water column disturbance, insufficient larval recruitment, or larval predation by other animals.

Figure 1: Jubail City, Gulf coast of Saudi Arabia.

The objectives of this study were: 1) To test the effect of brine discharge *in vivo* by immersing attachment slides into the brine discharge channel of Jubail's desalination and power plants and quantifying the type and extent of biofilm attachment in comparison with attachment at a site at a similar depth outside the discharge bay; 2) To test the effect of brine discharge *in vitro* by measuring hatching and larval survival of the rotifer *Brabchionus plicatilis*, and by measuring the inhibition of light emitted by a bioluminescent bacterium, in brine discharge and control seawater; and 3) to test the fate of chemical additives and corrosion metals from the plants and if they are exerting any toxic effects on representative marine biota.

2. Materials and Methods

2.1. Study Sites

The brine discharge channel of Jubail's desalination and power plants **(Figure 1)** receives and discharges directly to surface coastal water ≈11.2 Mm^3/d of brine and cooling water. The channel runs parallel to the coastline for a distance of ≈ 2 km and discharges at a point opposite to and farthest from the intake bay **(Figure 2)**. The discharge channel sits well below the separate discharge lines of the desalination units and flows towards the mixing point of brine into the sea. The depth of the discharge channel is ≈2 m.

The intake bay is an excavated man-made lagoon with a 330 m mouth entrance within the Arabian Gulf **(Figure 2)**. Water samples from three pick-up points were considered: brine discharge channel (test, S1), brine discharge site (test, S2), or open sea (control, S3)

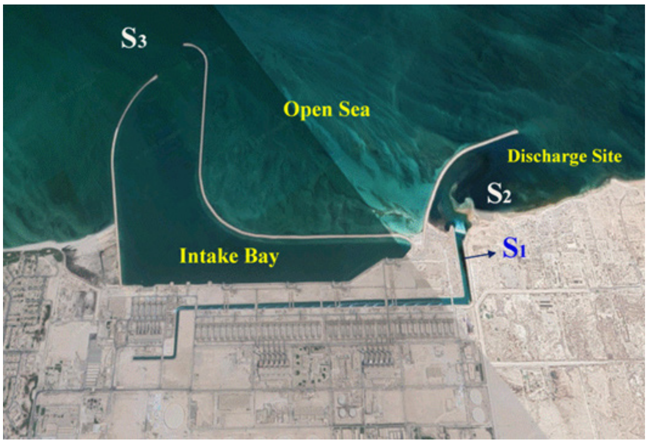

Figure 2: Experimental sites: S1 sampling point of the discharge channel; S2 sampling point of discharge site; S3 sampling point of control (open sea). (26°54'18.62" N 49°46'52.45" E, https://earth.google.com/web/).

2.2. Experimental Procedures

2.2.1. Water Samples

Experiments were carried out from February to May 2019 using both *in vivo* and *in vitro* methods. Comparative toxicities of water samples were used *in vitro* for the rotifer *Brachionus plicatilis* and bioluminescent bacterium *Vibrio fischeri* experiments. Commercial bacteria were used. Control experiments were performed with seawater obtained at open sea outside the intake bay for *in vivo* and *in vitro* tests respectively (**Figure 2**, S3). Water Temperatures and salinities during the experimental period from early February to early May were as follows: the temperature of the brine discharge channel during the experiments was 26-29 ^{o}C, the temperature of the discharge site was 23-27 ^{o}C and that of the open sea was 21-26 ^{o}C. The salinity of the discharge channel was 50-52 ‰ or psu, which of the discharge site was 45-50 ‰ or psu, and that of the open sea wads 40-42 ‰ or psu.

2.2.1.1. *In vivo* Experiments

These experiments involved direct immersion of biofilm attachment slides into the brine discharge channel in site 1 **(Figure 2)**. The research team fabricated Biofilm samplers, based on water quality database and plant operational conditions. Each sampler consisted of polyvinyl chloride (PVC) tube 15.0 inches long and 1.0 inches in diameter. Each tube was provided with a slit on either internal side, accommodating which can accommodate three glass slides each 2.5 × 2.8 cm in diameter. Thus, each sampler held six slides. Both ends of the holding tubes were cut in order to expose the attachment slides to the seawater stream while remaining attached to the slits. The attachment slides were held in place by rubber stoppers **(Figure 3)**.

Figure 3: Biofilm slide tube holder with attached glass slides.

The samplers and biofilm attachment slides were separately washed in 1% chlorine solution for disinfection and then cleaned in sterile distilled water. The samplers were loaded with the slides at the experimental site using sterile forceps and fixed to a nylon rope by stainless steel wire of 1-mm thickness. The rope was fixed by tying it to a block of cement at the bottom of either the common brine discharge channel for all the MSF and SWRO plants (test, **Figure 2**, S1) or in the open sea adjacent to the plant intake (control, **Figure 2**, S3). The samplers were suspended freely close to the surface using float. The float ensured the slide holders were submerged at a depth of 1.0 m. Slides were retrieved after a two-week exposure period. Three of the six slides from each sampler were used to enumerate the bacteria attached to them, while the other three slides were used for microscopic studies. The density of attached bacteria in colony-forming units per unit area (CFU/cm2) was determined, and the attached biofilm was examined by SEM **[6]**.

2.2.1.2. *In vitro* Experiments

These experiments involved exposure of test organisms to water samples taken from the brine discharge channel and discharge site (**Figure 2**, S2). Water samples were taken from either the brine discharge channel (test, S1), brine discharge site (test, S2), or open sea (control, S3) were brought to the laboratory and filtered using 0.45 μm and subsequently 0.2 μm filters to remove bacteria and particulate material. The water samples were then tested for their comparative toxicities on the rotifer *B. plicatilis* and the bioluminescent bacterium *V. fischeri*. Water samples were acclimated to laboratory room temperature (≈23 oC) before use. The discharged brine toxicity test on rotifer was performed using rotifer cysts (MicroBioTests Inc. Toxikit Cysts) following the bench protocol for estuarine/marine toxicity screening tests as described by the rotifer cysts provider-MicroBioTests Inc. **[7]**. Tests for cyst hatching and larval mortality rates were carried out on five samples collected on different sampling dates.

Toxicity to the bioluminescent bacterium was carried out by measuring the extent of the inhibition of light emitted by the bacterium. This test was performed on five samples collected on different sampling dates using Delta Tox® Analyzer as described by the manufacturer **[8]**. Inhibition of bacteria bioluminescence was measured in test samples.

Trace metals and chlorine were measured in the water samples obtained, and experiments were conducted to quantify the effect of chlorine and chemical additives on the inhibition of bacteria bioluminescence. Measurements were carried out on four sampling dates.

The concentrations of metals commonly produced from the corrosion of alloys in metallic components of the power/desalination plant (Fe, Cu, Ni, and Cr) were determined in test and control water samples to assess them as possible causes of the bioluminescence inhibition. The metals were identified by inductively coupled plasma-atomic absorption-emission spectroscopy with electrothermal atomization in a graphite furnace. Total Residual Chlorine (TRC) was assessed by the diethyl-*p*-phenylene-diamine (DPD) colorimetric method with a HACH pocket colorimeter [9,10].

Bioluminescence inhibition was measured in sterile seawater containing foam-control and scale-control additives used by the plants at the concentrations found in the process stream. The scale control additive is a polymer of polycarboxylic acid and the foam control additive is silicone-based.

The brine discharge channel was found to contain a low concentration of the trihalomethane species as bromoform (see 2.2.2, below) which could be a causal agent of bioluminescence inhibition. Because of this, chlorine was removed from water samples of the brine discharge channel by the addition of sodium metabisulfite (SBS), and the samples were tested for bioluminescence inhibition. To test if the chlorine in the discharge channel is the causal agent of bioluminescence inhibition, chlorine was added to normal seawater to a concentration of 0.04 mg/l where bioluminescence inhibition was tested in triplicate.

2.2.2. Sediment Samples

Sediments samples were analyzed on four sampling dates during March and April 2019 to reveal any accumulation of toxic corrosion metals or chlorination by-products. Shore sediment samples were collected at low tide from the discharge site 40 m from the discharge point and 3 m from the water line at approximately 0.75 m depth. A control sediment sample was obtained from the open sea outside the intake bay mouth by a diver. Sediments were obtained using a hand-held core sampler covering an area of 225 cm^2 and a depth of ≈10 cm.

Sediments were analyzed for trihalomethanes and corrosion metals as solid and as sediments wash. Sediment wash was prepared by washing 1 kg sediment in one liter of synthetic seawater constituting sodium chloride, magnesium sulfate, and sodium bicarbonate [9]. Sediment wash was decanted from sediment and filtered under gravity through a Whatman® No. 4 filter paper.

Sediment and water samples were prepared for assessing the trihalomethanes as per the standard of United States Environmental Protection Agency (USEPA) method 5021, and USEPA method 8260D for analysis [10]. Trace metals attributed to corrosion were determined by atomic absorption as mentioned above [10]. Toxic effects of sediment wash were determined by bacterial bioluminescence inhibition and hatching and survival rates of rotifer as described earlier.

3. Results and Discussion

3.1. Water Zone Samples

In vivo experiments showed bacterial growth and biofilm development in the discharge channel and open sea with variations depending on location. The initial bacterial count in the discharge channel was lower than that in the intake bay (**Table 1**). This was attributed to process-related impingement and cell injury resulting from turbulent water mixing in the channel [11]. Following 24 h incubation, bacterial counts in the discharge channel exceeded those of the intake bay. This was most likely due to the recovery of injured cells and the availability of more bacteria nourishing nutrients in the discharged brine than in the intake bay [11]. The Total Organic Carbon (TOC) concentration in the discharge channel was 4.3 mg/l compared to 2.3 mg/l in the intake bay [2].

It is known that feed water is chlorinated at the intake pits through the electrochemical generation of chlorine from seawater [11]. At the start point of water pumping, the residual chlorine concentration was ≈0.5 mg/l. This amount is sufficient to break down organic matter into smaller fractions that are readily assimilated by bacteria. This mechanism is well known in chlorinated natural waters and is well documented in desalination plants [12–14]. Bacterial biofilm densities in CFU/cm^2 were similar in the discharge channel and open sea (**Table 1**). Because of elevated temperature, salinity, chemical additives, and turbulence, one would expect less stability in water quality in the discharge channel with associated inhibition of biofilm attachment. However, this was not the case and bacterial biofilm density there reached a magnitude similar to that in the open sea, most likely due to less predation in the discharge channel because of turbulent conditions compared to the calmer open sea, and the presence of more assimilable nutrients as mentioned above. Algal mats with entrapped settled solids formed on all slide-holding tubes in the brine discharge channel (**Figure 4**). At the open sea, biofilm formation on the slides was less conspicuous with transparent biofilm and the growth of barnacles on the slide-holding tubes (**Figure 4**). There is probably greater predation from larval marine shelled animals in the open sea that resulted in reduced biofilm formation [13,15].

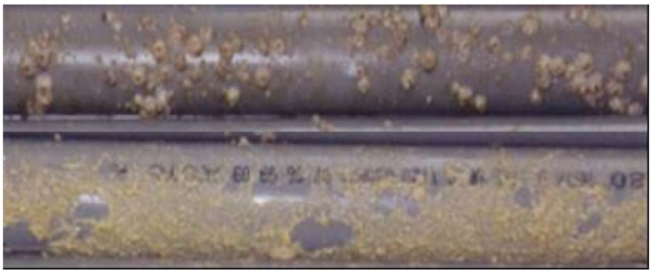

Figure 4: Two biofilm slide tube holders: above from open sea (location S3, **Figure 1**) and below from brine discharge channel (location S1, **Figure 1**). Note shells in the open sea and lack thereof in the brine discharge channel.

Table 1: Association of bacterial counts and biofilm densities in the brine discharge channel and open sea of the SWCC's Jubail desalination and power plants (n = 10).

Sampling Location	Bacterial Counts (CFU/ml)[1]		Bacterial Biofilm Density (CFU/cm^2)[4]
	0-h[2]	24-h[3]	
Brine discharge channel (Location-S1, **Figure 1**)	$3.06^a \pm 0.39 \times 10^3$	$3.60^c \pm 0.89 \times 10^5$	$1.82^d \pm 0.23 \times 10^5$
Open sea (Location- S3, **Figure 1**)	$1.33^b \pm 0.53 \times 10^4$	$3.33^c \pm 0.97 \times 10^5$	$0.51^e \pm 0.16 \times 10^4$

[1]Pour plate count in marine agar and incubation at 30°C in a thermostatically-controlled incubator; [2]Initial count; [3]Count after 24h incubation; [4]Upon 14 d exposure time.

[a, b, c, d, e]For the same parameter (vertical columns), means with same letter superscript are not different; means with different letter superscripts are different (analysis of variance and Tukey test, $P \leq 0.001$)

± 95% confidence interval.

Biofilm development glass slides in the discharge channel lacked barnacles but diatoms (Class: Bacillariophyceae), the most important photosynthetic group and the base of aquatic food chains, were present as well as scattered bacteria **(Figure 5)**. In biofilm formation, diatoms are pioneer settlers following bacteria **[2]**. Diatoms are by far the most abundant algal group in both the intake bay and coastal water adjacent to Jubail's desalination and power plants **[15]**. They are the most important photosynthetic group forming the base of aquatic food chains. Diatoms have previously been found to form 93% of the epiphytic phytoplankton population in both the intake and open sea adjacent to Jubail's desalination and power plants **[15]**. The presence of diatoms in the discharge channel indicates that they tolerated the process-related effects of entrapment and entrainment combined with intake design and the waterway through cooling, make-up, and discharge structures.

TRC in the discharge channel was found to be 0.04 mg/l, which is considered a negligible concentration compared to the initial one of ≈0.5 mg/l. Chlorine is consumed by organic matter and volatilization occurring through mixing **[11]**. There is vigorous mixing at points where individual discharge lines fall into one common discharge channel, the channel cascades towards the sea, and additional mixing occurs at the point of the brine outfall into coastal water. This mixing has the effect of replenishing oxygen and dissipating high temperatures. Dissolved oxygen concentrations in the discharge channel remained ≈5 mg/l during the study. This concentration is above optimal for sea in this latitude **[5]**. The flourishing of diatoms and the high production of chlorophyll in the outfall bay have been attributed to these mixing effects **[15]**. Besides the favorable effect of a cascading brine discharge channel, there is an inherent dilution effect that lowers temperature and salinity instantaneously. In the Jubail plants, (as well as in all water/power cogeneration desalination plants); the brine reject is greatly and immediately diluted with cooling water from the power plants **[2]**.

In vitro experiments showed hatching rates of rotifer cysts ≥ 98% in all water samples. No measurable larval mortality occurred 72 h after hatching in either control or test water samples. Mortality rates 96 h after hatching were 20.2±14.9 for open sea control, 22.2±15.0 for brine discharge channel, and 21.9±13.9 for brine discharge site water samples, with no statistically significant difference between the three locations.

Bioluminescence inhibition was significantly higher in water samples from the brine discharge channel than in water samples from the discharge site and the open sea **(Table 2)**. This result indicates that discharge channel water samples are more toxic toward the bacterium *V. fischeri* than the intake source water and coastal water in the discharge site. The most likely explanation for this difference is that light emission by the test bacterium is inhibited by chlorine. Brine discharge channel water contained 0.04 mg/l chlorine. The US Environmental Protection Agency sets a standard for discharges of not more than 0.019 mg/l TRC, which is normally higher than free residual chlorine **[16]**. This means the 0.04 mg/l free chlorine reported in this study could truly be the cause of bioluminescence inhibition. This was ascertained by the observation of significant bioluminescence inhibition in normal seawater samples chlorinated to 0.04 mg/l TRC **(Table 2)**. No chlorine was detected in the outfall area and consequently, water samples from the brine discharge site were not inhibitory to bacterial bioluminescence.

When chlorine is added to water, by-products are formed. Chlorine and its disinfectant by-products are known to exhibit variable degrees of toxicity to aquatic life **[17]**. Chlorination by-products were only detected in the brine discharge channel and exclusively in the form of the trihalomethane bromoform. The cause for bromoform dominance was ascribed to the existence of bromides in high concentrations in the source of the Jubail desalination and power plants **[18]**. The reason for the absence of trihalomethanes in the discharge site is probably the sharp outfall of brine from the brine discharge channel into coastal water and resulting in vigorous mixing and the volatilization of the volatile organic compound bromoform.

When water samples from the discharge channel were dechlorinated, they were not inhibitory to bacterial bioluminescence indicating bioluminescence inhibition was due to trace concentrations of chlorine and not to bromoform.

Bioluminescence was not inhibited by the antifoam and antiscalant used by the plants at the concentrations applied and hence these can be excluded as factors in the observed bioluminescence inhibition **(Table 2)**.

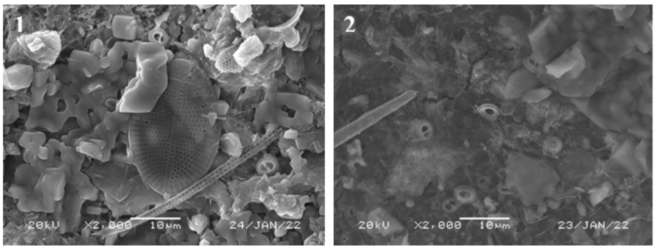

Figure 5: SEM images of biofilm coupons: 1. Open Sea (location S3, **Figure 1**), note light biofilm development with lack of algae; 2. Brine discharge channel (location S1, **Figure 1**), note the presence of diatoms and bacterial cells.

Table 2: Inhibition of bacterial bioluminescence in different water sources.

Water source	% Inhibition	Difference from control
Open Sea (control)	8.6±5.1	Control
Brine Discharge Channel	21.7±9.1	Significant*
Brine discharge site	10.9±6.2	Not Significant
Discharge site sediment wash	9.8±5.6	Not Significant
Feed water + Antifoam (0.04 mg/l)	9.0±5.1	Not Significant
Feed water + Antiscalant (1.5 mg/l)	10.4±5.9	Not Significant
Feed water + 0.04 mg/l chlorine	17.9±8.9	Significant

*(n=5, Analysis of variance and paired t-tests, P≤0.05).

Concentrations of heavy metals associated with corrosion are presented in **Table 3**. Copper, nickel, and chromium are the most toxic of metals formed by corrosion. The concentration of these metals is either below the detection limit or in a single-digit microgram quantity **(Table 3)**. Concentrations reported to cause 50% bioluminescence inhibition to *V. fischeri* are in mg/l quantities (0.5-2.0 mg/l Cu, 17.7 mg/l Ni and 16-58 mg/l Cr) [19]. Concentrations reported for these elements in water samples and sediments wash would thus need to be magnified one hundred to several hundred-fold to reach inhibitory levels **(Table 3)**. Therefore, we could rule out the impact of the metal on the bioluminescence assay. Iron concentrations are of particular interest because they are appreciably higher even in the control sample than reported concentration ranges in the Gulf. Iron concentration in Gulf water ranged between 0.15-8.63μg/l [20]. In the present study, higher than normal concentrations of iron in open sea samples (20.2 μg/l, **Table 3**) may result from iron input from Jubail Industrial City north of the desalination plants. The greater level of iron in the discharge sediments wash (166 μg/l) may be attributed to the accumulation of iron in sediments (see below) from the ferric chloride used as a coagulant in the SWRO plant and corrosion from the MSF plants. There is also accumulation of copper and chromium in discharge water samples compared to open sea, attributable to corrosion **(Table 3)**. On the other hand, their concentrations are within regional regulatory limits. The present concentrations of Ni, Cu, and Cr are well below regulatory standards. The abnormal high concentrations of iron should not be of concern as iron is not regulated because of its very low toxicity. However, abnormally high iron concentrations could cause turbidity with an associated effect on photosynthesis and fouling of nesting sites in sediments. A study of seawater quality and microbial communities in a desalination plant outfall on the Mediterranean coast revealed the inhibitory effect of brine discharge on primary production as decreased phytoplankton growth and bacterial production were recorded [21]. However, the inhibitory effect was not traced back to any causal agent. In any case, new seawater reverse osmosis plants are equipped with waste treatment facilities for spent filter backwashing and membrane cleaning solutions that should reduce the amount of iron and other chemicals in the brine discharge.

3.2. Sediment Zone Samples

Analyses of bottom sediments and their wash for metals of corrosion origin and trihalomethanes (THM) are presented in **Table 3**. Sediment wash was found to have significantly greater iron and copper concentrations than discharge water. The same was found for concentrations in sediments. Chromium, which is not detected in sediments wash, was abundant in sediments, while nickel is below the detection limit in sediment wash and sediment samples. Sediment standards for trace metals (mg/kg) coined by GPMEP: Fe - Not regulated, Ni - 16 Cu - 18 and Cr - 52 [22]. Present metals concentrations are well below regulatory limits **(Table 3)**. The concentration of iron in sediments of the discharge site is 1000 mg/kg **(Table 3)**. This concentration is below the concentration reported for Gulf coastal sediments at Al-Khafji, north of Jubail, where iron sediment concentration average was 1523 mg/kg [23]. It is also below concentrations reported from the southern Mediterranean Sea where the iron sediment concentration average was 2084 mg/kg [24].

Sediment wash was also not inhibitory to bacterial bioluminescence **(Table 2)** or toxic to rotifer. Sediment wash was free of THM and contained 166 mg/l of iron and 7.7 mg/l of copper implying the two elements are not toxic at these levels.

Table 3: Concentration of trace metals and trihalomethanes in water and sediments (dry weight) in the Jubail Desalination and Power Plants (n=4).

Source	Trace Metal				Trihalomethanes			
	Fe	Cu	Ni	Cr	Bromoform	Chloroform	DBCM	DCBM
Water (µg/l)								
Open Sea	20.2[a]	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Discharge Channel	22.6[a]	5.8[a]	BDL	BDL	35	BDL	BDL	BDL
Discharge Site	26.0[b]	3.5[b]	BDL	1.5	BDL	BDL	BDL	BDL
Discharge Site (sediment wash)	166[c]	7.7[c]	BDL	BDL	BDL	BDL	BDL	BDL
Open Sea (sediment wash)	80	0.2	BDL	BDL	BDL	BDL	BDL	BDL
Sediment (mg/kg)								
Open Sea	340[d]	1.4[d]	BDL	1.7[a]	BDL	BDL	BDL	BDL
Discharge Site	1000[e]	4.4[e]	BDL	2.0[a]	BDL	BDL	BDL	BDL

[a, b, c, d, e]For each metal (in either water or sediment samples) means with same letter superscript are similar. Those with different superscripts are different (Analysis of Variance and paired t-tests; $p < 0.05$).

DBCM = Dibromochloromethane; DCBM = Dichlorobromomethane.

BDL below detection limit in water (2.0 µg/l for iron, 1.0 µg/l for each of copper, nickel and chromium and 2µg/l for each of trihalomethanes compounds), and in sediments (0.5 mg/kg dry weight for each trace metal, 50µg/kg for each of the trihalomethanes compounds).

3.3. General

From the toxic effects of brine discharge determined in this study, the Jubail plants discharge should exert a minimal impact on the receiving coastal zone. If there is reduced distribution or even an absence of certain animal taxa from coastal zones receiving brine discharge, then factors other than brine discharge may be implicated in restricting animal distribution. These factors include the availability of suitable breeding sites, available substrate for attachment, water column conditions (e.g. agitation, turbidity, and tide), competition for space, and predation. For example, there are two seemingly similar adjacent coastal sections on the Gulf in Dammam, Saudi Arabia; one section abounds with mussels while very few mussel shells are observed in the other section. Neither section receives any form of discharge [25]. In a study of macrofouling community development in a tropical coastal environment, bivalve larvae, though present throughout the year, were poorly represented in the macrofouling community [26]. This is probably due to the effects of predation. Lack of marine shell growth (barnacles) on the biofilm slides tube holder in the brine discharge channel may be attributed either to these environmental effects or to their sensitivity to conditions in the brine discharge such as the presence of trace levels of chlorine. Attachment of larval barnacles to substrates was found to be inhibited by 0.05 mg/l for quite short exposure time [27]. Conditions in the discharge structures and sites are complex and potentially unpredictable. Information gathered from one geographical location may seldom be useful at another [6]. Should a desalination plant be warranted a legal mixing zone beyond which water quality returns to ambient sea conditions, the adequacy of the mixing zone for desalination discharges will have to be decided on a case-by-case basis.

4. Conclusions

The brine discharged from the SWCC's Jubail Desalination and Power plants was not toxic to rotifer cysts or larvae, but inhibited bacterial bioluminescence. The inhibition was attributed to the presence of residual chlorine at concentrations of 0.04 mg/l.

Bacterial counts were similar (though not the same) in brine reject and open sea. However, the open sea biofilm had a greatly reduced population of diatoms and an increased population of barnacles.

Accelerated bacterial after-growth was seen in brine reject which has been attributed to the effects of chlorination enhancing the bioavailability of dissolved carbon.

The discharge system design at Jubail's desalination and power plants enabled dissipation of temperature, replenishment of oxygen, and volatilization of chlorine, which should support healthy primary productivity at the discharge site.

The SWCC of Saudi Arabia is abandoning some of its thermal desalination plants in favor of membrane desalination plants. The new membrane plants will be equipped with waste treatment facilities. This should solve potential problems related to temperature rise and chemical additives. However, the effects of increased salinity should continue to be monitored.

Authors' Contributions

Mohamed O. Saeed: Experiment, ddata analysis, writing.

M. I. Mohamed Ershath: Data analysis, editing, drafting, and communication.

Anwar M. Barnawi: Sample collection and experiment.

Data Availability

The data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that there is no conflicts of interest.

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