



Original Paper

Rare Earth Elements Around the Barakah Nuclear Power Plant, UAE

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Received 1 September 2019; accepted 17 March 2020
Published online: 16 May 2020

Rare earth element (REE) contamination has major consequences for the environment and humans. Some forms of REEs have more serious environmental impacts than others. It is thus crucial to monitor their levels in areas where they are expected to be released. Concentrations of 13 REEs (La, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) around the Barakah nuclear power plant (NPP) area, Abu Dhabi, United Arab Emirates (UAE), were measured. Shore, soil, and marine samples were collected. REE concentrations were measured using inductively coupled plasma atomic emission spectroscopy. On average, REE concentrations were highest in the soil samples, followed by the marine samples and then the shore samples. La and Nd were the most abundant REEs in the soil, marine, and shore. The average (La/Yb)_n ratios for shore, soil, and marine samples were 8.96, 9.75, and 9.39, respectively. The REE concentrations were strongly positively correlated with Al₂O₃ values, suggesting low mobility of the REEs in the Barakah NPP area. Light REEs (LREEs) were more enriched than heavy REEs (HREEs). The shore samples have minor enrichments in La and Tm. Otherwise, based on enrichment factors that do not exceed 1.2 and geoaccumulation indices that were all below zero, the Barakah NPP area was considered uncontaminated with REEs. This area was not polluted according to the pollution load indices (0.67, 0.52, and 0.17 for shore, soil, and marine sediments, respectively). The spatial distribution maps show the highest concentrations of REEs in the south area of the Barakah NPP. Overall, the Barakah NPP area does not have any alarming REE concentrations, and the baseline values were provided as a reference for future comparisons.

KEY WORDS: Rare earth elements, Barakah nuclear power plant, Pollution, Contamination, Spatial distribution maps.

INTRODUCTION

The UAE established the Barakah nuclear power plant (NPP) in the western region of the Arabian Gulf. Greenhouse gas emissions from nuclear energy are low, which helps to mitigate the challenge of global warming (Hoffert et al. 2002). However, nuclear reaction in a nuclear power plant releases some REEs, such as Eu, Nd, Pr, and La, to the environment (Wang et al. 2013). In fact, the French AREVA was interested in recycling REEs

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from spent nuclear fuel from nuclear power plants (Bourg and Poinssot 2017). REEs are used in various industrial activities (Stegen 2015), e.g., permanent magnets for electric vehicles, generators for wind turbines (Massari and Ruberti 2013), manufacturing technology devices (Chen 2011) known as “The Vitamins of Modern Industry” (Balaram 2019), anticancer treatments (Wenhua et al. 2004), and fertilizers in agriculture (Zhenghua et al. 2001). However, REEs are harmful to the environment and to humans. For example, lanthanoids can travel across the cellular membrane into cells in both animals and plants (Cheng et al. 1999). Cheng et al. (2014) found that exposure of mice to lanthanoids affected their cell and humoral immunity and disturbed liver function. Children exposed to very high REE contents (i.e., approximately 45 times higher than an uncontaminated reference area) in the river at a mining area had severe human health risks such as liver function decline (Weifang et al. 1997). As reported in (Kyung et al. 2013), Y affects the respiratory system, La can lead to pneumoconiosis, Ce causes skin irritation, and accumulation of Nd causes liver damage. REEs also have severe impacts on the environment (Fu et al. 2010; Piper and Bau 2013; Akinlua et al. 2016; Kacmaz 2016). In its metallic form, Dy can easily catch fire, and it also reacts with water, producing flammable H₂ gas (Kyung et al. 2013). In their metallic forms, Er, Yb, and Lu can cause fires and explosions (Kyung et al. 2013). REEs have radiological impact because REE ores are typically found in conjunction with naturally radioactive material (Timothy et al. 2015). REEs are persistent pollutants that have low mobility and strong binding affinities to clay (Kimoto et al. 2006) and (Fu et al. 2010). Light REEs (LREEs) commonly scavenge on clay minerals and Mn–Fe oxyhydroxides (Byrne and Kim 1990). REEs cause sediment pollution because they form insoluble complexes with halides, oxides, phosphates, silicates, and carbonate ions in natural waters (Millero 1992).

Despite the harmful consequences of REEs, there is a paucity of data on the geochemical distribution of REEs in the UAE (El Tokhi et al. 2015). This work reports on the concentrations and distribution patterns of REEs along the coastal area in the vicinity of the Barakah NPP, Abu Dhabi, UAE. This study also compares the levels of REE contamination in three media, namely soil, shore, and marine samples, and compares these levels to the safe limits set by the Dutch guidelines adopted by governmental entities in the UAE. This study is

essential because despite the prominence of the Barakah NPP in the Middle East and North Africa (MENA) region and despite the known REE releases from nuclear plants, very little is known about the pollution levels around this area (Al Rashdi et al. 2017).

STUDY AREA

The UAE is located in the southeastern corner of the Arabian Peninsula, between latitudes 22° 50' and 26° N and longitudes 51° and 56° 25' E. The Barakah NPP is in the Barakah area, i.e., the western region of the UAE. The Barakah area is situated between Gharbia (west) and the Shuweihat Peninsula (east). It is approximately 224 km to the west of the capital, Abu Dhabi city, and approximately 75 km from the Saudi eastern border. The site is located on relatively flat terrain along the eastern edge of the Matti salt flat, approximately 100 m from the gulf shoreline (Alsharhan and Kendall 2003). The dominant geologic features in Barakah are dunes and salty sand (Alsharhan and Kendall 2003). These features occur because of the combined effects of strong winds, high temperature, low rainfall (average is less than 40 mm per annum), and high evaporation rates (Kendall and Skipwith 1969). The inland western area of the UAE is dominated by calcareous and gypsiferous silt and sand (Alsharhan and Kendall 2003). The distribution of the sediments in the Arabian Gulf is controlled by many factors: the arid climate, the influence of low or high wave energy, the coastal orientation to northwesterly winds, and the offshore barriers (Wagner and Togg 1973). Diurnal tides are predominant along the western coast of the Abu Dhabi emirate, while semidiurnal tides occur mostly along the eastern shores of the coastline (Sheppard et al. 1992).

SAMPLING AND ANALYSIS

A total of 58 samples were collected from the locations depicted in Fig. 1. The collected samples, which were labeled with different numbers of samples depending on the accessibility and nature of the area, were categorized into three types (marine sediment, shore and soil samples). Eighteen marine sediment samples (M1–M18) were collected from three areas: Sila, Barakah, and Jebel Dhanna. Sixteen shore samples (B1–B16) were collected

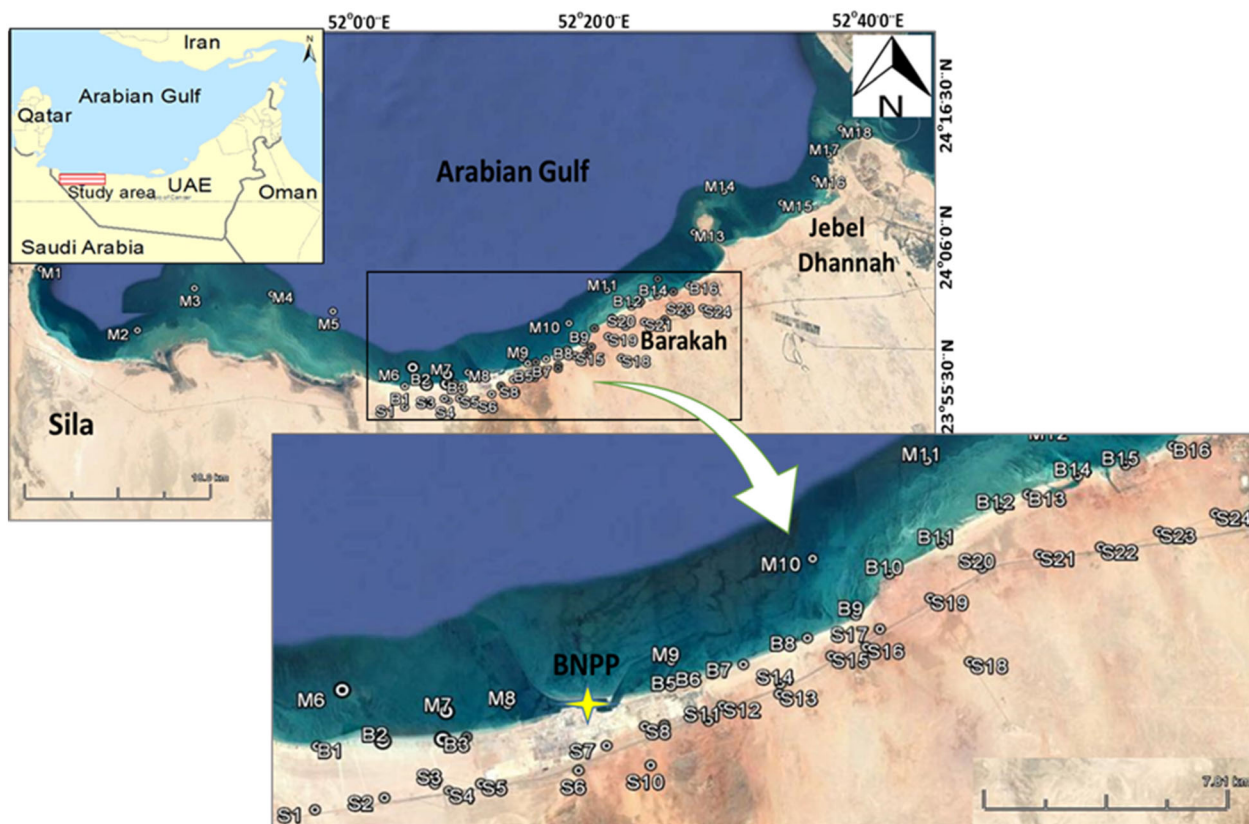


Fig. 1. Map of the study area showing the locations of the 58 sampling sites.

along the shoreline where the Barakah station is located. Twenty-four soil samples (S1–S24) were collected from sand dunes, i.e., 200 m inland. During sampling, large shell fragments were removed from the sediment samples. Grain size analysis was performed on the marine samples. They were categorized into coarse (> 0.5 mm), medium (0.25 to 0.125 mm), and fine (< 0.125 mm) fractions.

REE concentrations were measured in a certified lab at the Bureau Veritas Minerals Laboratories (BVML) in Vancouver, Canada, while the sample preparation was performed in their laboratory in Ankara, Turkey. Soil samples were fully dried in an oven at a temperature of 60 °C and pulverized to $\geq 85\%$ passing 75 μm . For the REEs, 0.5 g of soil samples was digested with a modified aqua regia solution using concentrated nitric acid and hydrochloric acid in a 1:3 ratio. After digestion (Nieuwenhuize et al. 1991), samples were mixed with a flux of lithium metaborate and lithium tetraborate ($\text{LiBO}_2/\text{Li}_2\text{B}_4\text{O}_7$) and fused in an induction furnace. Inductively coupled plasma atomic emission spec-

troscopy (ICP-AES) was used to measure REE concentrations according to the ACME QA/QC protocol. This protocol includes a sample-prep blank carried through all stages of analysis as the first sample, certified reference materials (STD DS10), a pulp duplicate to monitor analytical precision and two reagent blanks to measure background values. Crucibles were fused in a furnace. The cooled bead was dissolved in ACS grade nitric acid and analyzed by ICP-AES. The instruments used for this analysis were a Spectro Ciros Vision and PerkinElmer ELAN 9000. The error of analysis for REEs was within 0.01. The minimum detection limit (MDL) ranged from 0.5 ppm for La to 0.02 ppm for the other REEs. The validity of the analytical procedure was evaluated by accuracy and precision tests conducted on the reference sample. For details about the description of the methodology, please refer to www.bureauveritas.com.

REEs include the lanthanide series (atomic numbers 57–71; La to Lu) (Hedrick 1997). Light REEs (LREEs), i.e., lanthanum to europium, are

more common than heavy REEs (HREEs), i.e., gadolinium to lutetium and yttrium (Simandl 2014). In this study, the concentrations of the following REEs were measured: La, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu. Al concentrations were also measured with ICP-AES to calculate the contamination factor. The Al_2O_3 content was determined according to Coats and Redfern (1964), based on the percentages of Al reported from the ICP-AES analysis. Spatial distribution maps were constructed using ArcMap 10 by the interpolation method [kernel smoothing to distribute irregularly spaced data (Daley 1991)]. For the statistical analysis, undetermined values (i.e., too small to be detected) were replaced with half of the detection limit as listed in Supplementary Material (Table S1). Outliers were found using the interquartile range (IQR) with a multiplier of 3 (3IQR) criterion in SPSS 21.0.0.0. No outliers were detected in the data set from the shore and soil samples. For the marine sediments, the outliers from samples M17 and M18 were excluded.

RESULTS AND DISCUSSION

Concentrations of 13 REEs (La, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) in all the 58 samples are listed in Supplementary Material (Table S1) along with the statistical figures. Table S1 also lists reference values for sandstones (Turekian and Wedepohl 1961), the upper crust (Taylor and McLennan 1995), and chondrites (Taylor and McLennan 1985).

In the shore samples, the range of concentrations of La and Nd was 0.6–1.4 ppm, while it was 0.5–1.4 ppm in soil and marine sediments. S14 has the highest levels of La (6.4 ppm) and Nd (6.88 ppm). La levels fluctuate in the marine sediments with a minimum value of 0.3 ppm (M11 and M12) and a maximum value of 1.8 ppm (M14), while Nd has a minimum value of 0.24 ppm in sample M11 and a maximum value of 1.68 ppm in sample M8. The concentrations of Eu, Tb, Ho, Er, Tm, Yb, and Lu were below 0.15 ppm in the shore and marine samples. Among all 58 analyzed samples, soil sample S14 has the highest values of Pr (1.69 ppm), Sm (1.42 ppm), Gd (1.18 ppm), and Dy (1.00 ppm). Nd was the most abundant REE in soil samples (3.39 ± 1.35), whereas La was the most abundant REE in both shore samples (0.9 ± 0.3) and

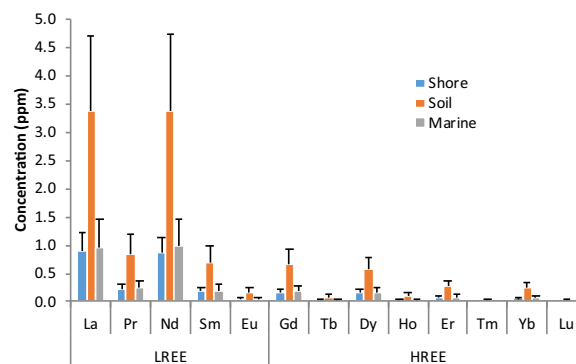


Fig. 2. Average concentrations of 13 REEs, with standard deviation bars, from all samples of shore, soil, and marine sediments.

marine sediments (1.0 ± 0.5) (Fig. 2; Table S1 in Supplementary Material).

The Pearson correlation coefficients (Rollinson 1993) for REE concentrations (excluding Lu) in the soil samples range from 0.93 to 0.99, indicating strong positive linear correlations between the REE concentrations in the soil samples of the Barakah NPP. These results suggest similarity in transport and depositional processes (Okay et al. 2013). The Pearson correlation coefficients of Lu with other elements range from 0.78 to 0.85. These results mean that Lu has positive, although weaker, correlations with the other elements.

The rankings of the average REE concentrations (in ppm) in the shore samples were: La (0.9) > Nd (0.87) > Pr (0.23) > Sm (0.19) > Gd (0.16) > Dy (0.15) > Er = Yb (0.07) > Eu (0.05) > Ho (0.03) > Tb (0.02) > Tm = Lu (0.01) (Fig. 2; Table S1 in Supplementary Material). In the soil samples, the rankings of the average concentrations (in ppm) were: Nd (3.39) > La (3.4) > Pr (0.85) > Sm (0.70) > Gd (0.66) > Dy (0.57) > Er (0.27) > Yb (0.24) > Eu (0.17) > Ho (0.11) > Tb (0.08) > Tm (0.04) > Lu (0.03). The order of the average REE concentrations (in ppm) in the marine sediments was: La (1.0) > Nd (0.98) > Pr (0.24) > Sm (0.20) > Gd (0.19) > Dy (0.16) > Er (0.08) > Yb (0.07) > Eu (0.04) > Ho (0.03) > Tb (0.02) > Tm = Lu (0.01). This order is similar to that of the elements in the Earth's crust (Taylor and McLennan 1995).

Shore samples, which are rich in carbonates as indicated by the presence of abundant shell fragments, show lower REE concentrations. Calcareous biological debris is known to dilute REE abundances in sediments (Chen et al. 2013). The standard

deviations for all elements in the shore samples (0.01–0.30 ppm) were the smallest compared to those in soil (0.02–1.35 ppm) and marine samples (0.01–0.50 ppm). The concentrations of each REE in the shore samples were relatively homogenized for samples B1–B16. In all three sets of samples (shore, soil, and marine sediments), La and Nd have the widest range of concentrations among samples, with standard deviations as high as 1.35 ppm. Among all 58 samples, the soil samples have the highest REE concentrations. Kasper-Zubillaga et al. (2008) stated that long-distance eolian transport results in low REE concentrations. In this study, the low REE concentrations may be related to the northern shamal wind. El Tokhi et al. (2015) reported that soil samples from Abu Dhabi were not affected by tide and water currents and that they do not come from different rock sources.

All REE concentrations measured in this study were below the abundances of REEs in the Earth's crust reported by Turekian and Wedepohl (1961) and below the upper crustal values reported by Taylor and McLennan (1995). These low concentrations of REEs in the study area suggest the absence of anthropogenic activities such as mining, cutting, drilling, blasting, transportation, and stockpiling (Zhang et al. 2000) or the application of REE fertilizers (Pang et al. 2001) or e-wastes (Balaram 2019). The concentrations of LREEs were higher than those of HREEs, which is in agreement with the general distribution of REEs in sandstones (Turekian and Wedepohl 1961). This behavior was expected because LREEs are normally more enriched than HREEs (Haskin et al. 1966).

Normalization was performed with respect to chondritic values (listed in Supplementary Material) (Taylor and McLennan 1985) (Fig. 3) because the

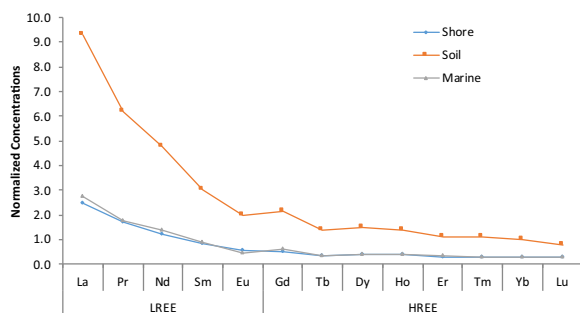


Fig. 3. Average concentrations of LREEs to the left (La, Pr, Nd, Sm, and Eu) and HREEs to the right (Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) after normalization with respect to chondrites in shore, soil, and marine sediments.

composition of chondrites is thought to be similar to that of the Earth's mantle as a reference. In this study, chondrites were used for the normalization of the REEs in sand samples (Taylor and McLennan 1985). Eu appears to have relatively low values in the soil samples, possibly because of the preferential dissolution of Eu-bearing minerals removing Eu from soil (Sultan and Shazili 2009). The normalized pattern was similar to those obtained in Malaysia (Sultan and Shazili 2009), in China (Fu et al. 2011), and in the UAE (El Tokhi et al. 2015).

In general, grain size, mineralogy, source rock composition, and chemical weathering were the main factors that control the REE concentrations in marine sediments (Yang et al. 2002). Clay minerals are rich sources of REEs due to their ability to incorporate REEs into their crystalline structures and their ability to adsorb REEs onto their surfaces (Dubinin 2004). Balaram (2019) grouped the economically important REE deposits into the following five categories: (i) alkaline igneous rocks: pegmatites and carbonatites; (ii) residual deposits; (iii) heavy mineral placers; (iv) REEs in coal; and (v) REEs in the sediments of the continental shelf and ocean bottom. Figure 4 shows the normalized REE concentrations for the different grain size fractions of the marine sediments. The inverse relation between grain size and contamination (Sholkovitz 1988; Dubinin 2004) is obvious from this figure. Fine grains have the highest contamination for all REEs.

LREE and HREE enrichments are controlled, to varying degrees, by two processes (Zuoping and Chuanxian 1996): infiltration and adsorption onto clays. The LREE enrichment with respect to HREEs is given by $(La/Yb)_n = (La_{sample}/La_{chondrite}) / (Yb_{sample}/Yb_{chondrite})$, where n stands for chondrite-normalized values (Tranchida et al. 2011). The calculated average $(La/Yb)_n$ values for shore, soil, and marine sediments were 8.96, 9.75, and 9.39, respectively. The average $(La/Yb)_n$ value of marine sediments was slightly higher than those of the soil and shore samples, denoting higher LREE enrichments than HREE enrichments in the marine sediments.

The mobility of metals, their uptake by plants, and their leaching into groundwater have consequences for the health of humans and animals (Bolan et al. 2003). Vural (2015a) worked on identifying the elements that were closely related to each other and/or have similar origins by measuring the quantity of their bioaccumulation in plants. To measure their mobility, REEs were typically correlated with

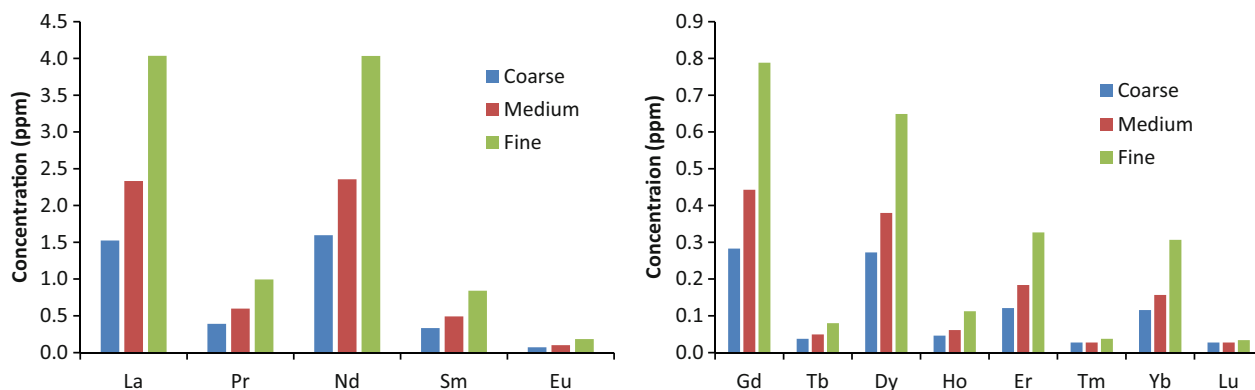


Fig. 4. Average REE concentrations in marine sediments normalized with respect to REE concentrations in chondrite. LREEs and HREEs are displayed on the left and on the right, respectively. Values are reported for three grain sizes [coarse (0.5–1.0 mm), medium (0.25–0.50 mm), and fine (125–250 μm)].

iron, aluminum, or zinc (Shiller and Boyle 1985). In this study, REE concentrations in marine sediments were correlated with Al, which is a major rock-forming element (Perryman 2011). Al is considered immobile over time during alteration processes, including temperature and chemical variations (Ligahat et al. 2003). This assumption is based on the fact that Al has low solubility in water under upper crustal conditions (Manning 2006). Linear correlations between Al_2O_3 and REEs can be used to estimate the REE compositions of sedimentary rocks and the upper continental crust within reasonable uncertainties by using Al_2O_3 concentrations (Shan and Zhang 1991). Figure 5 depicts the positive correlations between the REEs in the marine sediments and Al in the form of Al_2O_3 , with r^2 values ranging from 0.72 to 0.87. The strong correlations between REEs and immobile Al (Land et al. 1997) suggest low mobility for the REEs and their resistance to fractionation during weathering processes (Prudincio 1995; Fu et al. 2011). It is worth noting that this correlations between REEs and Al were stronger at lower concentrations of REEs than at higher concentrations. These results suggest that at higher concentrations, the REEs tend to be more mobile.

To assess soil contamination with REEs, which may be a significant source of pollution and may have ecotoxicological effects on terrestrial, groundwater, and aquatic ecosystems in the region (Vural 2015b), enrichment factors (EFs) were evaluated (Fig. 6). The EF is a good tool to differentiate between metal sources from anthropogenic and naturally occurring contamination (Rubio et al. 2000).

EFs were calculated with respect to a reference element, which is a “conservative” element with contents almost exclusively from the Earth’s crust (Wang and Liang 2015). The most common reference elements are aluminum (Al), zirconium (Zr), and iron (Fe) (Shiller and Boyle 1985; Schropp et al. 1990). The EF is given by $EF = (C_i/C_r)_{\text{sample}} / (C_i/C_r)_{\text{crust}}$ (Sutherland 2000), where C_i is the concentration of the element i and C_r is the concentration of the reference element r . In this case, C_r is the crustal value of Al obtained from the upper continental crust values reported by Turekian and Wedepohl (1961). Enrichment factors $EF < 1$, $EF = 1-3$, $3-5$, $5-10$, $10-25$, $25-50$, and $EF > 50$ indicate no enrichment (I), minor enrichment (II), moderate enrichment (III), moderate severe enrichment (IV), severe enrichment (V), very severe enrichment (VI), and extremely severe enrichment (VII), respectively (Birch 2003).

As shown in Fig. 6, all the REEs in the shore samples, except for Tm (EF was 1.24) and La (EF was 1.02), have an average EF less than unity, i.e., 0.05. There was no enrichment in any of the elements in any of the sampling areas. The shore samples have minor enrichments in Tm and La because their EF values were slightly above unity. Figure 6 illustrates that the shore samples were relatively more enriched than the soil samples, which, in turn, were more enriched than the marine samples. The EFs of LREEs were mostly higher than those of HREEs (except for Tm). The relatively higher enrichments of LREEs were congruent with the results obtained from the evaluated $(\text{La}/\text{Yb})_n$ ratios.

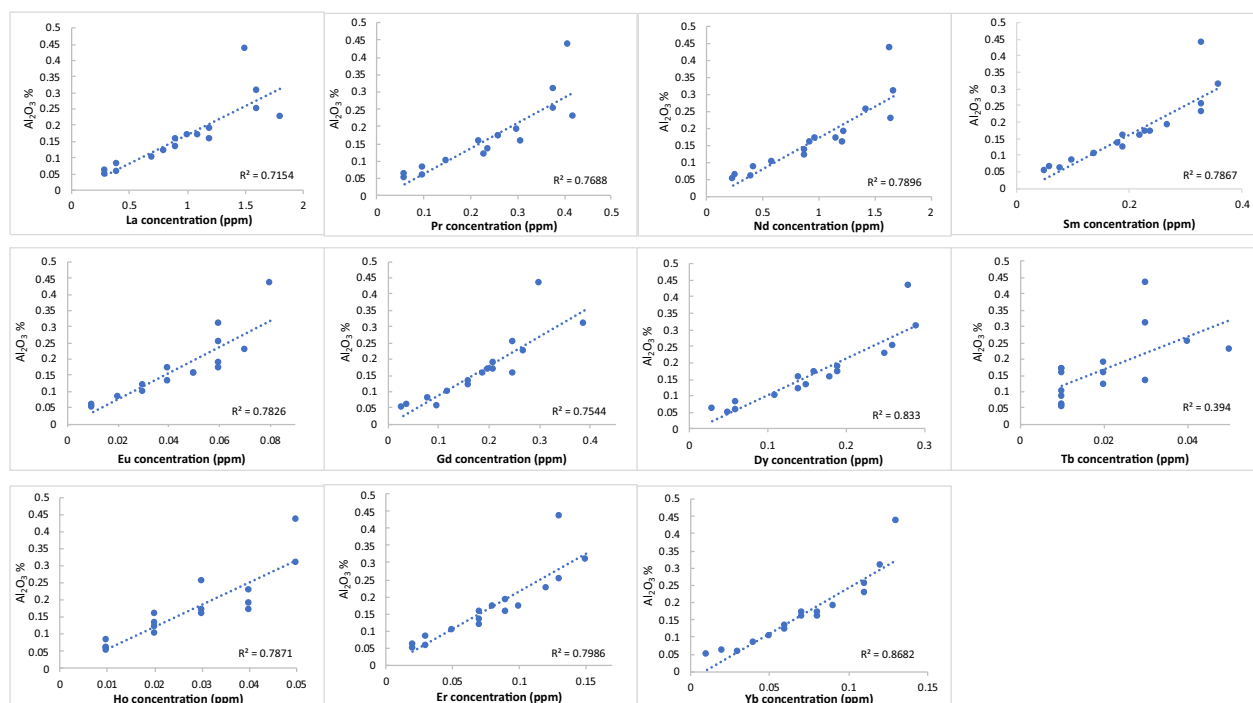


Fig. 5. Percent Al_2O_3 contents (%) versus REE concentrations in marine sediments (in ppm). The REEs Tb, Tm, and Lu were excluded because in most samples they were undetermined (i.e., below the detection limits).

The pollution load index is given by $\text{PLI} = (\text{EF}_1 \times \text{EF}_2 \times \text{EF}_3 \dots \times \text{EF}_n)^{1/n}$, where n is the number of metals (Tomlinson et al. 1980). The PLIs in the shore, soil, and marine samples were all less than unity (0.67, 0.52, and 0.17, respectively), denoting no pollution.

The geoaccumulation index is given by $\text{I-geo} = \log_2 [C_i / (1.5B_i)]$ (Müller 1979), where C_i is the measured concentration of element i in a given sample and B_i is the background value, i.e., the average sandstone value for element i from Turkian and Wedepohl (1961). As shown in Fig. 6, all values of I-geo were negative, denoting an uncontaminated area (Müller 1979).

Table 1 lists the distribution of REEs in many countries across three continents: Asia, Africa, and North America (Caccia and Millero 2007; Sultan and Shazili 2009; Xu et al. 2009; Antonina et al. 2013; El Tokhi et al. 2015; Wang and Liang 2015; Akinlua et al. 2016; Naidu et al. 2016; Zaremotlagh and Hezarkhani 2016). The REE concentrations in the Barakah NPP were compared to those reported in other studies where the grain size and geographical latitude were similar. The coastal areas of the UAE (this study), Malaysia (Antonina et al. 2013), and

India (Naidu et al. 2016) show lower REE concentrations than the Earth's crustal values. This similarity can be attributed to the presence of calcareous biological debris and its ability to dilute REE abundances in sediments (Chen et al. 2013). The highest REE concentrations were found in areas surrounded by mining activities in Baotou and China (Wang and Liang 2015), followed by Iran (Zaremotlagh and Hezarkhani 2016). Marine sediments in Korea and China have high contents of REEs (Xu et al. 2009). These values were controlled by rock composition and variations in the levels of chlorite and monazite, which were more abundant in Korean river marine sediments than in Chinese samples (Xu et al. 2009). Concentrations of REEs in the USA marine sediments (Caccia and Millero 2007) were relatively lower than those in other countries (according to the studies listed in Table 1), and the lowest concentrations were found in the UAE marine sediments. In general, these differences in REE concentrations may be attributed to anthropogenic activities in industrial areas or to geologic compositions of the areas because REE concentrations in nature are controlled by REE-bearing minerals (Müller 1986).

As depicted in Fig. 7, the spatial distributions of all REEs were similar; the highest concentrations were in the south, while the lowest concentrations were in the northern zone toward the shore. In fact, the soil samples, which have higher REE concentrations than the other samples, were collected from the south, while the marine sediments, which have

lower levels of REEs, were collected from the north. The east was less contaminated than the south, with respect to all elements except for Tm and Lu. Similarly, the west was contaminated to the same extent as the east with respect to all elements except for Tm, Tb, and Lu.

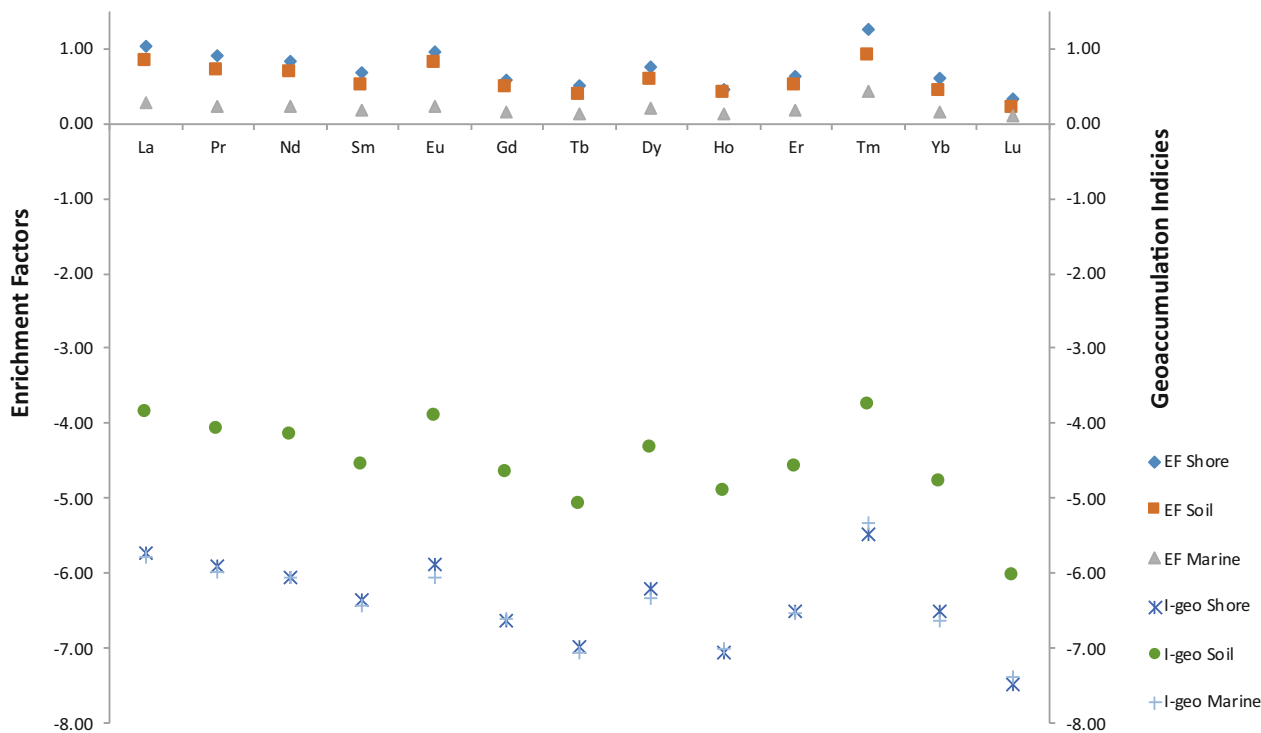


Fig. 6. Average enrichment factors (EFs) and geoaccumulation indices (I-geo) for the shore, soil, and marine samples.

Table 1. REEs concentrations (ppm) in the shore, soil, and marine samples from this study; and those from other international studies

| Location | La | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb |
|--|--------|--------|--------|-------|--------|--------|-------|-------|------|-------|-------|------|
| This study (Shore) | 0.95 | 0.23 | 0.87 | 0.19 | 0.05 | 0.16 | 0.02 | 0.15 | 0.03 | 0.07 | 0.01 | 0.07 |
| Malaysia (Antonina et al. 2013) | 16.30 | 4.30 | 12.80 | 4.20 | 3.39 | 2.47 | 0.65 | 1.54 | 0.59 | 1.04 | 0.42 | 1.20 |
| Nigeria (Akinlua et al. 2016) | 51.10 | 5.81 | 7.22 | 8.56 | 1.52 | 297.8 | 0.81 | 29.19 | 0.50 | – | 12.80 | 2.77 |
| India (Naidu et al. 2016) | 0.17 | 0.04 | 0.15 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.03 |
| This study (Soil) | 3.4 | 0.85 | 3.39 | 0.70 | 0.17 | 0.66 | 0.08 | 0.57 | 0.11 | 0.27 | 0.04 | 0.24 |
| Malaysia (Sultan and Shazili 2009) | 24.24 | 3.83 | 11.71 | 1.77 | 3.38 | 2.41 | 0.36 | 1.31 | 0.25 | 0.88 | 0.11 | 0.72 |
| Iran (Zaremotlagh and Hezarkhani 2016) | 454.44 | 59.89 | 306.98 | 52.71 | 151.92 | 117.72 | 34.83 | 26.36 | 6.81 | 13.22 | 7.64 | 14.3 |
| China (Wang and Liang 2015) | 891.59 | 355.20 | 384.44 | 48.16 | 2.76 | 10.30 | 2.50 | 7.85 | 2.06 | 3.19 | 1.36 | 2.90 |
| This study (Marine) | 1.0 | 0.24 | 0.98 | 0.20 | 0.04 | 0.19 | 0.02 | 0.16 | 0.03 | 0.08 | 0.01 | 0.07 |
| UAE (El Tokhi et al. 2015) | 3.43 | 0.74 | 2.83 | 0.60 | 0.18 | 0.50 | 0.11 | 0.48 | 0.16 | 0.30 | 0.10 | 0.27 |
| Korea (Xu et al. 2009) | 46.97 | 9.90 | 40.89 | 7.03 | 1.39 | 5.02 | – | 4.52 | 0.86 | 2.35 | – | 2.49 |
| China (Xu et al. 2009) | 33.29 | 7.38 | 31.15 | 5.77 | 1.15 | 4.41 | – | 4.24 | 0.83 | 2.29 | – | 2.48 |
| USA (Caccia and Millero 2007) | 14.10 | 3.50 | 13.70 | 2.70 | 0.65 | 2.60 | 0.41 | 2.29 | 0.50 | 1.50 | 0.20 | 1.20 |

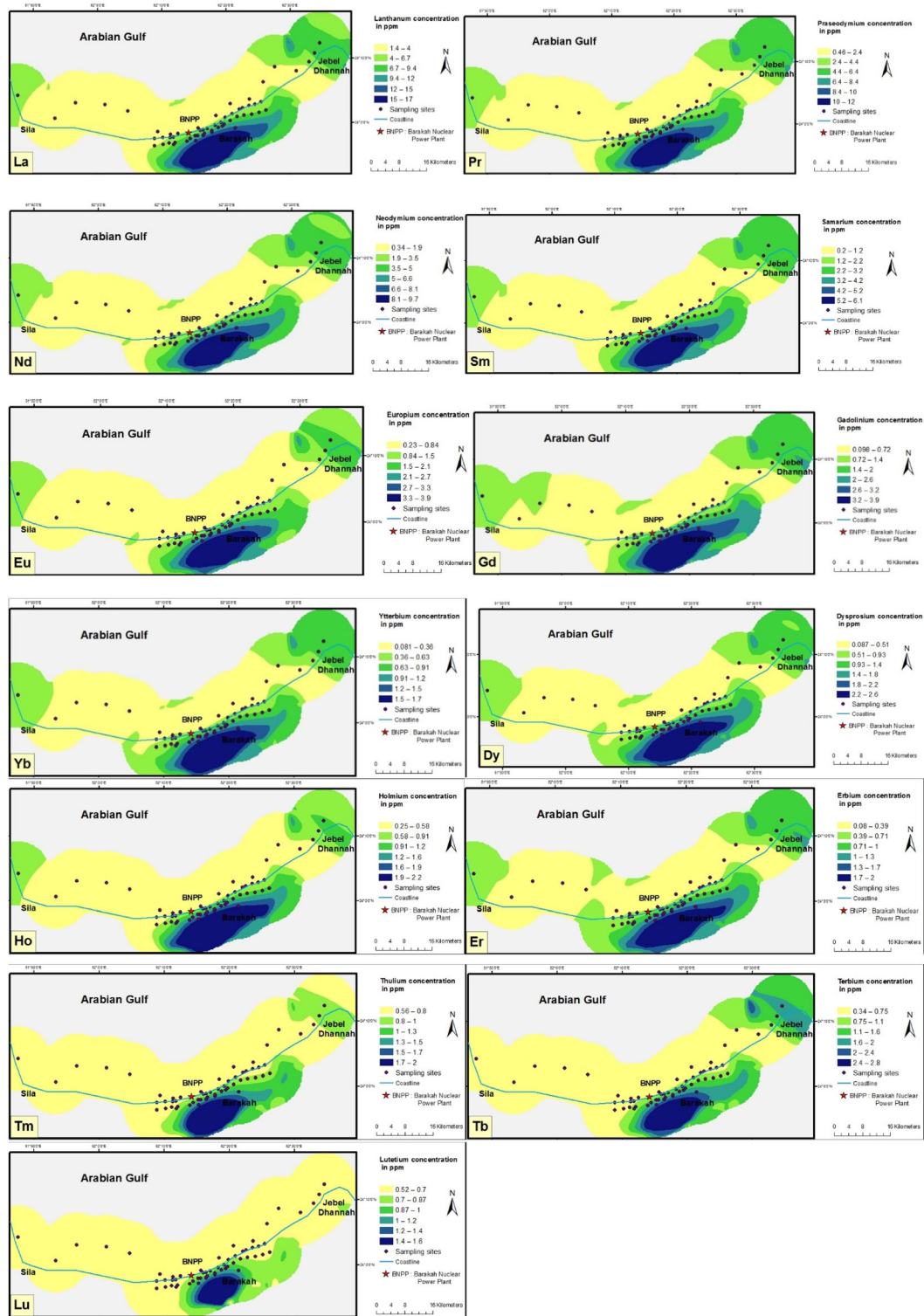


Fig. 7. Spatial distribution maps of the REEs around the Barakah NPP.

CONCLUSIONS

REEs pose serious environmental risks if they exceed certain limits. There is thus a need to establish a baseline for an area, e.g., around the Barakah NPP, where REE concentrations were expected to increase. Such a baseline will help determine the levels of increase in REE concentrations after the operation of the Barakah NPP over a period of time. This baseline will subsequently help in decision-making regarding preventive actions. The concentrations of REEs around the Barakah NPP were measured by ICP-AES. The total REE concentrations in the shore, soil, and marine samples were 2.80, 10.5, and 3.0 ppm, respectively. Among the 13 REEs, Nd was the most abundant element in the soil samples (3.4 ppm) on average, while La was the most abundant element in the shore and marine sediment samples (0.90 and 1.0 ppm, respectively). The REE concentrations reported in this study were close to those reported by El Tokhi et al. (2015). The chondrite-normalized REE patterns in the shore, soil, and marine samples indicate higher enrichments in LREEs than HREEs, with $(La/Yb)_n$ ratios of 8.96, 9.75, and 9.39, respectively. There were significant positive correlations between Al_2O_3 and REEs (r^2 ranges from 0.72 to 0.87), suggesting that REEs were rather immobile and of geogenic origins and were not influenced by anthropogenic sources. The enrichment factors (0.10 to 1.24) and geoaccumulation indices (-7.49 to -3.76) indicate that the study area was uncontaminated with REEs. The pollution load indices for the samples from the soil, shore, and marine sediments were all below unity (0.67, 0.52, and 0.17, respectively), denoting the absence of pollution in the area. The spatial distribution shows relatively higher concentrations of REEs in the south than elsewhere and almost none in the north. Overall, the REE levels around the Barakah NPP were within the safe limits, and the values reported in this paper will be useful for future monitoring to avoid contamination resulting from anthropogenic activities.

ACKNOWLEDGMENTS

The authors are grateful to the College of Graduate Studies at the United Arab Emirates University, UAEU, for covering all the costs associated with this research project.

ELECTRONIC SUPPLEMENTARY MATERIAL

The online version of this article (<https://doi.org/10.1007/s11053-020-09661-z>) contains supplementary material, which is available to authorized users.

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