

# Mineralogical Characteristics of Sabkhas along the Coastline of Kuwait

Adeeba Al-Hurban<sup>1\*</sup>, Fahd Al-Askar<sup>2</sup>, Nihaiia Said<sup>1</sup>

<sup>1</sup>Earth and Environmental Sciences Department, Faculty of Science, Kuwait University, Al-Shadaddiah, Kuwait

<sup>2</sup>Geography Department, Faculty of Art, Kuwait University, Al-Shadaddiah, Kuwait

Email: \*adeeba.alhurban@ku.edu.kw, fahad.alaskar@gmail.com, nihaiia.said@ku.edu.kw

**How to cite this paper:** Al-Hurban, A., Al-Askar, F. and Said, N. (2026) Mineralogical Characteristics of Sabkhas along the Coastline of Kuwait. *Journal of Geographic Information System*, **18**, 28-55.  
<https://doi.org/10.4236/jgis.2026.181003>

**Received:** November 23, 2025

**Accepted:** January 31, 2026

**Published:** February 3, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

Surficial deposits of Kuwait are mostly of Quaternary sediments, including coastal deposits such as sabkha deposits. Sabkha is the English form of the Arabic nomenclature (*Sebkha*), which means a land of salt and water inmates (salt flat) that intersects with the underlying shallow groundwater table and extends over the high tide level, covered with clastic sediments rich in evaporites. In Kuwait, there are two kinds of coastal sabkhas: clastic coastal sabkhas along the northern coast of Kuwait and carbonated sabkhas along the southern coastal line. This study aims to investigate the mineralogical composition and characteristics of sabkha deposits along the coastal line of Kuwait using GIS and remote sensing techniques. Landsat 8 images, dated back to May 2024, were used, with a map color combination of 4, 3, 2 (True color combination – RGB bands only). The images were radiometrically corrected using the raster calculator to measure the TOA. LST, SMI, and NDVI indices to locate and categorize sabkhas in the study area based on their spectral reflectance, as obtained from satellite-analyzed imagery. Surficial samples were collected from nine locations in the study area and subjected to XRD analysis for their mineralogical constituents. Results showed the absence of evaporite minerals in the surface deposits of the sabkhas as well as the existence of 5 other minerals, with different percentages of distribution. Quartz and Calcite are the only minerals found in all sabkha locations, indicating the predominance of these two minerals in the study area. One of the identified minerals was Petedunnite, which rarely occurs in sabkha environments, suggesting its existence due to provenance transport.

## Keywords

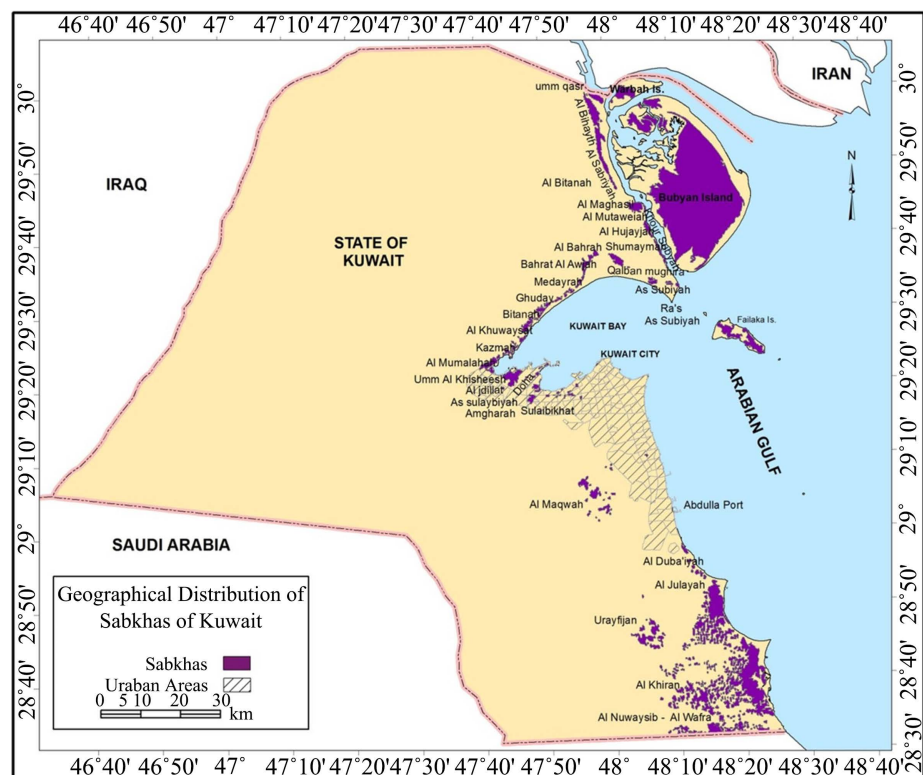
Sabkhas, Coastline, Mineralogy, Clastic, Evaporites, GIS, Remote Sensing

## 1. Introduction

Kuwait is situated in the northwestern corner of the Arabian Gulf in a transitional zone between the stable Arabian Foreland on the southwest and the vast compound delta of the Mesopotamian Plain in the north and northwest (Purser, 1973) [1]. The state of Kuwait is located in the northwestern side of the Arabian Gulf between Longitudes 46°30' to 48°30' East, and 28°45' to 30°05' North according to the geographic coordinate system, and it is also located within R38-R39 zones according to the Universal Transverse Mercator coordinate system (UTM). Kuwait was subjected to tectonic movements and geomorphic processes (weathering, aeolian and coastal) during the late Pliocene-Pleistocene age, which in turn resulted in the formation of variant geomorphological features along the coastal area (Kassler, 1973 [2]; Al-Sarawi, *et al.*, 1993 [3]; Al-Sulaimi & El-Rabaa, 1994 [4]).

Surficial deposits of Kuwait are mostly of Quaternary sediments including Al-Dibdibbah Pleistocene gravel deposits and Holocene sediments. These deposits and sediments comprise desert surface deposits, alluvium, aeolian sands and beach and coastal deposits such as sabkha deposits, sand shoals, beach rocks and tidal flat deposits (Khalaf, *et al.*, 1984 [5]).

Generally, sabkhas in Kuwait are of two kinds clastic coastal sabkhas along the northern coast of Kuwait and coastal sabkhas carbonated along the southern coastal line (Figure 1).



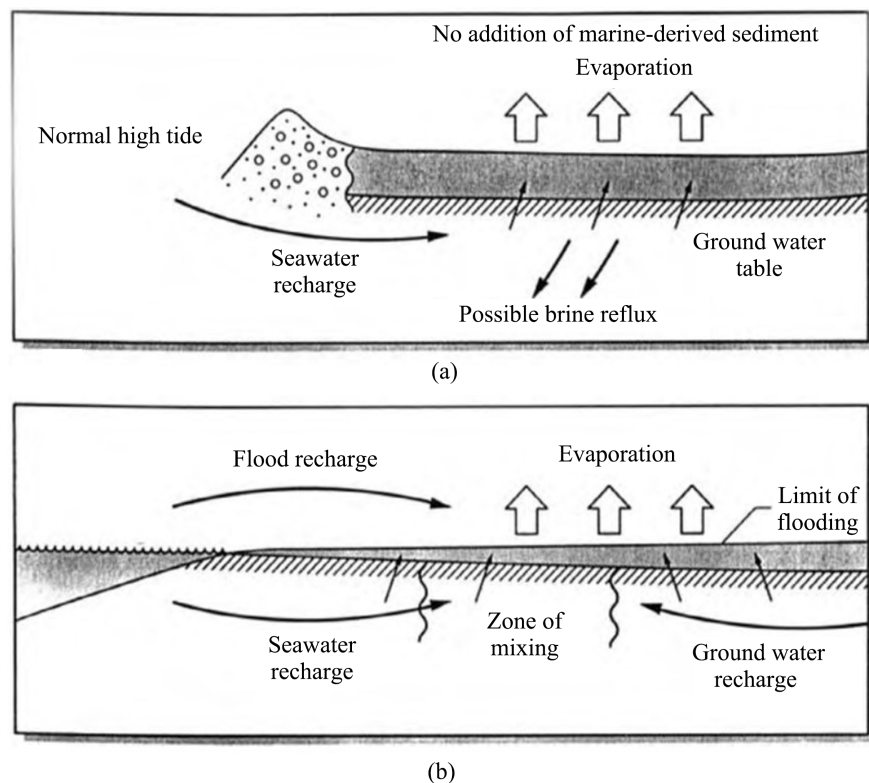
**Figure 1.** The geographical distribution of coastal and inland sabkhas (north and south) (modified after Saleh *et al.*, 1999 [6], Al-Hurban & Gharib (2003 [7] & 2004 [8]) and Kleo & Al-Otaibi, 2011 [9]).

These two kinds differ in their composition properties, which can be attributed to the differences in the geomorphology and source of sediments of each area. The deltaic sedimentation of the Shatt-Al-Arab (Tigris-Euphrates rivers) influences the northern clastic sabkhas. In contrast, it doesn't have such an influence on the southern carbonate sabkhas, which are the same as the other sabkhas along the southern coastal line of the Arabian Gulf, e.g., in Abu Dhabi and Qatar [1].

This study aims to investigate the mineralogical composition and characteristics of sabkha deposits along the coastal line of Kuwait using Geographic Information System (GIS) and remote sensing techniques. Different maps were constructed to show the distribution of the minerals in both sectors, the northern and the southern.

## 2. Previous Studies

The groundwater, which is mostly seawater, that is either continually recharge beneath the sabkha or from the vicinity landmass (**Figure 2**) is the main source of most of the evaporite sediments precipitated in sabkhas, where the circulation of this saline groundwater is continuously taking place by the capillary action and evaporative pumping, in addition to the intermittent sea flooding and the action of the beach ridges as a reservoir of seawater.



**Figure 2.** Sabkhas receive water from a variety of sources (After Walker, 1984 [10]). (a) Sabkha with seawater recharged through the subsurface and with relatively little groundwater influx. (b) Sabkha groundwater is recharged by a mixture of seawater and groundwater, plus seawater flooding from major storms.

Typically, such sabkha evaporites are mineralogically composed of anhydrite, gypsum and dolomite, where gypsum crystals are altered from their original formation within layers of interbedded carbonate mud or shale; and the anhydrite deposits are formed in a structure (particularly common in sabkha evaporates) called “chickenwire” which a mixture of elongate, irregular clumps of anhydrite separating thin strings of carbonate and/or silticlastic mud [8].

Sometimes the surface of sabkhas in arid regions would be crusted with a veneer of salt and scattered discoidal gypsum crystals and covered by a layer of drifting quartz sand due to the frequently occurring dust and sand storms.

Inland sabkhas usually occur when water intermittently floods from the wadis in the vicinity into the low-lying depressions leaving a damp and salt encrusted sediments. They also develop in depression where a leveling of water table and the sabkha’s surface is reached.

The surficial salt crust in inland sabkhas develops due to the evaporation of the captured water, which concentrates salt sediments of which commonly is gypsum. It is worth mentioning that algal mats that occur in the coastal sabkhas are absent in the inland sabkhas. On the other hand, coastal sabkhas are distinguished by marine flooding, as well as, evaporitic conditions, which in turn constitute and diagenetic environment which have sediments of both continental and adjacent marine origin.

In this study, sabkhas are defined as low coastal dissecting the underlying shallow groundwater table. Variant-sized quartz sand is the major component of the sabkha deposits mixed with carbonate mud and scattered gypsum crystals encrusted with a thin veneer of salts left after the evaporation of collected water after rainy seasons. Sometimes, the surface of some of these sabkhas is underlain by calcrete (locally known as gatch), which exists as a friable or hard-consolidated sediments containing a heterogeneous mixture of gravel, sand, mud and calcium carbonate and gypsum that came from the direct precipitation from mineral bearing water within the pore spaces of the clastic deposits as a cementing material.

At the northern part of Kuwait Bay, the recent sabkha sediments overlie similar Tertiary deposits, distinguished by large amounts of anhydrite. The tidal regime in the area is marginal between the semidiurnal and mixed type (Al-Zamel & Al-Sarawi, 1998) [11]. Southwesterly wind causes much higher normal tides, which is a significant process, where elevated waters of storm surges can cause breaching and inundation several kilometers inland (Al-Sarawi, 1988 [12]). Extensive sabkha deposits are included in the supratidal flat, being devoid of vegetation and rarely flooded by seawater. In this area, deposition may sometimes intersect the water table and fill with seawater. On the outer edge of the depressions well-defined cubic halite crystals are found [11].

The sabkha surface itself is up to 2 km wide and in summer the flat supratidal plain is usually covered by a thin white veneer (less than 3 cm) of gypsum and some other evaporites, sourced from the water table 1.5 m below the sabkha surface, with development of some recent isolated algal mats within the tidal channels

at the intertidal zone [11]. In winter, the surficial evaporites do not occur continuously, nevertheless, there exist some scattered salt pans and salt crusts within little centimeters of the sabkha surface, which indicates that salt in the area begins to formulate in early May to Late November. Tidal channels are generally short less than 150 m long and of average depth of 80 cm and filled with interlaminated silts and algal mats [11].

The northeasterly part of Kuwait Bay is believed to be subjected to both extensive sediment deposition and sea-level fluctuations during the marine transgression and regressions of the Holocene period. This area is 5.5 km wide which constitutes the widest part of the tidal flat along the northern coast of Kuwait Bay with a maximum thickness of Holocene sediments guesstimated to be 8 - 12 m [6]. In the eastern and western parts of this featureless tidal flat, there exists a low lying desert plain covered in Quaternary fluvial gravels. This nearly flat sabkha is also interrupted by a high relief sand and pebble spit, unchangeable shoreline with beach rock, marine terraces and coastal vegetated dunes [6]. This area has a unique tidal regime as the sea water covers the intertidal and parts or all of the supratidal area depending on the variant flooding conditions, which are controlled by four factors: 1) tidal range (2 - 4 m); 2) wind speed and direction; 3) tidal phase at flooding time; and 4) gradient and morphology of sabkha surface [6].

According to their nature, geographic settings, and mode of occurrence, southern sabkhas are classified into two types: inland and coastal sabkhas. The former occurs in the irregular slopes in the western side whereas the latter extend along the elongated depressions in the southern coastal area [8].

## **2.1. Mineralogical Characteristics of Sabkha Deposits**

### **2.1.1. Northern Sabkhas**

The sabkhas surface, specifically the flat supratidal in northern Kuwait Bay area, is covered by a thin veneer of gypsum and other evaporitic minerals sourced from the existing water table 1.5 m below the sabkha surface.

The sabkha deposits in the northern area are different from those in the southeastern area of the Arabian Gulf (e.g., Holocene evaporitic settings of Abu Dhabi coastal area), where in the muddy part of the sabkha of the latter the calcium rich dolomite deposits are dominant and associating the well-defined tidal channels (Mckenzie, 1981 [13] and Patterson and Kinsman, 1982 [14]). Nevertheless, the southern sabkhas at Al-Khiran area are lacking for dolomite, which was attributed by Picha (1978) [15] to the composition of the underlying pre-Pleistocene substrate, which has almost no dolomitic material in their constitution as they are mainly composed of continental clastic sediments. Moreover, no dolomite was found in the northern area of the Arabian Gulf, which indicates that if any dolomite will exist in the subtidal and intertidal sediments, it would be partly sourced from the blown dust by the prevailing winds (Pilkey and Noble, 1966 [16]).

The upper most layer of the supratidal flat sabkhas are rich in gypsum having some halite along with few amounts of anhydrite. The x-ray diffraction reveals the

presence of aragonite in this subfacies but the most abundant mineral is gypsum, which exists as scattered deposits, as well as, in the form of gypsum mush that develops as a thin horizon of loosely packed crystals matrixed with the remnants of the original deposits (Evans, *et al.*, 1969 [17]). Gypsum also exists in the fine grain on the top of the thin horizon, and as going deeper it develops in the form of very coarse needle-shaped crystals, which by time passing will be overgrowth. It is worth mentioning that in the sabkhas landward the gypsum developed as elongated needle-shaped crystals. This can be attributed to more rapid rate of crystal growth resulting from the rapid rate of brine concentration (Kinsman, 1969) [18].

The lower subfacies is rich in anhydrite which develops in the form of well-defined nodules cemented with calcium carbonate, which its precipitation can be attributed according to Taylor and Illing (1969) [19] to burrowing animals that are abundant in the middle and upper tidal flats particularly in the tidal channels, nevertheless, they are absent in supratidal sabkha zone. X-ray diffraction indicated that dolomite presents in small amounts about 70 cm below the surface, quantitatively varying laterally and decreasing landward from the supratidal zone.

The above discussion of the obtained results shows that mineralogy within the sabkhas varies vertically and laterally, which indicates the effect of at least four factors on the development of the evaporitic sediments in the area: 1) evaporation rate, 2) water table position, 3) seawater flooding rate, and 4) groundwater salinity [11].

Recent marine deposition is reflected in subfacies, that is rich in gypsum with some halite crystals on the surface and deposition under subaqueous conditions is reflected by the development of the thin (5 mm) bands of algal mat. West, *et al.*, (1979) [20] conducted a study on the Mediterranean coast of Egypt and suggested a mechanism for the development of the gypsum nodules in the studied area. The same mechanism could be used to justify the presence of gypsum in the form of nodules displacing the fine grains. This mechanism suggests that gypsum is probably lagoon wise originated, which was dissolved and transported from below the water table to the surface above by capillary water and later on was precipitated as nodules that displace the sediments.

An earlier cycle of marine deposition is rich in anhydrite, where dehydration of gypsum resulted in the development of anhydrite above the groundwater. This mechanism for the development of anhydrite is evidenced by the absence of anhydrite at the surface, which means that this dehydration of gypsum resulted in the development of anhydrite replacing gypsum crystals at depth not at the surface. It is worth mentioning that Butler (1969) [21] suggested such a replacement for the Arabian Gulf sabkhas. X-ray diffraction results indicated the increment of anhydrite deposited amounts landward.

The mechanism of precipitation diagenetically within this unit could be used to justify the lack of dolomite in the Tertiary substratum and in the vicinity areas, as no primary dolomite was found in the top layers of this unit contrasting the situation in the Abu Dhabi sabkhas (Kinsman, 1964 [13] [14] [22]).

### 2.1.2. Southern Sabkhas

Data reveals that the grains are composed of quartz, feldspar, rock fragments, calcareous grains and gypsum [7] [8]. Due to their location closed to the fossiliferous oolitic limestone ridges, the coastal sabkhas contained the calcareous grains represented by skeletal fragments and oolites, which absent in the inland sabkhas. Quartz and feldspars are more abundant in inland sabkhas rather than the coastal sabkhas, whereas gypsum in on the contrary more abundant in the coastal sabkhas than the inland sabkhas. As for the rock fragments, which are mainly of detrital carbonates that possibly originated from the prevailing calcretic hills in the southern desert area, they were found to be equally distributed between the coastal and inland sabkhas.

Petrographic investigations under the polarizing microscope revealed that the quartz grains are of two types: 1) mostly monocrystalline with straight extinction and a little with slightly undulose extinction; and 2) least polocrystalline [7] [8]. The first type reveals that they might be originated from igneous and stressed igneous rocks, whereas the second type reveals that they might be originated from metamorphic rocks (Tucker, 1981) [23].

The fine size fraction was subjected for heavy mineral separation from two representative samples from the topmost recent sediments from the coastal sabkhas and the inland sabkhas. According to the obtained data, there was slight difference in the heavy minerals percentage between the coastal sabkhas (0.5%) and the inland sabkhas (0.4%). In the same context, the petrographic studies revealed that both sabkhas have nearly similar heavy minerals with slight difference. Those heavy minerals are mostly composed of hornblende, which is most abundant in inland sabkhas, apatite, which is most abundant in coastal sabkhas, zircon, epidote, spinel and magnetite.

According to the heavy minerals analysis, it is proposed that such sediments are originated from sialic igneous (apatite, hornblende, spinel, and zircon), mafic igneous (epidote, hornblende, and magnetite) and high rank metamorphic rocks (apatite, garnet, epidote, hornblende, magnetite, and zircon). According to the textural and mineralogical data, it is suggested by [7] [8] that such sediments could be mostly originated from the exposed Al-Dibdiba Formation composed mostly of a mixture of sand and mud.

## 3. Materials and Methods

### 3.1. Sampling and Field Work

Based on topographic maps of Kuwait (scale 1:50,000), aerial photographs (1991 with a scale of 1:29,000), Google Earth Engine maps, and field observations, the sabkha areas were identified and delineated. Accordingly, surface samples (about 30 cm deep with manual auger) were collected from 9 different locations along the coastline of Kuwait (**Figure 3**) with respect to their different spectral reflectances. The samples were visually inspected, described in the field, photographed, and prepared for further analyses. The samples were subjected to X-Ray-Diffrac-

tion (XRD) analysis to determine the mineralogical properties of sediments deposited in the area.



**Figure 3.** Sampling location map of the collected samples from the study area.

### 3.2. Laboratory Analysis

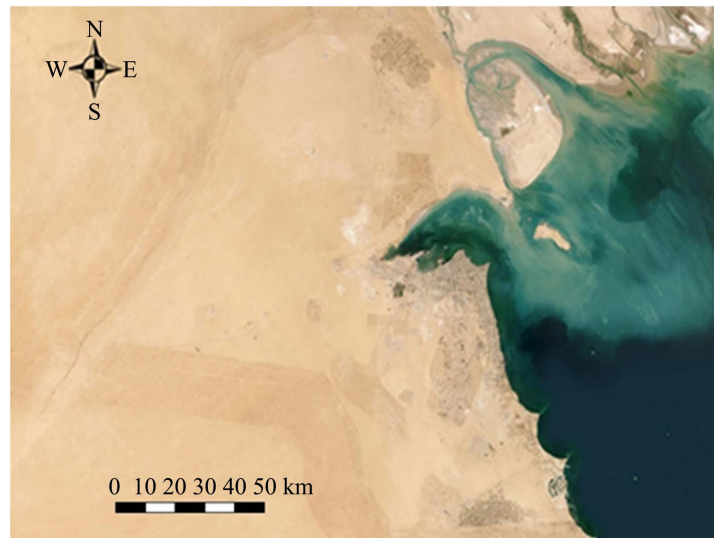
The collected surficial samples were subjected to XRD analysis. This technique is a non-destructive analytical technique used to identify the crystallographic structure, chemical composition, and physical properties of crystalline materials. It works by directing monochromatic X-rays at a crystalline sample, then measuring the scattering angles and intensities of the diffracted X-rays. The energy and intensity of these emitted X-rays are then measured to identify and quantify the elements present.

### 3.3. GIS and Remote Sensing

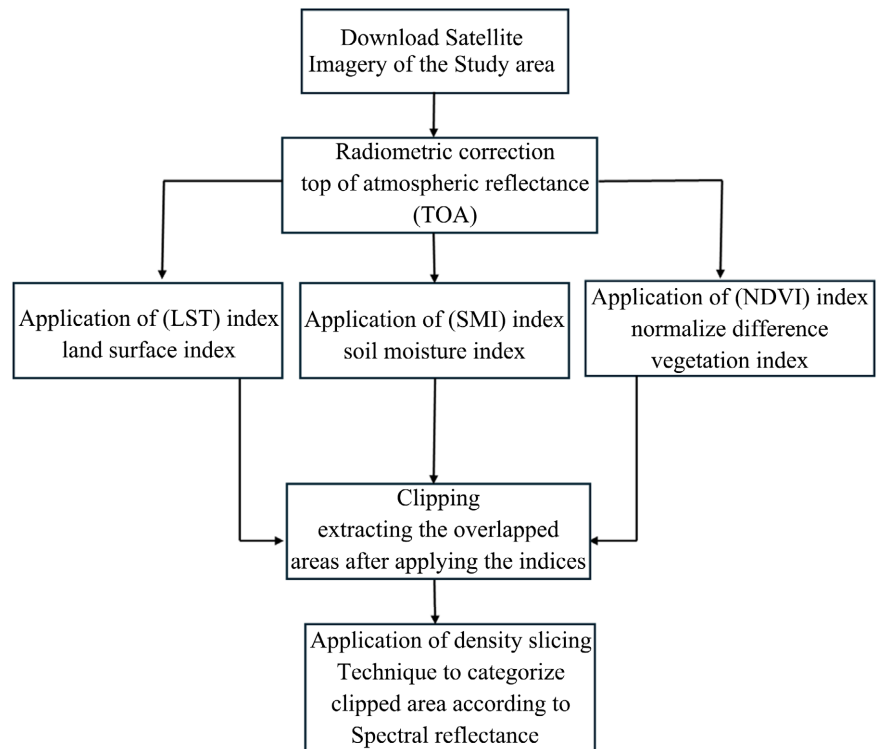
The state of Kuwait is located within R38 - R39 zones according to the Universal Transverse Mercator coordinate system (UTM). The satellite images of the two (UTM) zones that encompass the coastal areas of Kuwait were downloaded from the United States Geological Survey (USGS) site. These images were downloaded from Landsat 8 with the whole set of bands that include the full range of the spectrum that Landsat 8 supports and dated back to May 2024, as shown below. The map color combination is 4, 3, 2 (True color combination-RGB bands only) (**Figure 4**).

The workflow is divided into two main tasks (**Figure 5**): 1) locating sabkha areas in the study area, and 2) categorizing sabkhas into further diagnosed areas based on their spectral reflectance, as obtained from satellite-analyzed imagery.

A process of radiometric correction was conducted to the satellite images to improve the quality and accuracy of image data by reducing or removing distortions caused by factors like atmospheric conditions (haze, water vapor... etc.). This process is fulfilled by Aop of Atmosphere Reflectance or radiance (TOA),



**Figure 4.** The map color combination is 4, 3, 2 (True color combination-RGB bands only).



**Figure 5.** A chart of the procedures followed to locate sabkhas and categorize them according to spectral reflectance.

referring to the amount of solar radiation reflected or radiated by a surface, including the atmosphere, as measured by a satellite sensor. It compares data from different sensors and serves as a foundation for further atmospheric corrections to derive surface reflectance. This process was conducted for the whole set of bands of the satellite images; each band was separately processed for the two zones in question. Calculating (TOA) can be achieved via the raster calculator, a tool of

GIS (Geographic Information System) applications that is capable of eliminating atmospheric effects upon reflected and/or emitted radiations from the earth's surface. The elimination process is calculated by the following mathematical equation.

$$\rho_{\lambda} = \left( \pi * L_{\lambda} * d^2 \right) / \left( E_{sun\lambda} * \cos(\theta_s) \right) \quad (1) \text{ (Bakaeva \& Tuan Le, 2022) [24]}$$

where:

- $\rho_{\lambda}$ : is the TOA planetary reflectance for a specific wavelength ( $\lambda$ ).
- $\pi$ : is the mathematical constant approximately equal to 3.14159.
- $L_{\lambda}$ : is the spectral radiance at the sensor's aperture.
- $d$ : is the Earth-Sun distance in astronomical units.
- $E_{sun\lambda}$ : is the mean solar spectral irradiance for the specific wavelength band.
- $\theta_s$ : is the solar zenith angle.

After measuring (TOA) for all bands of Landsat images of the study area, a set of indices was applied to different bands of each zone to assess possible sabkha locations. These indices are Soil Moisture Index (SMI), Land Surface Temperature (LST), and Normalized Difference Vegetation Index (NDVI).

### 3.3.1. Processing Satellite Imagery with (LST)

The temperature of land surfaces varies among different locations of the study area. This variation is influenced by a variety of factors, such as reflectivity or what is called albedo, which is the fraction of solar radiation reflected by a surface or body. Vegetation cover, soil moisture, and the time of day and season. The LST index is concerned in measuring the temperature at the very top layer of the Earth's surface. It was applied to distinguish surfaces of relatively low temperatures, especially lowlands where the water table is close to the surface, aided by the season in which satellite images were taken (May 2024), where sabkhas may remain wet soon after the rainy season. The application of the LST index shows a clear contrast between high and relatively low temperature areas, which could represent potential locations of sabkhas. The raster calculator tool is applied to calculate the LST index. This tool can demonstrate any mathematical equations of various indices in terms of colored pixels or gradient color with an 8-bit range (256 color range), converting mathematical values into a visual representation, giving a better and comprehensive understanding of the phenomenal distribution over the map. **Figure 6** shows the resulting map after the application of the LST index.

The resulting map distinguishes between high and low surface temperatures. For better understanding, surface temperatures were categorized into two categories rather than a gray scale gradient map, where white color indicates low temperature surfaces, and black represents higher temperatures. The white area of the map refers to the relatively low temperature earth surfaces, including the wet sabkhas. Since not all relatively low temperature areas on the map are sabkhas, further application of indices could categorize these white areas into different land cover, (water bodies, agricultural areas, and of course, sabkhas... etc.).



**Figure 6.** The resulting map after the application of the LST index.

### 3.3.2. Application of SMI

SMI is used to quantify the amount of water in the soil, and it can be calculated in various ways, often using remote sensing data. One common formula, based on LST and NDVI. SMI is an important index that was applied to the white or relatively low temperature area of the previous map. It is able to further classify the white area according to moisture level, which helps minimize the potential areas of sabkhas, by the removal of highly moisture areas, especially water bodies. The formula of (SMI) used in this study is:

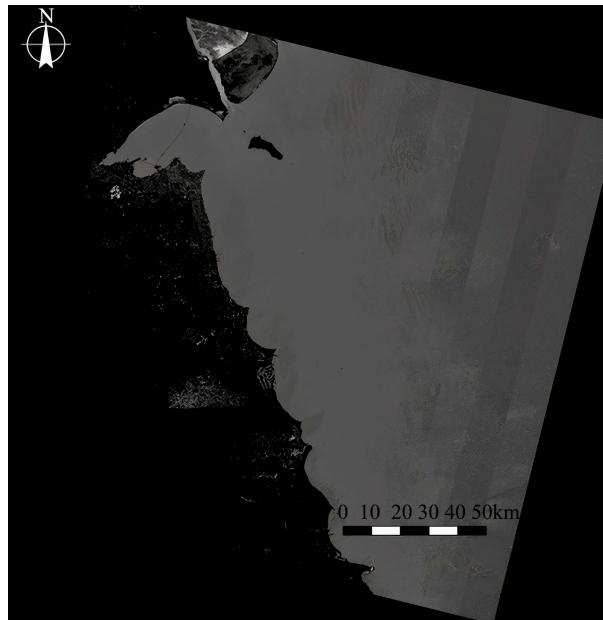
$$SMI = (LST_{max} - LST) / (LST_{max} - LST_{min}) \quad (2) \quad (\text{John } et al., 2022) [25]$$

**Figure 7** shows the resulting map after applying the SMI formula to the map.

Soil moisture is further classified into five categories regarding its wetness quantity; thus, low wetness values (dry soil) were excluded from the potential sabkhas area according to **Table 1**.

**Table 1.** The five categories of soil moisture (source: Lu *et al.*, 2021) [26].

Grade	Type	Standard
1	Very dry	$0 \leq \text{Index} < 0.2$
2	Dry	$0.2 \leq \text{Index} < 0.4$
3	Moderate	$0.4 \leq \text{Index} < 0.6$
4	Moist	$0.6 \leq \text{Index} < 0.8$
5	Very wet	$0.8 \leq \text{Index} \leq 1$



**Figure 7.** The resulting map after applying the (SMI) formula.

**Figure 8** shows the resulting map after the exclusion of dry areas. As white areas represent soil area equal to or above 0.4 according to the given values in **Table 1**.



**Figure 8.** The resulting map after the exclusion of dry areas, where white areas represent soil area equal to or above 0.4 according to the given values in **Table 1**.

### 3.3.3. Isolation of Sabkhas by Application of (NDVI)

Agricultural areas in Kuwait, such as Sulaibyah, Wafra, and Abdaly, are characterized by their low surface temperature and their wet soil as well. Sharing these features with sabkhas may result in a map showing a common area of both agricultural fields and sabkhas; thus, a further step is required to differentiate these two areas from one another. Agricultural fields are characterized by high crop density compared with sabkhas, as well as the vitality of crop leaves (more greenish color). The application of the NDVI could be helpful for this purpose. This index uses the following formula:

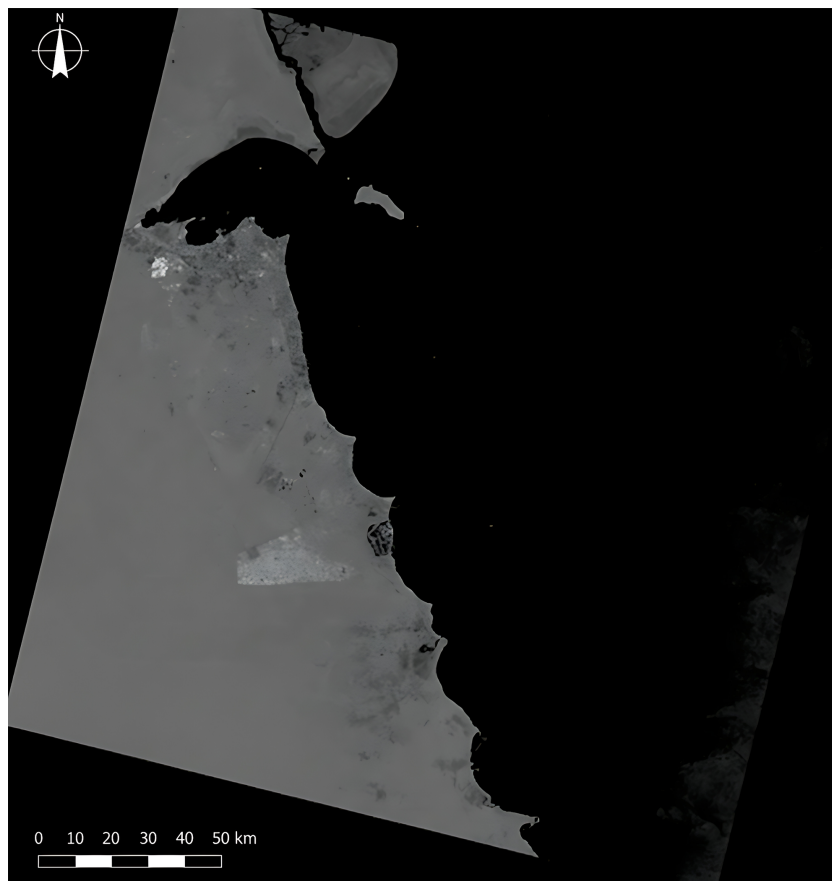
$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{red}}) / (\rho_{\text{NIR}} + \rho_{\text{red}}) \quad (3) \quad (\text{Campbell \& Wynne, 2011}) \quad [27]$$

NDVI values range from  $-1$  to  $1$

where NIR = near infrared satellite band (band No. 5 in Landsat 8 used in this study)

Red band (band No. 4 in Landsat 8 used in this study)

According to the range of (NDVI), the higher the value, the healthier the crops, where the value  $1$  denotes the highest crop vitality and the value of  $-1$  the lowest (Table 2). Due to values provided in Table 2, the values of  $0.4$  or higher were adopted to assign the agricultural areas. Extraction of high (NDVI) value pixels eliminates these areas and leaves only the potential sabkhas area (Figure 9).



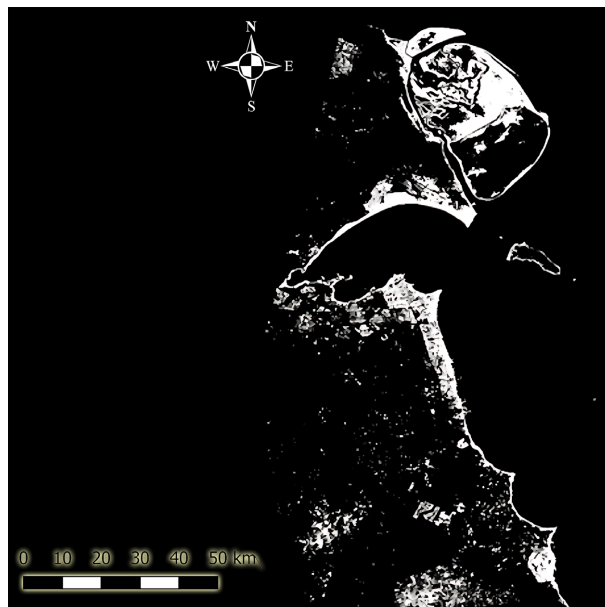
**Figure 9.** The map resulting from assigning high (NDVI) values.

**Table 2.** The applied range of (NDVI) in this study (source: Atun *et al.*, 2020) [28].

Pixel Range	Class
<0	water
0.03 - 0	bare soil
0.03 - 0.3	sparse vegetation
0.3 - 0.5	moderate vegetation
0.5>	dense vegetation

The brighter areas on the map refer to high (NDVI) values that represent agricultural fields, whereas darker areas show low (NDVI) or no vegetative cover. Thus, by means of extracting the bright pixels, the agricultural fields were eliminated from possible sabkha areas. Regarding the water bodies, water as a substance is highly absorptive to near infra-red radiation, resulting in opaque or high dark areas as shown in the map in **Figure 9**.

The assignment of sabkhas is achieved by finding the areas that meet all criteria (relatively low surface temperature, moderate or high soil moisture, and sparse or no vegetation) of sabkha areas. The overlapped areas that are characterized by relatively low surface temperature, moderate or high soil moisture, and sparse or no vegetation are most likely sabkha areas. These overlapped areas were represented as white areas on the map showing sabkhas (**Figure 10**).

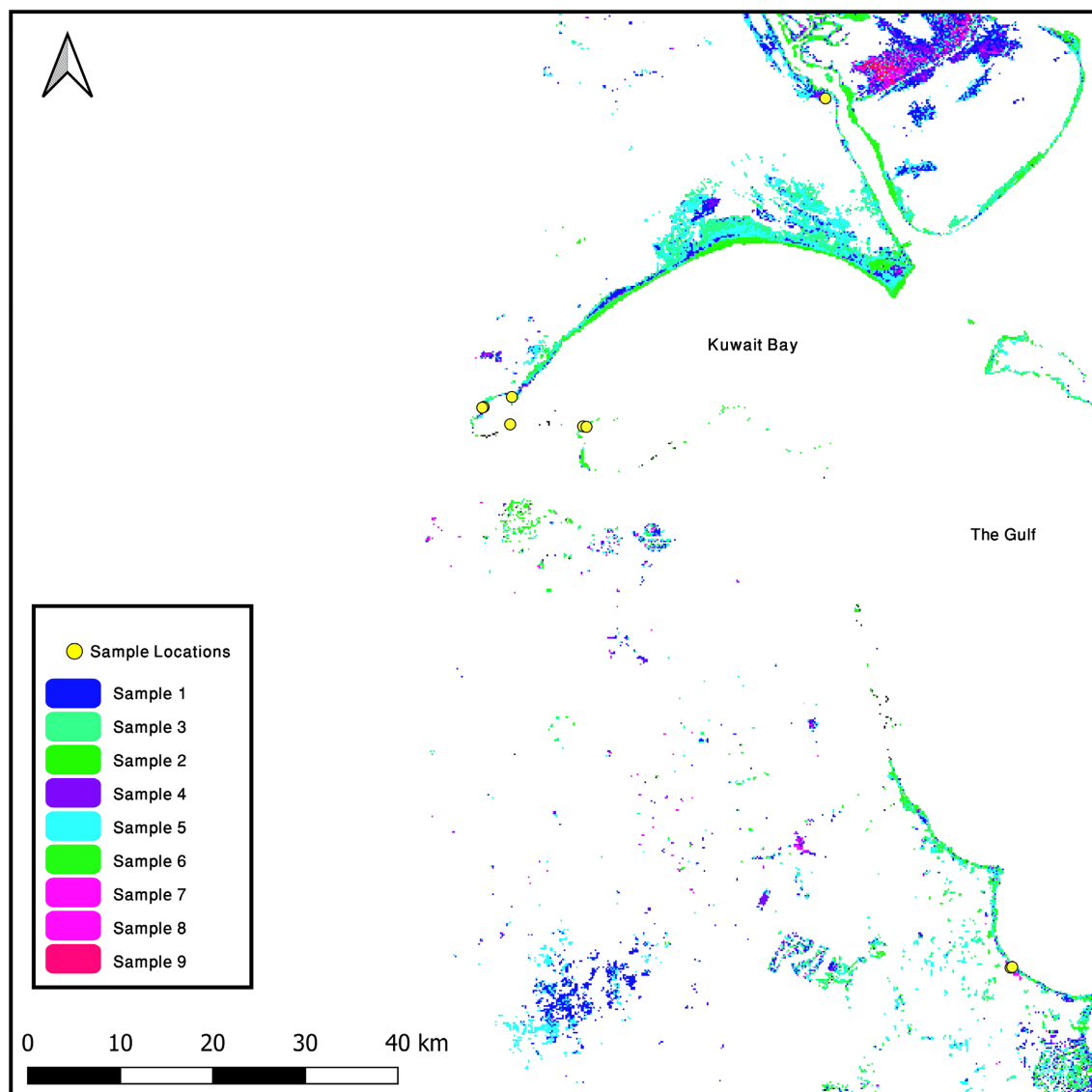


**Figure 10.** A map showing sabkha areas represented in white color achieved after overlapping the areas characterized by relatively low surface temperature, moderate or high soil moisture, and sparse or no vegetation.

By assigning sabkhas in the study area, mineralogical distribution over the sabkhas was done to draw the regolith map of sabkhas. The density slicing technique

was applied for the demonstrating how minerals are distributed. This technique is specifically tailored to differentiate among minerals that have closely related spectral reflectance, also known as spectral signatures. Density slicing, or level slicing, converts a grayscale image into a series of density intervals, also called slices. Each slice corresponds to a specific range of pixel values and is displayed using a distinct color or grayscale color range, effectively highlighting areas within the image based on their brightness or intensity. This method is particularly useful for simplifying image data and emphasizing subtle differences in grayscale values that might be difficult to discern with the naked eye.

**Figure 11** shows the obtained map by the application of the density slicing technique for the study area, indicating a clear contrast among various mineralogical formations of sabkhas.



**Figure 11.** The obtained map by the application of the density slicing technique for the study area, indicating a clear contrast among various mineralogical formations of sabkhas.

Sabkha areas were classified using the density slicing technique to differentiate the mineralogical composition of sabkhas by means of spectral reflectance (spectral signature). Each area with similar spectral reflectance was assigned a specific color to distinguish it from others, where each color on the map represents a distinct mineralogical percentage, which produces a unique spectral signature over the sabkhas. Samples were collected from the field with respect to their different spectral reflectances. Accordingly, nine diagnostic areas were obtained due to their different reflectance. Each color on the map represents a unique percentage for each mineral of the five minerals in question (Quartz, Calcite, Aragonite, Anorthite, and Petedunite) and not a distribution of a specific mineral.

Regarding the mineralogical distribution map obtained by density slicing of sabkha areas, GPS locations for each distinctive color were registered for field sampling and later laboratory analysis, as each color represents a distinctive lithological distribution. Combining the data obtained from laboratory analysis of the sampled specimens reveals the lithological composition of the sampled location. Accordingly, separate maps were made showing the distribution of each distinctive color separately; each color represents a distinctive spectral signature of the mineralogical composition of that area, and other areas of closely related mineralogical composition and percentage.

It is noteworthy, that the spectral signature of each distinctive area may not reflect the spectral reflectance of one mineral in specific, but a collection of minerals in aggregate also known as mixed pixel (where multiple mineral coexist in one area may participate in creating one diagnostic spectral signature related to their percentage), as long as they coexist in same percentage, however, any remarkable change in percentage of these minerals, will yield in different spectral signate and accordingly different color.

#### 4. Results and Discussion

The mineral distribution maps were generated by correlating the spectral classes identified via density slicing with the quantitative mineralogy determined by XRD analysis of the nine targeted samples (**Table 3**). Accordingly each different area of different spectral reflectance was appended with the quantitative percentages obtained from the XRD analysis of each sample. Five maps were made for each of the five most abundant and remarkable reflectances throughout the study area. These minerals included quartz, calcite, aragonite, anorthite, and petedunnite. Every map shows the percentage of these minerals over the sabkhas, as the darker color refers to a higher percentage of the mineral, while the lighter color refers to a lower percentage.

Evaporite minerals (e.g., gypsum, halite, and anhydrite) in Kuwait's sabkha are considered a major constituent. Nevertheless, the results of the XRD and Landsat imagery analysis of the collected surficial deposits in this study showed the absence of these minerals in all sabkha locations. Based on published geological and environmental studies, this can be attributed to the fact that evaporite minerals

**Table 3.** XRD analysis results for the collected surficial samples from the sabkhas in the study area.

Ser. No.	Sample ID	Quartz (SiO <sub>2</sub> )	Calcite (CaCO <sub>3</sub> )	Albite (NaAlSi <sub>3</sub> O <sub>8</sub> )	Aragonite (CaCO <sub>3</sub> )	Cryolite (Na <sub>3</sub> AlF <sub>6</sub> )	Paragonite (NaAl <sub>2</sub> (Si <sub>3</sub> Al)O <sub>10</sub> (OH) <sub>2</sub> )	Anorthite (CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub> )	Pettedunnite (Ca(Zn, Mn <sup>2+</sup> , Mg, Fe <sup>2+</sup> )Si <sub>2</sub> O <sub>6</sub> )
1	A	50.60	15.10	11.60	22.70	0.00	0.00	0.00	0.00
2	B	16.05	20.89	0.00	63.07	0.00	0.00	0.00	0.00
3	C	70.00	16.40	0.00	6.60	0.83	6.11	0.00	0.00
4	D	56.38	43.62	0.00	0.00	0.00	0.00	0.00	0.00
5	E	53.50	11.03	0.00	35.40	0.00	0.00	0.00	0.00
6	F	22.60	8.75	0.00	68.60	0.00	0.00	0.00	0.00
7	G	93.81	6.19	0.00	0.00	0.00	0.00	0.00	0.00
8	H	44.60	4.03	6.84	0.00	0.00	0.00	43.80	0.00
9	I	35.40	16.70	0.00	0.00	0.00	0.00	0.00	47.90

are not absent in Kuwait's sabkha deposits but are typically found just below the surface, not on it.

Several factors, primarily seasonal freshwater influx and the nature of the shallow water table, contribute to the lack of a visible surface crust of evaporites like gypsum or halite as follows:

#### 1) Hydrological conditions:

a) Seasonal freshwater recharge: Kuwait receives more winter rainfall, and its sabkhas are influenced by occasional rainstorms and runoff from the surrounding desert. This influx of less saline water can dissolve or prevent the formation of a permanent evaporite crust on the surface ([8]; Khalaf & Al-Ajmi, 1993 [29]).

b) Dissolution by groundwater: The near-surface groundwater in many Kuwaiti sabkhas can be less saline than the brines required for widespread surface precipitation of minerals. The influx of this water can also dissolve existing surface salts, especially during cooler, wetter periods [8] [29].

c) Depth of the capillary zone: In the context of the Kuwait Group aquifer, specific studies mentioned (Khalaf, F.I., 1989) [30]; (Al-Sarawi, M., 1989) [31] would provide the precise measurements for that specific location, but based on general sabkha hydrology, the process occurs within a shallow, surface-connected capillary system typically measured in a few meters at most.

#### 2) Climate and wind action:

a) Aeolian sediment cover: Kuwait's coastal sabkhas are frequently subjected to the invasion of mobile sands transported by the prevailing northwesterly winds. This sand can bury recent surficial evaporite formations, masking them from view and altering the surface texture of the sabkha ([8] [29]; Khalaf & Al-Hashash, 1987 [32])

b) Deflation and disturbance: Strong winds can cause deflation, or the erosion of surface sediments. This can remove thin, delicate surface salt crusts, leaving behind a less prominent surface [8] [29] [32].

### 3) Diagenetic processes and subsurface precipitation:

a) In sabkhas, evaporite minerals like gypsum and anhydrite frequently form in the subsurface capillary zone, just above the shallow saline water table, but based on general sabkha hydrology, the process occurs within a shallow, surface-connected capillary system typically measured in a few meters at most. The Kuwait Group aquifer, which underlies the sabkhas, contains evaporite deposits, but these are typically encountered during subsurface investigations [30] [31].

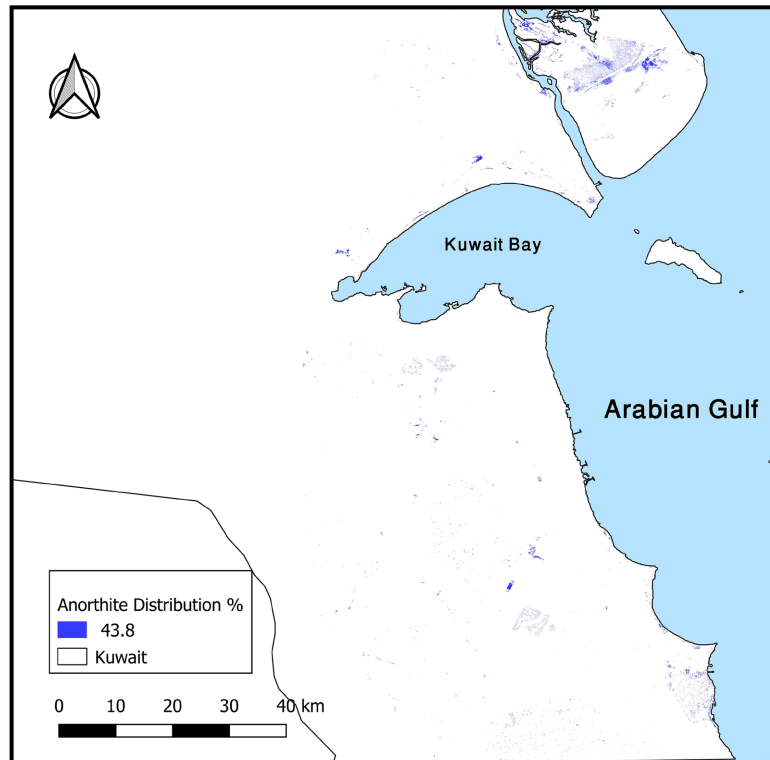
b) Gypsum hydration and dehydration, the reversible process of gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) converting to anhydrite ( $\text{CaSO}_4$ ) and back again can occur based on changes in temperature, salinity, and water availability. This process can cause the evaporites to be buried or texturally altered, and a simple surface observation might not reveal the full evaporite mineralogy [30] [31].

### 4) Microbial mat activity:

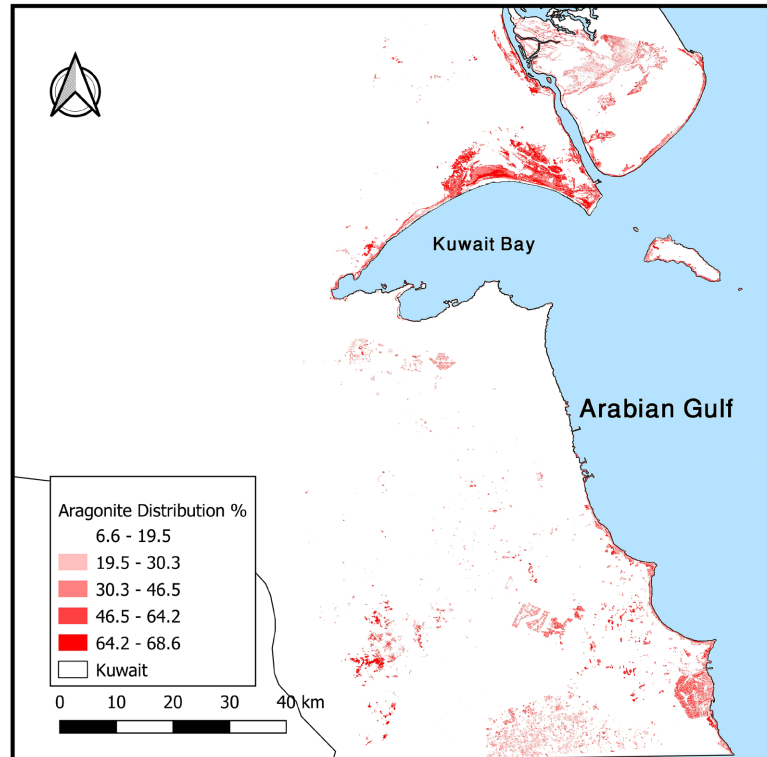
Microbial mats are an active component of Kuwait's sabkha ecosystems. Their presence and activity provide a physical and biological mechanism that helps explain why surface evaporite minerals may be less common or absent, as the mats can stabilize surface sediments and the associated microbial processes can influence the timing and location of mineral precipitation ([8]; Al-Zaidan & Jones, 2006 [33]; Ahmad, 2016 [34]; Taj & Aref, 2014 [35]; Aref & Taj, 2018 [36]).

The percentage distribution of Anorthite mineral in the study area is shown in **Figure 12**, appearing in blue on the map, and within the range of 0% - 43.8% in the sabkha areas. The anorthite distribution reveals that it is mostly concentrated in the northern sabkhas rather than the southern sabkhas. This can be attributed to as the northern sabkhas in Kuwait tend to contain more detrital plagioclase (including anorthite) because they receive coarser, more siliclastic/river-derived sediment (provenance), experience different hydrology/groundwater and salinity regimes that limit plagioclase dissolution, and preserve wind-blown and deltaic silicate material in sheltered (sabkha) settings, whereas southern sabkhas are more strongly dominated by carbonate/evaporite deposition and more intense chemical alteration that removes labile feldspars ([6] [8]; Khalaf *et al.*, 1995 [37]; Strohmenger *et al.*, 2010 [38]; Wasel *et al.*, 2025 [39]).

The concentration of aragonite varies among different locations in the sabkha areas, as it ranges from 6.6% - 68.6% (**Figure 13**). According to the variance in darkness intensity, with darker colors indicating a higher percentage of the mineral's concentration in the area. It is noticed that higher concentrations are along the coastal sabkhas around the northern and southern coasts of Kuwait Bay.



**Figure 12.** A map showing the distribution of Anorthite mineral (blue color) in the sabkha areas.



**Figure 13.** A map showing the distribution of Aragonite mineral with variant percentages in different locations in the sabkha areas.

This can be attributed to several reasons.

1) Proximity to marine input & biogenic carbonate sources: Coastal sabkhas are regularly flushed or influenced by seawater (tidal or episodic marine ingress), which brings carbonate organisms (shells, mollusks, echinoderms, foraminifera) whose biogenic carbonate is often aragonite (Alshemmari, *et al.*, 2013 [40]).

2) High evaporation rates and hypersaline pore/water-surface brines: Coastal flats are exposed to high solar radiation, high temperature, low freshwater input, promoting evaporation. This increases concentration of  $\text{Ca}^{2+}$  and carbonate/anions in shallow pore waters, promoting aragonite precipitation or stabilization (at least initially before conversion) ([15]; Gunatilaka, 1991 [41]).

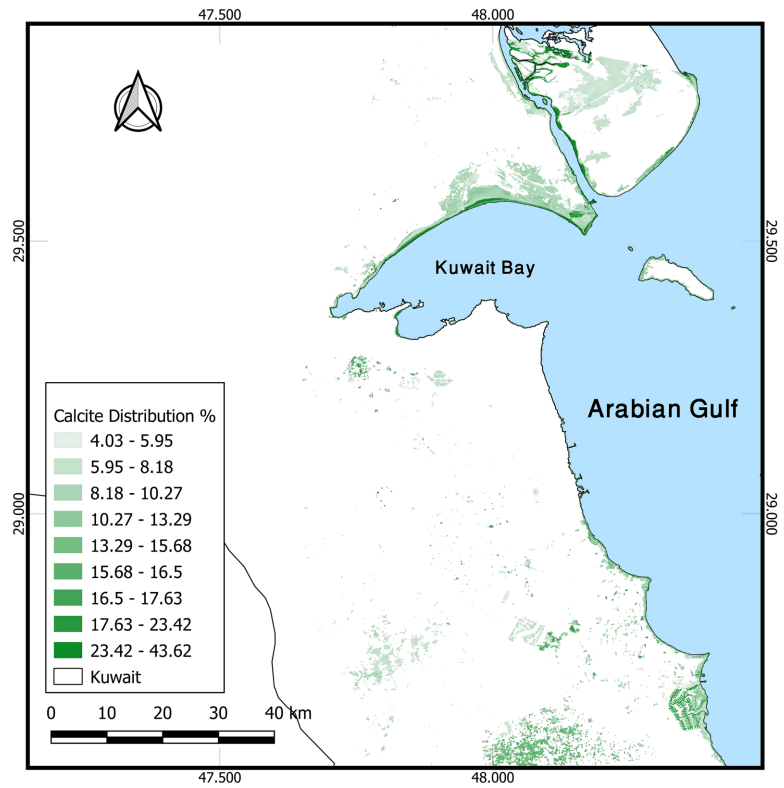
3) Sediment texture & hydrology: Coarser, better-drained sediments or those receiving sediment with skeletal fragments allow for preservation of aragonite, reducing fine clay/silt that may bury or promote heavier diagenesis. Coarse, sandy/bioclastic sediments correlate with higher carbonate content (often aragonite) in bay sediments. In contrast, muddy/silted zones with high clay tend to have lower aragonite content [15].

4) Shallow water, frequent flooding, tidal influence: When areas are flooded (tidal channels, beach fronts) the marine water brings in organisms, alkalinity, and tends to inhibit extreme evaporation and extreme diagenesis. These episodic marine incursions help maintain conditions favorable to forming or preserving aragonite [6].

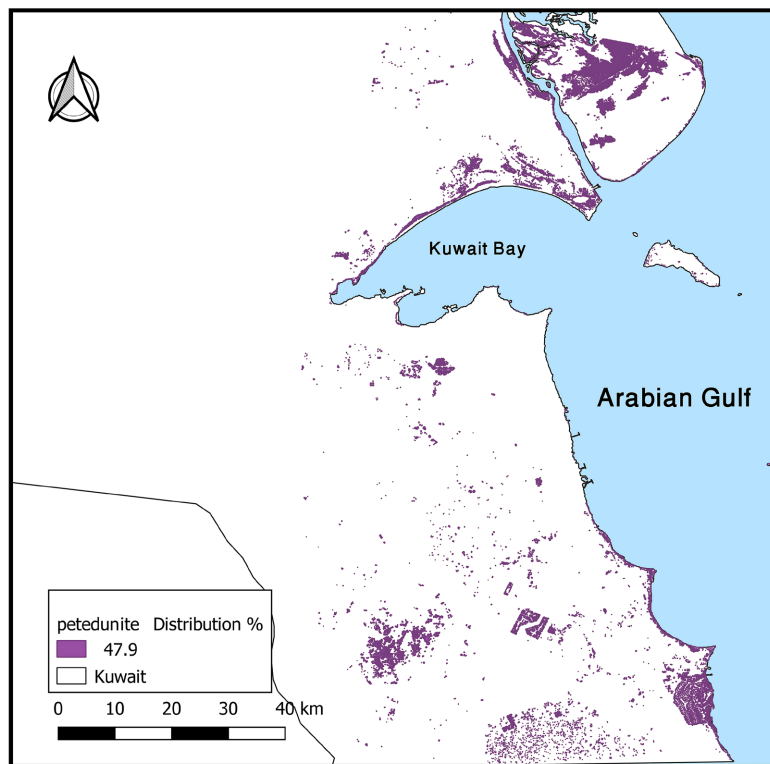
5) Limited replacement/diagenetic alteration: Aragonite is less stable over geological timescales and tends to convert to calcite or be replaced if buried too long, or if exposed to certain chemical conditions (e.g., low Mg/Ca, lower salinity, more open groundwater flow). Coastal sabkhas often have shallow burial and conditions that delay or mitigate full diagenetic transformation. Some studies in Kuwait show local dolomitization or replacement of aragonite occurring but not uniformly; aragonite is preserved in many surface and near-surface sediments [41].

The calcite mineral is distributed in different percentages in different locations in the study area ranging from 4.03% - 43.62% (Figure 14). The color's darkness intensity was also used as a key to represent the variation in the percentage concentration of the Calcite mineral, with darker colors indicating a higher percentage.

The XRD and Landsat imagery showed the existence of Petedunnite mineral with a range of 0% - 49.7% without variation in distribution as in calcite or quartz (Figure 15), and this is due to the appearance of the mineral in one sampling location of the 9 sites. It is a zinc-rich silicate rare mineral associated with metamorphic rocks formed under high temperature and pressure environments. A literature review revealed no prior reports of the existence of the rare mineral Petedunnite in the coastal sabkha deposits of Kuwait. This study is the first to document its presence in this geological setting. The fundamental difference in the geological conditions necessary to form each of the sabkha minerals prevents Petedunnite from existing in the coastal sabkhas of Kuwait. Petedunnite requires



**Figure 14.** A map showing the distribution of Calcite mineral with variant percentages in all locations in the sabkha areas.



**Figure 15.** A map showing the distribution of Petedunnite mineral in the sabkha areas.

the heat and pressure of metamorphism in a zinc-rich deposit, while the sabkha minerals form at or near the surface through the low-temperature process of evaporation. This suggests that this mineral is not locally formed but due to the provenance transport by the Al-Rimmah-Al-Batin wadi deltaic fluvial system ([8]; Khalaf & Ala [42]).

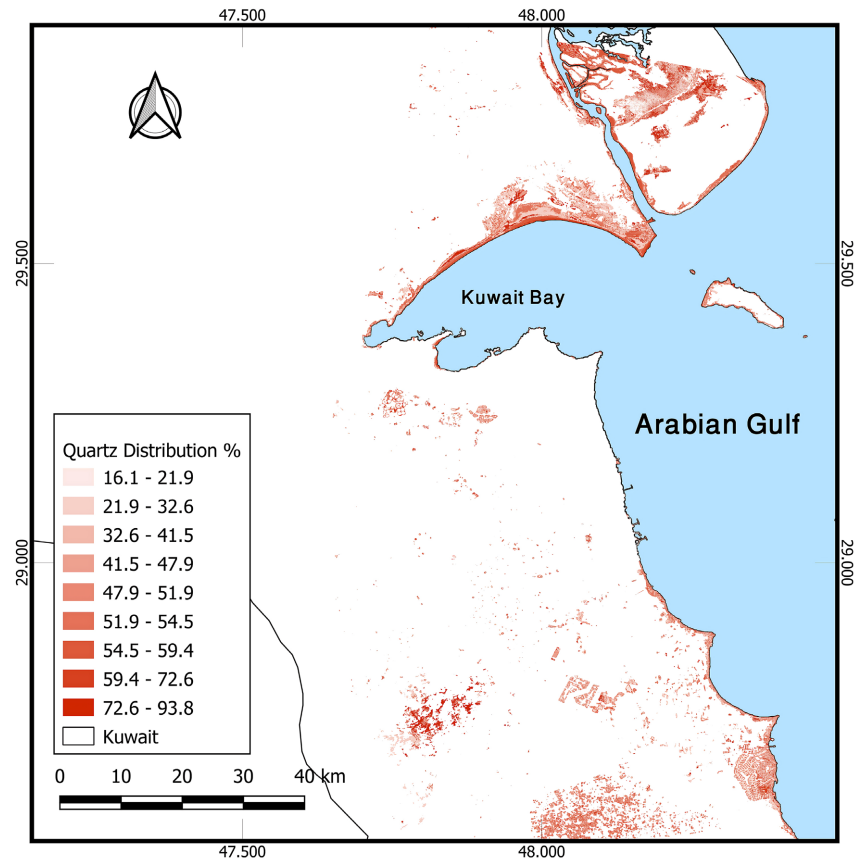
The occurrence of Petedunnite within sediments attributed to the Al-Dibdibah Formation is best interpreted as detrital rather than authigenic. The Al-Dibdibah Formation, of Neogene to Quaternary age, is composed predominantly of unconsolidated to weakly lithified gravels, sands, and silts deposited within fluvial and alluvial fan environments across eastern Saudi Arabia, Kuwait, and southern Iraq. These deposits are chiefly clastic in nature, consisting largely of quartz, chert, limestone, and dolomite fragments, reflecting derivation from the erosion of older sedimentary and carbonate successions (Powers *et al.*, 1966 [43]; Al-Sayari & Zötl, 1978 [44]; Alsharhan & Nairn, 1997 [45]).

In contrast, Petedunnite ( $\text{ZnMnSi}_2\text{O}_6$ ) is a zinc–manganese pyroxene known to crystallize under high-temperature metamorphic or hydrothermal regimes, typically within Mn-rich silicate rocks or skarn assemblages associated with metamorphosed Zn-Mn ore deposits. Its type locality in the Franklin–Sterling Hill district (New Jersey, USA), and other reported occurrences (e.g., Dunn, 1985 [46]; Anthony *et al.*, 2003 [47]) indicate formation under medium- to high-grade metamorphic conditions, often exceeding 500°C, within carbonate–silicate contact zones or hydrothermal alteration systems.

Given these contrasting formation environments, the presence of Petedunnite within the Al-Dibdibah Formation cannot reasonably be attributed to authigenic or diagenetic mineralization. Instead, it most plausibly represents detrital reworking of mineral grains or rock fragments derived from older, metamorphosed Zn-Mn-bearing lithologies exposed in the regional provenance area. This interpretation supports a multicycle sedimentary origin for certain heavy-mineral components within the Al-Dibdibah Formation and reinforces the view that these sediments serve as secondary repositories of mineral species formed under conditions markedly different from their current depositional setting.

Quartz mineral has a wide range of percentage distribution, as indicated in the map legend in **Figure 16**. This is because all collected samples have Quartz in their ingredients but with different percentages.

Quartz and Calcite are the only minerals found in all samples, indicating the abundance of these two minerals in the study area. Quartz (detrital origin) is primarily sourced from the Arabian Shield, a large landmass of ancient igneous and metamorphic rock. Sediments from the Arabian Shield are transported into Kuwait via the Wadi Al-Rimmah-Al-Batin fluvial system. These sediments are then widely distributed across the country by wind, forming extensive sand sheets that cover most of Kuwait's surface. As a result of its durability and high resistance to chemical and physical weathering, quartz is the most common mineral found in these sediments.



**Figure 16.** A map showing the distribution of Quartz mineral with variant percentages in all the locations in the sabkha areas.

Calcite (biogenic and marine origin) in coastal sabkhas is derived from the skeletal fragments of marine organisms. The underlying geology, including the Eocene carbonates that form the local aquifer, also supplies calcite. Seawater infiltrates the sabkha and interacts with the carbonates, influencing the mineral composition of the sediments.

The specific characteristics of coastal sabkhas combine both marine and terrestrial sediment inputs. Terrigenous input, sediment from the land, rich in quartz, is delivered to the coastal areas. Marine input, seawater and marine life provide the calcite. High preservation potential: The arid climate and high evaporation rates in coastal sabkhas mean that these durable minerals are well preserved, leading to their concentration in the deposits.

## 5. Conclusions

The coastal line of Kuwait witnesses the distribution of sabkhas in relation to definite morphological features such as depressions and gentle slopes. Accordingly, there exist two types of sabkhas: coastal and inland sabkhas. The former is distributed in the elongated depression zone and along the northern and southern shorelines, whereas the latter is distributed in desert side along western areas of the southern coastal line and recently covered with aeolian sediments.

Mineralogically, the sabkha recent sediments in northern areas are composed of clastic carbonate mud, including micrite and silt size low-Mg calcite and dolomite with fewer quantities of terrigenous silt, which quantitatively magnifies landward as a result of the drifting wind action, to coarse sand (majorly quartz). The existing calcite carbonates are being brought to the area originating from the salt weathered remote limestone terrains in the Middle East. According to the previous studies and from mineralogical point of view, the sediments of both sabkhas are composed of quartz, feldspar, calcareous, and evaporites (gypsum and halite grains) and rock fragments. But in this study, evaporite minerals such as gypsum and halite were absent in all collected samples. Depending on the fact that evaporite minerals are not absent in Kuwait's sabkha deposits but are typically found just below the surface, not on it, suggests the burial or, coverage, and accumulation as subsurface sediments, where the precipitation of such sediments is a function of several factors including the hydrological conditions, climate and wind action, diagenetic processes and subsurface precipitation, and microbial mat activity. This led to the removal of the crustal thin veneer of evaporite minerals by deflation, dissolution, or coverage by the recently witnessed increased aeolian action either by encroachment of mobile sand sheets or the increasing migration rate of sand dune belts in the north-northwestern towards the coastal areas. Another possibility is depth of the capillary zone, which suggests that the depth of the collected surficial samples in the study excluded the subsurface deposits of the evaporite minerals.

As for the quartz grains, they are believed to be from the erosion of nearby Pleistocene-Holocene coastal ridges or/and from the sand drift by the prevailing northwesterly wind, while the rest of the components are believed to be of marine origin generated by present-day processes. Therefore, quartz and calcite minerals were the predominant and most abundant minerals in the study area.

The interpretation of petedunnite existence in the sabkha deposits supports a multicycle sedimentary origin for certain heavy-mineral components within the Al-Dibdibah Formation and reinforces the view that these sediments serve as secondary repositories of mineral species formed under conditions markedly different from their current depositional setting. So it is likely that the primary source Petedunnite, is the Al-Dibdibah deposits, which were carried to the area by the Al-Rimmah-Al-Batin wadi system. These deposits originated from the erosion of the Arabian Shield, which contains igneous and metamorphic rocks [8] [42].

The presence of Anorthite, which is a plagioclase mineral in the mafic igneous rocks, and Petedunnite, is a dependable base to believe that most of the sabkha deposits are originated from Al-Dibdibah Formation gravelly deposits, which in their turn are originated from the Arabian Shield rocks during the glacial period of the Pleistocene age. This was proved by the surface features on the quartz grains due to the glacial action in this period (conchoidal fractures and the stepped cleavage planes) [8]. Moreover, the existence of the skeletal fragments and oolites only in the coastal sabkhas and their absence in the inland sabkhas make it eligible to consider the elongated coastal fossiliferous oolitic limestone ridges as a secondary

contributor to the coastal sabkha sediments.

Most of both sabkhas are composed of variant sized sand deposits intercalated with mud, gypsum or hard pan layers of gatch. Due to the action of the prevailing northwesterly wind the surface of both sabkhas is subjected to the mobile sand encroachment, which resulted in the formation of a sand sheet blanket on the surface of these sabkhas. This is supported by the abundance of quartz mineral in all sabkha surface deposits and the absence of evaporite minerals in the surficial deposits.

The encroachment of mobile sand sheets onto sabkha surfaces in coastal Kuwait presents significant challenges due to the unique characteristics of sabkha soils and the arid environment. The practical implications affect coastal infrastructure stability, comprising foundation instability and corrosion, burial and damage to facilities, and disruption of transport networks; land use planning concerning urban expansion risks and decline of natural habitats; and environmental management strategies in relation to ineffectiveness of traditional measures, need for integrated planning, sustainable solutions requirement, and policy and enforcement gaps; leading to considerable economic and social cost (Al-Awadi & Misak, 2000 [48]; AlHelal & AlAwadhi, 2006 [49]; Al-Otaibi & Aldaihani, 2021 [50]; Kuwait Foundation for the Advancement of Sciences (KFAS), 2024 [51]).

As a general conclusion, the Kuwaiti sabkhas in the northern sector are distinctly different from those in the other coastal sabkhas in the southern shoreline of Kuwait or even the southern coastal areas of the Arabian Gulf, as they are characterized of occupying abundant siliciclastic carbonate host sediments of sabkhas, absence of algal mat growth, which is associated to the tidal channels in the area, and lack of recent diagenetic dolomite formation. GIS and Remote Sensing techniques are of significant benefit in extracting sabkha areas from the coastal geomorphological features by applying the density slicing technique using different remote and GIS techniques. In the same context, they are very useful in recognizing the mineralogical characteristics of sabkha depending on their reflecting categories.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

- [1] Purser, B.H. (1973) The Persian Gulf, Holocene Carbonate Sedimentation and Diagenesis in a Shallow Epicontinental Sea. Springer, 6-7.
- [2] Kassler, P. (1973) The Structural and Geomorphologic Evolution of the Persian Gulf. In: Purser, B.H., Ed., *The Persian Gulf*, Springer, 11-32.  
[https://doi.org/10.1007/978-3-642-65545-6\\_2](https://doi.org/10.1007/978-3-642-65545-6_2)
- [3] Al-Sarawi, M.A., Al-Zamel, A. and Al-Rifaiy, I. (1993) Late Pleistocene and Holocene sediments of the Khiran area (South Kuwait). *Journal of University of Kuwait (Science)*, **20**, 145-156.
- [4] Al-Sulaimi, J.S. and El-Rabaa, S.M. (1994) Morphological and Morphostructural Features of Kuwait. *Geomorphology*, **11**, 151-167.

- [https://doi.org/10.1016/0169-555x\(94\)90079-5](https://doi.org/10.1016/0169-555x(94)90079-5)
- [5] Khalaf, F.I., Gharib, I.M. and Al-Hashash, M.Z. (1984) Types and Characteristics of the Recent Surface Deposits of Kuwait, Arabian Gulf. *Journal of Arid Environments*, **7**, 9-33. [https://doi.org/10.1016/s0140-1963\(18\)31399-5](https://doi.org/10.1016/s0140-1963(18)31399-5)
- [6] Saleh, A., Al-Ruwaih, F., Al-Reda, A. and Gunatilaka, A. (1999) A Reconnaissance Study of a Clastic Coastal Sabkha in Northern Kuwait, Arabian Gulf. *Journal of Arid Environments*, **43**, 1-19. <https://doi.org/10.1006/jare.1999.0529>
- [7] Al-Hurban, A. and Gharib, I. (2003) Morphological, Sedimentological, and Hydrogeochemical Studies of Sabkhas in Southern Kuwait. Suppl. *Geografia Fisica e Dinamica Quaternaria Journal*, **6**, 13-18.
- [8] Al-Hurban, A. and Gharib, I. (2004) Geomorphological and Sedimentological Characteristics of Coastal and Inland Sabkhas, Southern Kuwait. *Journal of Arid Environments*, **58**, 59-85. [https://doi.org/10.1016/s0140-1963\(03\)00128-9](https://doi.org/10.1016/s0140-1963(03)00128-9)
- [9] Kleo, A.A. and Al-Otaibi, O. (2011) The Sustainable Development of Kuwaiti Sabkhas. *Digest of Middle East Studies*, **20**, 27-49. <https://doi.org/10.1111/j.1949-3606.2011.00064.x>
- [10] Walker, R.G. (1984) Facies Models. 2nd Edition, Geological Association of Canada, 271.
- [11] Al-Zamel, A.Z. and Al-Sarawi, M. (1998) Late Quaternary Sabkha Sedimentation along Kathma Bay Coast, Kuwait, Arabian Gulf. *Arab Gulf Journal for Scientific Research*, **16**, 471-495.
- [12] Al-Sarawi, M.A. (1988) Morphology and Facies of Alluvial Fans in Kadhmah Bay, Kuwait. *SEPM Journal of Sedimentary Research*, **58**, 836-844. <https://doi.org/10.1306/212f8ea9-2b24-11d7-8648000102c1865d>
- [13] McKenzie, J.A. (1981) Holocene Dolomitization of Calcium Carbonate Sediments from the Coastal Sabkhas of Abu Dhabi, U.A.E.: A Stable Isotope Study. *The Journal of Geology*, **89**, 185-198. <https://doi.org/10.1086/628579>
- [14] Patterson, R.J. and Kinsman, D.J.J. (1982) Formation of Diagenetic Dolomite in Coastal Sabkha along Arabian (Persian) Gulf. *AAPG Bulletin*, **66**, 28-43. <https://doi.org/10.1306/03b59a17-16d1-11d7-8645000102c1865d>
- [15] Picha, F. (1978) Depositional and Diagenetic History of Pleistocene and Holocene Oolitic Sediments and Sabkhas in Kuwait, Persian Gulf. *Sedimentology*, **25**, 427-450. <https://doi.org/10.1111/j.1365-3091.1978.tb00320.x>
- [16] Pilkey, O.H. and Noble, D. (1966) Carbonate and Clay Mineralogy of the Persian Gulf. *Deep Sea Research and Oceanographic Abstracts*, **13**, 1-16. [https://doi.org/10.1016/0011-7471\(66\)90002-7](https://doi.org/10.1016/0011-7471(66)90002-7)
- [17] Evans, G., Schmidt, V., Bush, P. and Nelson, H. (1969) Stratigraphy and Geologic History of the Sabkha, Abu Dhabi, Persian Gulf. *Sedimentology*, **12**, 145-159. <https://doi.org/10.1111/j.1365-3091.1969.tb00167.x>
- [18] David J. J. Kinsman (2), (1969) Modes of Formation, Sedimentary Associations, and Diagnostic Features of Shallow-Water and Supratidal Evaporites. *AAPG Bulletin*, **53**, 830-840. <https://doi.org/10.1306/5d25c801-16c1-11d7-8645000102c1865d>
- [19] Taylor, J.C.M. and Illing, L.V. (1969) Holocene Intertidal Calcium Carbonate Cementation, Qatar, Persian Gulf. *Sedimentology*, **12**, 69-107. <https://doi.org/10.1111/j.1365-3091.1969.tb00165.x>
- [20] West, I.M., Ali, Y.A. and Hilmy, M.E. (1979) Primary Gypsum Nodules in a Modern Sabkha on the Mediterranean Coast of Egypt. *Geology*, **7**, 354-358. [https://doi.org/10.1130/0091-7613\(1979\)7<354:pgniam>2.0.co;2](https://doi.org/10.1130/0091-7613(1979)7<354:pgniam>2.0.co;2)

- [21] Butler, G.P. (1969) Modern Evaporite Deposition and Geochemistry of Coexisting Brines, the Sabkha, Trucial Coast, Arabian Gulf. *SEPM Journal of Sedimentary Research*, **39**, 70-89. <https://doi.org/10.1306/74d71be5-2b21-11d7-8648000102c1865d>
- [22] Kinsman, D.J.J. (1964) The Recent Carbonate Sediments near Halat El Bahrani, Trucial Coast, Persian Gulf. In: Van Straaten, L.M.J.U., Ed., *Developments in Sedimentology*, Elsevier, 185-192. [https://doi.org/10.1016/s0070-4571\(08\)70485-0](https://doi.org/10.1016/s0070-4571(08)70485-0)
- [23] Tucker, M.E. (1981) *Sedimentary Petrology an Introduction*. Blackwell Scientific Publication, 161-173.
- [24] Bakaeva, N. and Le, M.T. (2022) Determination of Urban Pollution Islands by Using Remote Sensing Technology in Moscow, Russia. *Ecological Informatics*, **67**, Article 101493. <https://doi.org/10.1016/j.ecoinf.2021.101493>
- [25] John, J., Jaganathan, R. and Dharshan Shylesh, D.S. (2021) Mapping of Soil Moisture Index Using Optical and Thermal Remote Sensing. In: Marano, G.C., Ray Chaudhuri, S., Unni Kartha, G., Kavitha, P.E., Prasad, R. and Achison, R.J., Eds., *Lecture Notes in Civil Engineering*, Springer International Publishing, 759-767. [https://doi.org/10.1007/978-3-030-80312-4\\_65](https://doi.org/10.1007/978-3-030-80312-4_65)
- [26] Lu, Z., Wang, D., Ding, Z., Shi, Y., Ning, H., Zhao, J., et al. (2021) Study on Remote Sensing Retrieval of Soil Moisture in Arid Desert Area Based on FTVDI. *IOP Conference Series. Earth and Environmental Science*, **826**, Article 012051. <https://doi.org/10.1088/1755-1315/826/1/012051>
- [27] Campbell, J.S.B. and Wynne, R.H. (2011) In *Introduction to Remote Sensing*, 5th Edition, Guilford Publications, 484. <https://www.guilford.com/p/campbell2>
- [28] Atun, R., Kalkan, K., Uzay, T. and Gürsoy, Ö. (2020) Determining the Forest Fire Risk with Sentinel 2 Images. *Journal of Turkish Geosciences*, **1**, 22-26. <https://dergipark.org.tr/en/pub/turkgeo>
- [29] Khalaf, F.I. and Al-Ajmi, D. (1993) Aeolian Processes and Sand Encroachment Problems in Kuwait. *Journal of Arid Environments*, **25**, 195-212.
- [30] Khalaf, F.I. (1989) Desertification and Aeolian Processes in the Kuwait Desert. *Journal of Arid Environments*, **16**, 125-145. [https://doi.org/10.1016/s0140-1963\(18\)31020-6](https://doi.org/10.1016/s0140-1963(18)31020-6)
- [31] Al-Sarawi, M. (1989) A Study of the Coastal Sediments in Kuwait. *Journal of Arid Environments*, **16**, 263-272.
- [32] Khalaf, F.I. and Al-Hashash, M.A. (1987) Aeolian Sedimentation in Kuwait: Depositional Processes and Their Environmental Significance. *Journal of Arid Environments*, **12**, 183-195.
- [33] Al-Zaidan, A., Kennedy, H., Jones, D. and Al-Mohanna, S. (2006) Role of Microbial Mats in Sulaibikhat Bay (Kuwait) Mudflat Food Webs: Evidence from  $\delta^{13}\text{C}$  Analysis. *Marine Ecology Progress Series*, **308**, 27-36. <https://doi.org/10.3354/meps308027>
- [34] Ahmad, E.A. (2016) The Role of Microbes in Early Lithification of Sabkha and Near-shore Sediments in Ras Kadhma, Kuwait (Manuscript). Central Library, Kuwait University.
- [35] Taj, R.J., Aref, M.A.M. and Schreiber, B.C. (2014) The Influence of Microbial Mats on the Formation of Sand Volcanoes and Mounds in the Red Sea Coastal Plain, South Jeddah, Saudi Arabia. *Sedimentary Geology*, **311**, 60-74. <https://doi.org/10.1016/j.sedgeo.2014.06.006>
- [36] Aref, M.A. and Taj, R.J. (2018) Recent Evaporite Deposition Associated with Microbial Mats, Al-Kharrar Supratidal-Intertidal Sabkha, Rabigh Area, Red Sea Coastal Plain of Saudi Arabia. *Facies*, **64**, Article No. 28.

- <https://doi.org/10.1007/s10347-018-0539-y>
- [37] Khalaf, F.I., Misak, R. and Al-Dousari, A. (1995) Sedimentological and Morphological Characteristics of Some Nabkha Deposits in the Northern Coastal Plain of Kuwait, Arabia. *Journal of Arid Environments*, **29**, 267-292.  
[https://doi.org/10.1016/s0140-1963\(05\)80107-7](https://doi.org/10.1016/s0140-1963(05)80107-7)
- [38] Strohmenger, C.J., Al-Mansoori, A., Al-Jeelani, O., Al-Shamry, A., Al-Hosani, I., Al-Mehsin, K., et al. (2010) The Sabkha Sequence at Mussafah Channel (Abu Dhabi, United Arab Emirates): Facies Stacking Patterns, Microbial-Mediated Dolomite and Evaporite Overprint. *GeoArabia*, **15**, 49-90. <https://doi.org/10.2113/geoarabia150149>
- [39] Wasel, S.O., Al-Dubai, T.A., Al-Zubieri, A., Mahyoub, J.A. and Al Thabiani, A. (2025) Mineralogical Characteristics and Surface Texture of Quartz Grains in Coastal Sabkha Deposits on the Southern Red Sea Coast. *Iranian Journal of Earth Sciences*.  
<https://doi.org/10.57647/j.ijes.2025.17008>
- [40] ALshemmari, H., AL-Dousari, A.M., Talebi, L. and AL-Ghadban, A. (2013) Mineralogical Characteristics of Surface Sediment in Sulaibikhat Bay, Kuwait. *Kuwait Journal of Science*, **40**, 159-176.  
<https://www.sciencedirect.com/journal/kuwait-journal-of-science>
- [41] Gunatilaka, A. (1991) Dolomite Formation in Coastal Al-Khiran, Kuwait Arabian Gulf—A Re-Examination of the Sabkha Model. *Sedimentary Geology*, **72**, 35-53.  
[https://doi.org/10.1016/0037-0738\(91\)90122-t](https://doi.org/10.1016/0037-0738(91)90122-t)
- [42] Khalaf, F.I. and Ala, M. (1980) Mineralogy of the Recent Intertidal Muddy Sediments of Kuwait—Arabian Gulf. *Marine Geology*, **35**, 331-342.  
[https://doi.org/10.1016/0025-3227\(80\)90124-3](https://doi.org/10.1016/0025-3227(80)90124-3)
- [43] Powers, R.W., Ramirez, L.F., Redmond, C.D. and Elberg Jr., E.L. (1966) Geology of the Arabian Peninsula: Sedimentary Geology of Saudi Arabia. U.S. Geological Survey Professional Paper 560-D.
- [44] Al-Sayari, S.S. and Zötl, J.G. (1978) Quaternary Period in Saudi Arabia, Vol. 1: Sedimentological, Hydrogeological, Hadrochemical, Geomorphological, and Climatological Investigations in Central and Eastern Arabia. Springer-Verlag.
- [45] Alsharhan, A.S. and Nairn, A.E.M. (1997) Sedimentary Basins and Petroleum Geology of the Middle East. 1st Edition, Elsevier Science.
- [46] Dunn, P.J. (1985) Petedunnite, a New Zinc-Manganese Pyroxene from Franklin, New Jersey. *American Mineralogist*, **70**, 283-286.
- [47] Anthony, J.W., Bideaux, R.A., Bladh, K.W. and Nichols, M.C. (2003) Handbook of Mineralogy, Vol. 2: Silica, Silicates. Mineral Data Publishing.
- [48] Al-Awadhi, J. and Misak, R. (2000) Field Assessment of Aeolian sand Processes and Sand Control Measures in Kuwait. *Kuwait Journal of Science and Engineering*, **27**, 156-176.
- [49] Al-Helal, A.B. and Al-Awadhi, J.M. (2005) Assessment of Sand Encroachment in Kuwait Using Gis. *Environmental Geology*, **49**, 960-967.  
<https://doi.org/10.1007/s00254-005-0134-8>
- [50] Al-otaibi, F.A. and Aldaihani, H.M. (2021) Determination of the Collapse Potential of Sabkha Soil and Dune Sand Arid Surface Soil Deposits in Kuwait. *Jurnal Teknologi*, **83**, 93-100. <https://doi.org/10.11113/jurnalteknologi.v83.14863>
- [51] Kuwait Foundation for the Advancement of Sciences (KFAS) (2024) Mitigating and Combating Sand Encroachments in Kuwait. A White Paper for Decision-Makers.  
<https://www.kfas.org/Publications/Mitigating-and-Combating-Sand-Encroachments-in-Kuwait>