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Elemental mapping of dead sea beach sands using X-Ray fluorescence technology: Implications for industrial applications and economic development

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Abstract

The Dead Sea reservoir contains high concentrations of natural salts, and its beach sands contains elements relevant of industrial applications. This study aims to identify and quantify the elemental composition of beach sands in the Ayn al-Zara area, located on the eastern shore of the Dead Sea. Field survey was conducted over an area of 30,000 square meters and 50 samples were collected from a one-kilometer length of coast along 30 meters inland. Portable X-ray fluorescence (PXRF) combined with geographic information systems (GIS) mapping was used to analyze samples. High concentrations of calcium, potassium, iron, sulfur, and mercury were observed in the analyses, indicating industrial potential. The findings confirm that the eastern Dead Sea beach sands contain economically valuable elements. Coupling PXRF with GIS mapping was efficient in mapping elemental distributions, which offered critical environmental and resource information. This research focuses on the industrial use of Dead Sea beach sands, pointing to high economic potential.

Keywords: Beach sands, Dead sea, Economic development, Elemental mapping, Industrial applications, PXRF technology.

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1. Introduction

Natural elements, particularly minerals and salts, are critical for economic development and industrial progress [1-3]. The production requirements of multiple industries depend on these natural elements, which serve as fundamental raw materials in agriculture, manufacturing, defense, pharmaceuticals, energy production, and therapeutic applications [4-6]. Nations benefit from these resources through technological advancement and economic growth via investment, employment, and contributions to sustainable development goals [7, 8].

In addition to their widespread importance, the spatial distribution of natural elements within various environments is critical in determining their accessibility and potential industrial applications. Natural elements are distributed across varied environments such as mountains, deserts, seas, and beach areas. Riverbanks and beaches serve as key storage zones for these elements [9-14]. Additionally, many studies have investigated mechanisms to monitor aquatic systems and trace sources of pollution in rivers, lakes, and seas [15, 16].

The Dead Sea is a terminal lake located on the border between Jordan and Palestine in the Middle East, close to 31.5°N latitude and 35.5°E longitude. It is the lowest surface on Earth, situated 440 meters below sea level. It is a unique hypersaline lake covering an area of 605 square kilometers. The region attracts both scientific and recreational interest due to its mineral-rich waters and element-enriched sediments, which reflect its unique and valuable geological characteristics. The Dead Sea is a global landmark known for its natural chemical wealth and geological significance, containing substantial valuable mineral concentrations [17]. The Dead Sea maintains high salinity in its water, and its sediments are rich in fundamental water-derived chemicals, including chlorine, sodium, magnesium, bromine, and potash, which are essential to various industrial processes. The agricultural sector primarily depends on potash for fertilizer production, while the chemical industry also uses it in various manufacturing processes [18, 19]. Magnesium and bromine serve as important elements for the chemical, automotive, pharmaceutical, and aerospace industries [20-23].

Several studies have highlighted the efficiency of portable X-ray fluorescence (PXRF) analyzers in mineral exploration and elemental analysis during mining processes [24, 25]. This device offers rapid in-situ assessment of element composition to conduct resource surveys and identify elemental composition. Geologists and mining professionals find these portable devices essential because of their accurate measurements, which reduce reliance on time-intensive laboratory procedures.

The aim of this study is to identify and assess elements present in a specified area through organized sample collecting procedures followed by analysis. The study creates a spatial distribution map to develop a sustainable resource framework that ensures proper Dead Sea natural wealth management for economic and industrial applications. The study contributes to both the geological understanding of the Dead Sea and also highlights its potential as a future source of valuable industrial elements.

2. Methodology

Samples were collected from several spots near the freshwater inflow of Ayn al-Zara, located on the coast near the Dead Sea beach. As it is shown in Figure 1, the location of Ayn al-Zara at the point where freshwater interacts with seawater. This shows its significance for research into interactions of different water sources. Ayn al-Zara region is of tremendous geological and hydrological value, primarily due to its unique geological configuration characterized by a high level of minerals and sediments. The influx of freshwater into the watershed significantly impacts the environmental chemistry of the region. The dynamic interaction between freshwater and saltwater is a major factor in the accumulation of elements such as salts and metals in sediments in the area. The peculiarities of the region, which include constant salinity, sediment accumulation, and nutrient circulation, result in the creation of special, specific ecological environments. This site is therefore appropriate for research purposes when it comes to studying elemental profiles of sand affected by freshwater, where the combination of freshwater and saltwater environments assists in the accumulation of natural elements.

Figure 1.
Location of the Ayn al-Zara area.

2.1. Target Area

The study area was systematically divided into two zones: one extending 500 meters to the north and the other 500 meters to the south of the point of freshwater inflow into the Dead Sea. This division was established to capture potential spatial variations in elemental distribution resulting from freshwater intrusion. The primary sampling points were located at ten designated sites (SN1 to SN5) in the northern section and (SS1 to SS5) in the southern section, as illustrated in Figure 2. These sites were strategically selected based on their proximity to the inflow and their relative positions along the shoreline to represent different degrees of exposure to freshwater. At each sampling site, five subsamples were systematically collected and later combined to form a composite sample, enhancing the statistical reliability and representativeness of the elemental content at each location.

To capture the lateral variation in elemental composition, sampling was conducted along a 30-meter-wide transect oriented perpendicular to the shoreline at each site. This approach was designed to evaluate how the interaction between freshwater and seawater influences the spatial dispersion of elements across the shore. By integrating both longitudinal (north-south) and lateral (shore-inland) sampling strategies, the study was able to detect gradients in elemental concentration that correlate with proximity to the freshwater source. The selected sampling framework thus allowed for a comprehensive assessment of the freshwater impact on elemental deposition and accumulation in the surrounding sediments, highlighting key zones of geochemical change in the study area.

Figure 2.
Sampling target area on the eastern beach of the Dead Sea, showing the northern and southern main sampling points near the Ayn al-Zara.

2.2. Sand Sampling Analysis

PXRF analyzers provide a non-destructive, rapid, and accurate method of analyzing the element content in solid substances such as sand, soil, and ore. Consequently, PXRF technology is widely used across many disciplines, from mining to sediment investigations, environmental pollution monitoring, and geological surveys. The main strengths of PXRF technology are its portability and ease of use in different environments, avoiding the need for sampling preparations and enabling timely evaluations based on measurements conducted in the field. PXRF is crucial in mineral exploration and mining for the rapid identification of economically valuable elements like gold, copper, lead, and zinc, aiding in planning extraction. Detection of hazardous elements and the estimation of contamination in soils and sediments are also important applications of PXRF in environmental studies.

In this research, a PXRF analyzer combined with multivariate analysis and geographic information systems (GIS) was used to assess the elemental content of sand samples taken from the Ayn al-Zara area. Using PXRF technology allowed quick on-site measurements of concentrations of elements that were essential to determine the impact of the influx of freshwater on the makeup of sediment. PXRF analysis was conducted using the scientific instrument SciAps X-200, a high-tech PXRF analyzer that has a silicon drift detector of 20mm² and an X-ray tube capable of delivering 6-50 K V, 200 µA with a gold anode. The analyzer's sensitivity across a large number of elements and its feasibility for geochemical and environmental investigations make it an ideal instrument for this kind of study. The device was calibrated using manufacturer-provided basic parameters and Compton normalization as per U.S. EPA Method 6200, thereby confirming the accuracy and reliability of the results. Since the PXRF instrument could be easily moved and operated in the study area, it enabled rapid, regular, and statistically sound sampling of elements across several locations.

3. Results

Samples were collected and analyzed to determine elemental concentrations at points 500m north and 500m south of where freshwater meets the Dead Sea water. The analytical device PXRF measures the elemental concentration as a percentage by weight, which was subsequently converted into parts per million (ppm), where 1% equals 10,000 ppm. This conversion facilitates a more accurate comparison of elemental abundances across samples. The concentration values are shown in Table 1 for both northern and southern segments of the zone where freshwater meets the Dead Sea water. Each value presented in the table is the average of five subsamples taken from each sampling site, providing a more representative estimate of elemental concentration.

Table 1.
Distribution of Elements in the Northern and Southern Areas of the Freshwater Point. ND = Not Detected (element not found within the detection limits of the instrument).

	Sample concentration, parts per million (ppm)									
Element	**SS5**	**SS4**	**SS3**	**SS2**	**SS1**	**SN1**	**SN2**	**SN3**	**SN4**	**SN5**
Ca	>100,000	93,702	85,718	79,837	75,545	74,545	79,840	84,718	91,702	>100,000
Fe	454	1892	5368	7947	8863	8863	7987	5467	1773	465
K	6953	6877	5237	4552	4388	4348	4596	5321	6927	6989
S	547	1214	1547	1868	2088	2128	1824	1507	1184	513
Ti	234	589	874	1357	1600	1641	1347	890	521	247
Sr	53	193	284	320	345	342	328	277	195	49
Mn	43	120	189	200	269	273	198	187	123	45
Zr	8	46	88	137	183	182	139	90	44	9
Ba	ND	ND	73	148	175	178	144	77	ND	ND
Hg	1784	900	350	220	150	155	223	351	912	1818
Rb	ND	66	79	87	106	103	87	78	53	ND
Zn	ND	8	13	22	45	49	32	23	18	8
Ni	ND	6	11	18	30	33	19	15	7	ND
Ta	ND	ND	ND	13	21	20	12	ND	ND	ND
Nb	ND	ND	ND	ND	5	7	ND	ND	ND	ND

The results in Table 1 show increasing concentrations of Ca, K, and Hg with increasing distance from the central freshwater inflow point. The total calcium (Ca) content reaches above 100,000 ppm at SS5 and SN5. The total potassium (K) content increases as distance increases northward or southward from the freshwater inflow point, reaching approximately 7,000 ppm at points SS5 and SN5. A significant increase in mercury (Hg) concentration was observed, for example, rising from 155 ppm at SN1 to 1,818 ppm at SN5. The data suggest that the Dead Sea is the primary source of these elements, with minimal contribution from the freshwater inflow. Concentrations of Fe, S, Ti, Sr, Mn, Zr, Ba, Rb, Zn, Ni, Ta, and Nb exhibited a general decreasing trend from the freshwater inflow point to the south and north. In both northern and southern extensions (SN1 to SN5 and SS1 to SS5), iron (Fe) concentrations decreased away from the freshwater inflow point. Elements such as nickel, tantalum, and niobium drop below detection limits at various points, as shown in the table. This indicates limited distribution or potential dilution of these trace elements in the affected zone.

Elemental concentrations show various patterns of distribution across the sampling locations. Figure 3 shows the increasing element concentrations that occur when moving along the north or south sampling directions. Comparatively low calcium (Ca) levels occurred at the location between SS1 and SN1 before concentrations increased at the sampling sites beyond these areas. The elemental potassium (K) and mercury (Hg) concentrations slightly increase while moving from south to north locations of the study point where freshwater meets the Dead Sea water.

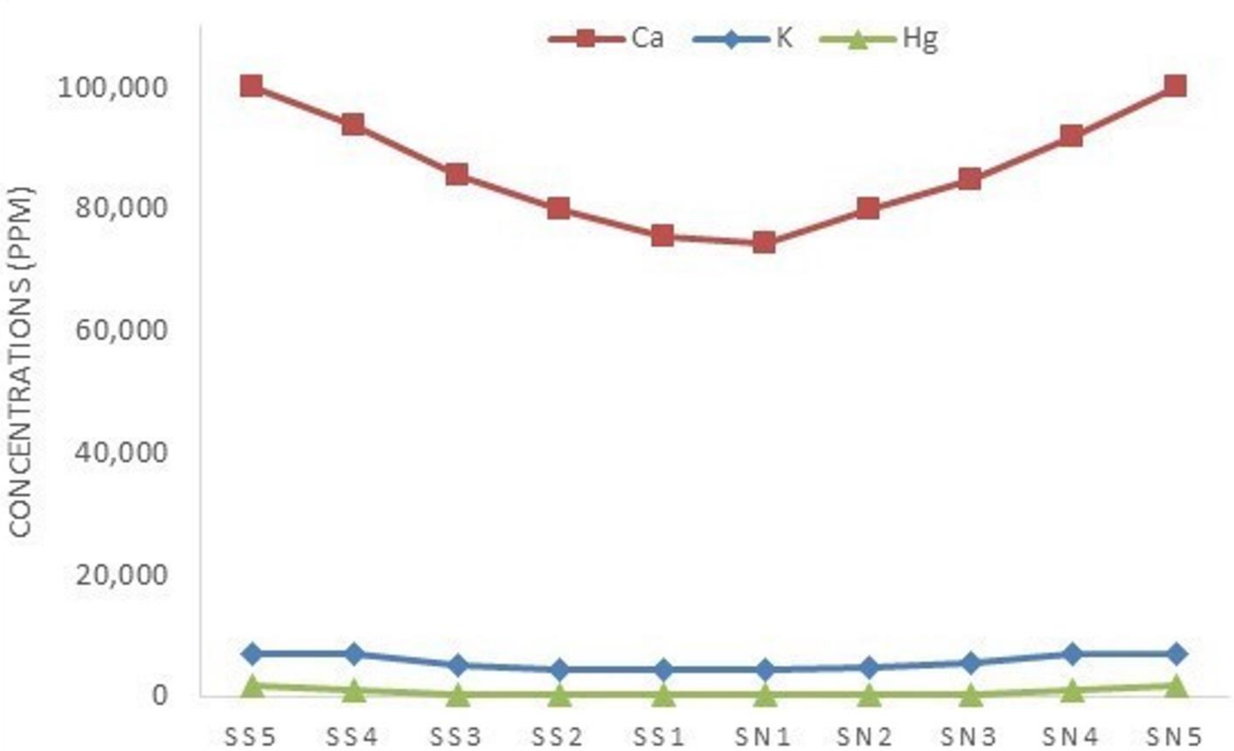

Figure 3.
Elemental concentrations increasing with distance from the freshwater source.

Figure 4 depicts selected elements whose concentration levels decrease when the sampling points move away from the freshwater inflow point. The highest levels of iron (Fe) occur at SS1 and SN1, but the levels decrease significantly at both sampling ends. The chemical elements sulfur (S), titanium (Ti), strontium (Sr), manganese (Mn), and zirconium (Zr) have their maximum levels in the middle points of the study area, and concentrations reduce slightly throughout both northern and southern areas.

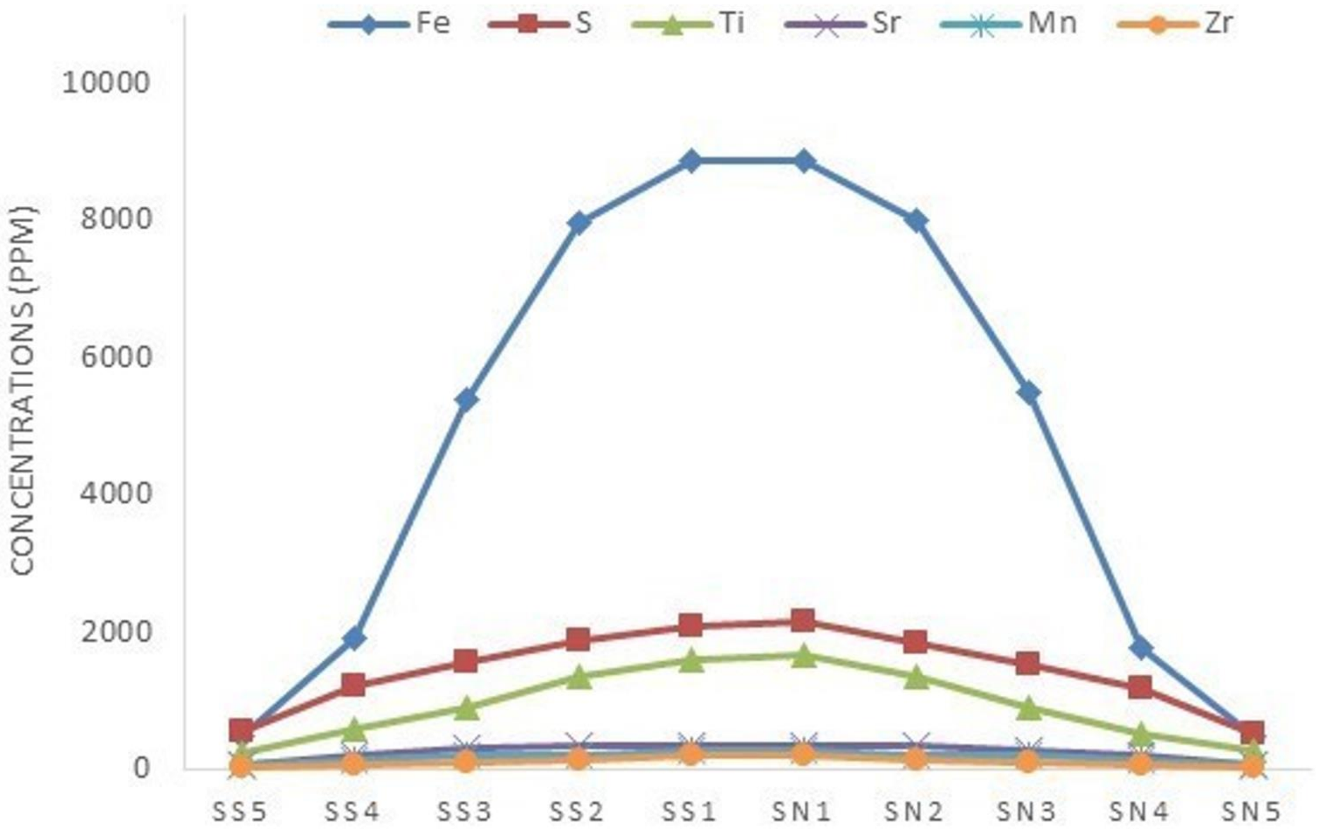

Figure 4.
Elemental concentrations decreasing with distance from the freshwater source.

Figure 5 identifies the sampling sites next to the elemental concentration data from Table 1 and indicates areas of high concentrations of materials potentially of industrial significance. The elemental distribution statistics show that geochemical processes control the elements' distribution because some elements build up in certain locations while others decrease at the same time. Different elements in the Dead Sea area have different distribution patterns because environmental, geological, and man-made factors control where they are found.

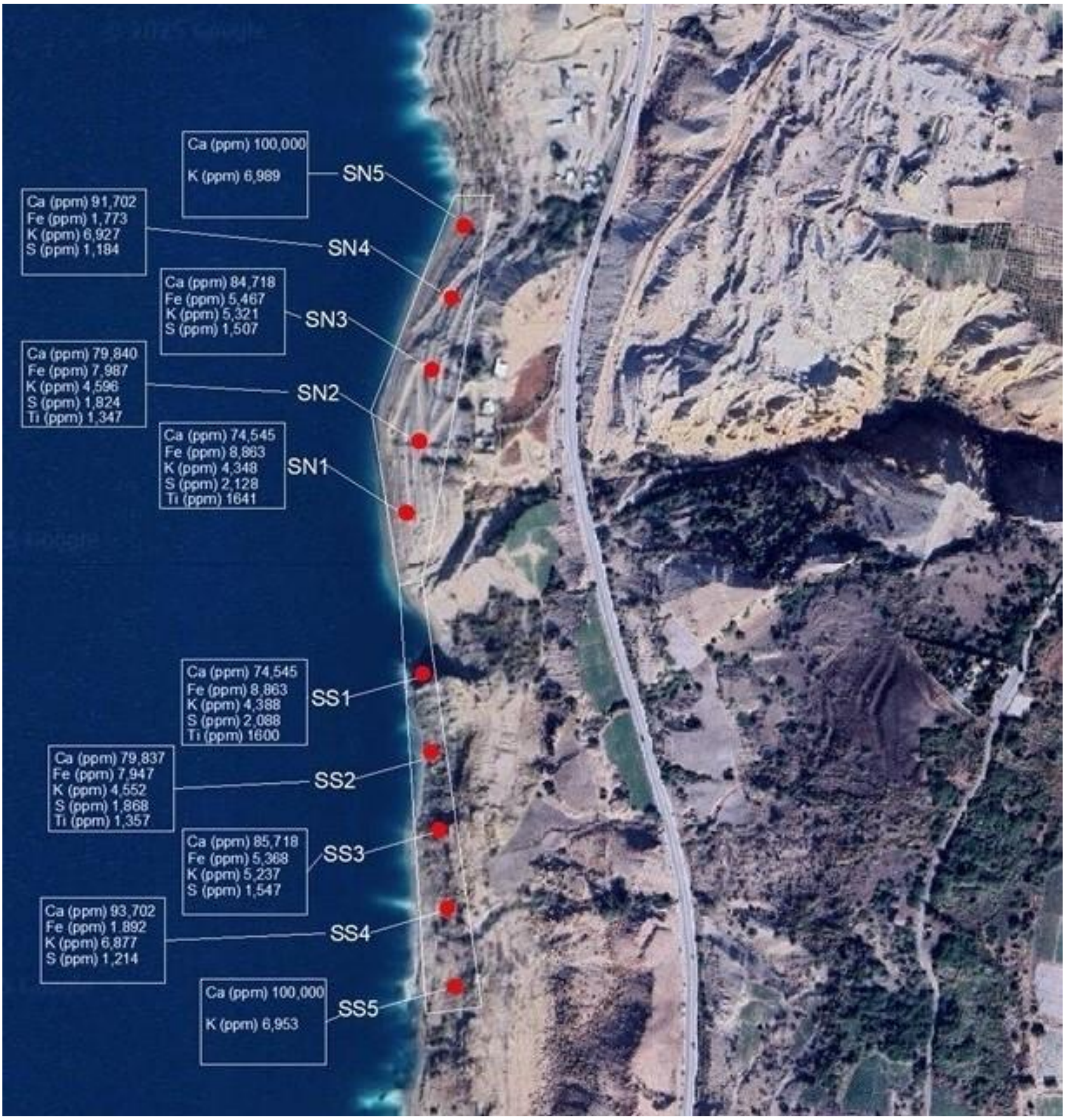

Figure 5.
Geographical Distribution of High-Proportion Elements

3. Industrial Perspective and Exploitation Potential

The economic and operational capabilities of elemental constituents of the study area were analyzed to establish their prospects in industry. Table 1 depicts a remarkable key element in the area, indicating possibilities for the region's development in the industrial sector. Of particular importance is the appearance of calcium (Ca), which often appears at levels in excess of 100,000 ppm. Due to its high concentration, calcium is a major element of attention in industrial uses, with significant importance in cement, construction, and chemical manufacturing processes where calcium is an essential component.

Widespread spread of potassium (K) in the northern and southern sampling regions underlines its industrial applicability. The increased gradient within the potassium concentration from the shoreline is an opportunity for extraction of this element. Dead Sea sands rich in potassium are quite critical to the manufacture of potash fertilizers, hence enabling increased agricultural output, improved food security through the infusion of necessary soil nutrients whose deficiency is amply evident in developing countries.

Mercury measurements at SS1/SN1 were 150–155 ppm, which shows 1784 and 1818 ppm at SS5 and SN5 respectively. Even though the elevated level of mercury concentration indicates a potential value in the economy through its use in electronics, instruments, and specialized chemicals, caution should be exercised regarding the use of mercury. Due to the high levels of toxicity and low environmental degradation rates of mercury, comprehensive regulatory measures and advanced control mechanisms are required to ensure the well-being of the environment and the public.

Elements iron (Fe), sulfur (S), titanium (Ti), strontium (Sr), manganese (Mn), zirconium (Zr), barium (Ba), rubidium (Rb), zinc (Zn), nickel (Ni), tantalum (Ta), and niobium (Nb) showed a progressive decrease in concentration from the southernmost to northernmost sediment samples. Iron, titanium, and manganese are of particular interest because of their metallurgical applications and use in alloying. While the focus areas showed moderate levels, the overall decline, specifically for the northern sites, suggests freshwater input may dilute or displace such elements, limiting the potential for large-scale mining activities within these locales.

Overall, the prospects for calcium, potassium, and mercury extraction offer promising economic opportunities in the construction, agricultural, and chemical sectors. However, these must be preceded by thorough environmental impact assessment, cost-benefit analysis, and infrastructural planning to ensure sustainable and responsible exploitation. Although central locations manifested comparatively higher iron and manganese levels compared to peripheral locations, the levels are still too low to be economically extractable, implying modest profitability for commercial extraction based on current conditions.

4. Conclusion

This paper analyzed Dead Sea beach sand at Ayn al-Zara using PXRF for elemental mapping and investigating resource potential and environmental concerns. The strategic significance of the Ayn al-Zara area strengthens its position as an industrial resource hub because the sand materials exceed 100,000 ppm in calcium content and 7,000 ppm in potassium levels. Contamination occurs due to freshwater intrusion from agricultural runoff and underground water leakage, creating the potential for major ecological destruction.

Geological surveys near the entire Dead Sea beach need to be executed in detail because they will help identify profitable mining zones and detect environmental contamination sources. The implementation of advanced tracking systems for pollutants needs to occur for both tracking source locations and creating effective pollution reduction strategies. Techno-economic feasibility studies must lead the development of sustainable mining operations, which minimize environmental impact by taking into consideration the particular salinity gradients and elemental distribution throughout the area.

The research concludes that industrial development must be carefully balanced with environmental conservation to achieve sustainable mining operations compatible with the national development plan.

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