

Review

The Abu Dhabi Coastal Sabkha: A Literature Review on Its Scientific Value, Environmental Vulnerability, and Sustainable Conservation as a UNESCO Tentative List Geoheritage Site

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Abstract

Abu Dhabi Sabkha, located along the southern margin of the Arabian Gulf, is among the most scientifically significant arid coastal systems on Earth. Submitted by the United Arab Emirates to the UNESCO World Heritage Tentative List in 2018 under natural heritage criterion (viii), the site is currently the only documented coastal sabkha where all four diagnostic sedimentary layers, lagoon mud, microbial mat, gypsum mud, and anhydrite nodules, co-occur within a single coastal setting, south of Al Dhabaya and Abu Al Abyadh Islands. This review evaluates Abu Dhabi Sabkha as a geological heritage system by synthesizing its formation processes, UNESCO significance, complete sabkha sequence, microbial and evaporite processes, climatic setting, environmental sensitivity, and conservation requirements. The site operates under a hyper-arid climatic regime with a documented warming trend of +0.43 °C per decade over 1981–2025 (NASA POWER MERRA-2), confirming that the evaporative processes sustaining its geological record are intensifying. Microbial mats facilitate dolomite mineralization via Extracellular Polymeric Substances at a scale unmatched elsewhere in the Arabian Gulf, while gypsum mud and anhydrite nodules record advanced supratidal evaporitic development. Comparative analysis with sabkha systems in Qatar, Kuwait, Saudi Arabia, and Oman confirms that no other regional coastal sabkha preserves equivalent stratigraphic completeness within a single, actively forming setting. The site faces mounting pressures from urban expansion, coastal reclamation, off-road vehicle movement, groundwater modification, and the increasing frequency of extreme rainfall events, all of which can permanently damage fragile surface structures and microbial systems. Sustainable conservation requires protection zoning, controlled access, multi-scale satellite and drone monitoring, groundwater tracking, and integration into coastal planning frameworks. Abu Dhabi Sabkha should be recognized not as marginal saline terrain, but as a globally important geoheritage system whose scientific value depends on the active preservation of biological, chemical, and physical processes operating together within an irreplaceable coastal setting.

Keywords: Abu Dhabi Sabkha; UNESCO World Heritage; Carbonate-evaporite; microbial mat; Geoheritage



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1. Introduction

Arid and hyper-arid coastal regions are among the most geologically and ecologically distinctive environments on Earth. These landscapes are shaped by intense evaporation, low rainfall, saline groundwater, tidal flooding, sediment movement, and increasing infrastructure development, all of which interact closely with natural coastal processes. Under such conditions, coastal sabkhas develop as salt-rich flats in the transition zone between marine and terrestrial environments. Despite being widely regarded as difficult or marginal landscapes because of their salinity, shallow groundwater, and geotechnical limitations, coastal sabkhas hold considerable geological, environmental, and heritage value that has only recently received the scientific attention it deserves [1,2].

Coastal sabkhas in the Arabian Gulf occupy a particularly important position in Earth science because they preserve active carbonate-evaporite processes under extreme arid climatic conditions that are rare elsewhere on the planet. These systems record the interaction between seawater, groundwater, evaporation, microbial activity, sedimentation, and mineral precipitation in ways that are directly observable at the surface today. As a result, coastal sabkhas serve as natural laboratories for understanding carbonate-evaporite successions and their relevance to ancient sedimentary records, including hydrocarbon-bearing formations of significant economic interest. In this context, the Abu Dhabi coastal sabkha is particularly important because it is widely recognized as one of the best modern analogues for ancient mixed carbonate-evaporite formations [3], making it a globally referenced system in sedimentological and petroleum geology research (Figure 1).

Geoheritage recognition within the UNESCO World Heritage framework has expanded steadily since geological values were formally written into the Convention through criterion (viii), yet global assessments show this recognition remains geographically and thematically uneven. A recent systematic review of geoheritage properties on the World Heritage List found that around half of all listed geological sites are concentrated in Europe and North America, with karst landscapes, mountains, and glacial features receiving far more attention than arid or evaporitic systems [4]. The same review noted that aesthetic and visually dramatic aspects of abiotic nature have historically carried more weight in the selection process than subtler geological themes tied to ongoing sedimentary or geochemical processes, a pattern also discussed by [5] in relation to how geomorphological and process-based sites are evaluated for Outstanding Universal Value. Ref. [6] similarly argue that geomorphological heritage is often undervalued relative to more conventional scenic criteria, while [7] documented a comparable aesthetic bias in the assessment of karst Natural World Heritage sites. Within this global context, coastal sabkha systems remain almost absent from both the World Heritage List and national Tentative Lists, despite their well-documented role as active analogues for ancient carbonate-evaporite successions. Abu Dhabi Sabkha, submitted to the UNESCO Tentative List in 2018 under criterion (viii), therefore represents one of the few arid coastal geoheritage systems formally recognized at this level, offering an opportunity to broaden the geographic and thematic scope of geoheritage inscribed under the Convention.

The scientific importance of Abu Dhabi Sabkha extends beyond its sedimentological relevance. The site was submitted by the Ministry of Culture and Knowledge Development of the United Arab Emirates to the UNESCO World Heritage Tentative List on 20 June 2018, reflecting its potential global heritage significance [8]. The sabkha located south of Al Dhabaya and Abu Al Abyadh Islands is especially notable because it has been reported as the only documented coastal sabkha where all four diagnostic layers co-occur within a single site: lagoon mud, microbial mat, gypsum mud, and anhydrite nodules [9]. This complete sequence provides strong and rare evidence of the natural processes that define

sabkha development, including marine influence, microbial activity, evaporation, salinity evolution, and evaporite mineral formation.

Among these layers, the microbial mat stands out as one of the most scientifically important components of the sabkha system. Microbial mats contribute to sediment binding, organic matter accumulation, mineral precipitation, and carbonate transformation. In the Abu Dhabi coastal sabkha, Bontognali et al., 2010 [10] documented a close relationship between microbial mats and dolomite formation, suggesting that microbial processes play a meaningful role in dolomite mineralization, a process that remains one of the unresolved problems in sedimentary geology. Similarly, gypsum mud and anhydrite nodules reflect intense evaporation, capillary rise, and hypersaline groundwater conditions that are key characteristics of arid coastal sedimentary systems [2,11]. Together, these components make Abu Dhabi Sabkha a scientifically layered site where biological, chemical, and physical processes operate simultaneously.

What makes the conservation of this site particularly urgent is the pace of change occurring around it. The Arabian Gulf coastline has experienced rapid urban expansion, industrial growth, coastal reclamation, and infrastructure development over the past five decades [12]. Coastal development, road construction, off-road vehicle movement, groundwater modification, and surface disruption can damage fragile salt crusts, microbial mats, evaporite deposits, and sedimentary structures with consequences that are difficult or impossible to reverse. Recovery of disturbed sabkha surfaces and microbial systems operates over geological timescales, meaning that physical damage today represents a permanent loss of scientific record. Conserving Abu Dhabi Sabkha should therefore go beyond protecting a landscape feature. It must include the protection of active natural processes, sedimentary records, microbial systems, and geoheritage values that give the site its global importance.

The UNESCO Tentative List status of Abu Dhabi Sabkha provides an important opportunity to connect geological heritage with sustainable coastal management. Yet existing studies tend to treat sabkhas either as geotechnical constraints or as sedimentological analogues, while limited attention has been given to linking their geoheritage value with environmental sensitivity, conservation planning, and long-term sustainability. This gap matters because effective management of sabkha environments requires both scientific understanding and practical protection strategies that can be implemented within a rapidly developing regional context.

This review addresses that gap by evaluating Abu Dhabi Sabkha as a geological heritage system, with three specific objectives. First, it examines the scientific basis for the site's UNESCO Tentative List status, focusing on the complete sabkha sequence of lagoon mud, microbial mat, gypsum mud, and anhydrite nodules, and the microbial and evaporite processes that sustain it. Second, it assesses the environmental sensitivity of the site by identifying the coastal development pressures, groundwater changes, and climate-related risks most likely to disturb these sedimentary and biological features. Third, it evaluates existing and proposed conservation and monitoring approaches to determine what is needed to support long-term protection and future UNESCO nomination readiness. By linking these three strands, the review positions Abu Dhabi Sabkha as a globally significant arid coastal geoheritage system and provides a structured basis for conservation planning and sustainable coastal management in the region.

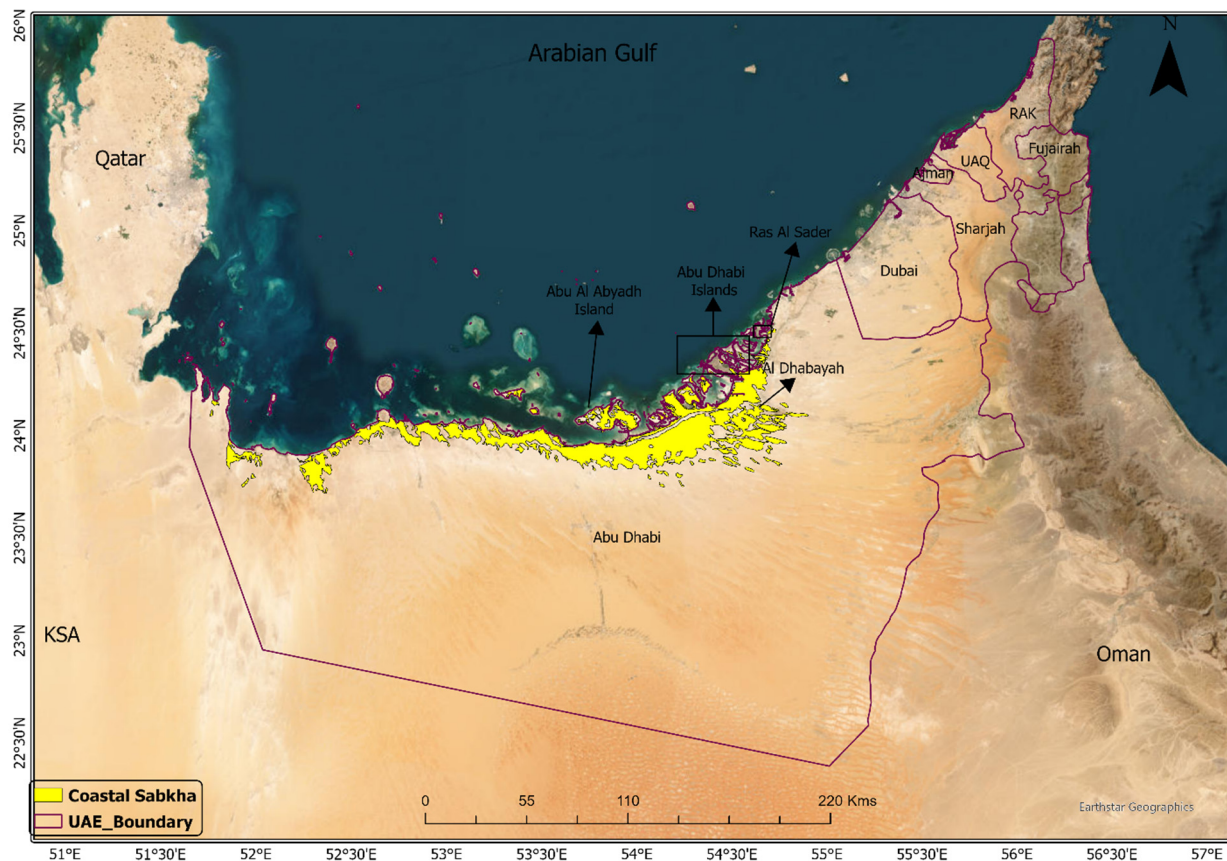


Figure 1. Spatial distribution of coastal sabkha along the southern margin of the Arabian Gulf, UAE. The yellow polygons show the mapped sabkha extent, forming a near-continuous supratidal belt along the Abu Dhabi coastline, consistent with published estimates of up to approximately 16 km in width and 300 km in length [9,13]. UAE administrative boundaries are shown for spatial reference.

2. Coastal Sabkhas in Arid Regions: Concept and Formation

2.1. Definition of Coastal Sabkha

Coastal sabkhas are low-lying, salt-rich flats that commonly form in arid and hyper-arid coastal regions where evaporation exceeds rainfall. They usually occur in the supratidal zone, landward of tidal flats, lagoons, and shallow marine environments, and represent one of the most characteristic saline landforms of dry coastal settings [1,2,14]. In geological studies, the term *sabkha* refers to saline flats where evaporite minerals accumulate at or near the surface due to the concentration of salts from seawater, shallow groundwater, capillary rise, and intense evaporation [2,13,15]. As a result, coastal sabkhas act as transitional environments between the sea and the inland desert, where marine influence gradually decreases and salinity generally increases landward.

Coastal sabkhas should not be viewed simply as barren or unused saline lands. They are active natural systems shaped by the interaction of seawater, shallow groundwater, evaporation, sediment supply, microbial activity, and mineral precipitation [3,11]. These processes allow coastal sabkhas to preserve valuable records of arid coastal evolution, sea-level change, carbonate sedimentation, evaporite formation, and early diagenesis [2,3]. For this reason, they are scientifically important for understanding both modern coastal environments and ancient carbonate-evaporite successions.

2.2. Formation Processes of Coastal Sabkhas

As discussed, the formation of coastal sabkhas is controlled by the combined influence of evaporation, tidal flooding, seawater input, shallow groundwater, salinity, and sediment movement. In arid coastal regions, high temperatures and low rainfall create strong evaporative conditions. When seawater, stormwater, or saline groundwater reaches the sabkha surface, water is removed through evaporation, leaving dissolved salts behind. Over time, this process supports the formation of salt crusts and evaporite minerals such as gypsum, anhydrite, halite, and other saline deposits [16].

In Abu Dhabi, coastal sabkha systems are strongly influenced by groundwater movement, evaporation, and solute recycling within the shallow subsurface environment. Ref. [13] showed that solutes in the Abu Dhabi coastal sabkha are not controlled only by direct seawater flooding, but also by groundwater and brine movement, with salts returning toward the surface through capillary processes. This makes the Abu Dhabi sabkha a dynamic hydrogeological system where water movement, evaporation, and salt precipitation interact over time.

The formation process can be understood as a repeated cycle. Tides, storm-driven flooding, and shallow marine processes supply seawater and sediment to low-gradient coastal areas. After flooding, intense evaporation removes water from the surface and shallow pore spaces, causing salinity to increase. At the same time, saline groundwater can move upward through capillary action and bring dissolved salts toward the surface. Repeated wetting, evaporation, capillary rise, and salt precipitation gradually produce strong salinity gradients, salt crusts, and evaporite-rich sediments. These processes are especially active in supratidal zones where flooding is periodic rather than continuous [11,13].

Sediment supply also supports sabkha development. Carbonate mud, skeletal grains, microbial-bound sediments, wind-blown particles, and fine clastic materials may be transported by tidal channels, lagoons, wind activity, and shallow marine processes. After deposition, these sediments are modified by evaporation, salinity changes, microbial activity, and early mineral formation. In the Arabian Gulf, the interaction of these processes creates distinctive carbonate-evaporite successions, making the region one of the best modern settings for studying coastal sabkha formation and preservation [11].

2.3. Difference Between Coastal and Inland Sabkhas

Abu Dhabi is an important region for sabkha studies because both coastal and inland sabkhas occur within its broader arid landscape. Although both are saline environments, they differ in their water sources, geomorphic settings, sediment supply, salinity pathways, and mineralogical development. Coastal sabkhas are mainly influenced by seawater flooding, tidal inundation, storm surges, marine sediment supply, and shallow coastal groundwater. They commonly develop near lagoons, tidal flats, coastal plains, and shallow marine platforms, where evaporation, marine water input, sedimentation, and groundwater movement interact under arid climatic conditions [2,13].

Inland sabkhas, in contrast, are generally controlled by continental hydrology rather than direct marine influence. Their development is mainly associated with groundwater discharge, episodic rainfall, surface runoff, closed-basin drainage, and evaporation from low-lying desert depressions. The chemistry and mineral composition of inland sabkhas are strongly affected by groundwater composition, basin geology, evaporation rate, and long-term solute accumulation [17,18].

Therefore, the main distinction is that coastal sabkhas are closely linked with marine processes, whereas inland sabkhas are more strongly controlled by continental groundwater systems and desert-basin conditions. This distinction is important because it affects sediment composition, salinity evolution, evaporite mineral formation, environmental sensitivity, and land-use suitability. In Abu Dhabi, recognizing these differences is essential for sustainable land-use planning, environmental assessment, and geoheritage conservation.

2.4. Approximate Spatial Extent of Selected Sabkhas in Abu Dhabi and the Arabian Gulf

In Abu Dhabi, urban planning documents indicate that sabkha environments occupy approximately 7% of the emirate's total land area, highlighting their importance as both a land-cover category and a planning consideration in arid coastal development [19]. This value should be understood as a broad planning-level estimate rather than a fixed measured boundary, because sabkha extent may vary depending on the mapping approach used, including soil surveys, geomorphological mapping, remote sensing, hydrological assessment, or land-use classification.

The Abu Dhabi coastal sabkha has also been described as a major supratidal belt along the southern Arabian Gulf coast. UNESCO also describes the Abu Dhabi coastal sabkha as reaching up to approximately 16 km in width in some areas, with channels, inlets, islands, and shoals forming part of its coastal setting [9]. Similarly, hydrogeological studies describe the coastal sabkha of Abu Dhabi as an exposed sedimentary belt approximately 300 km long and 15 km wide in places [13]. Other regional descriptions of the At Taf coastal strip report a sabkha-dominated belt of approximately 320 km long, with the coastal sabkha reaching up to 24 km wide in some areas. These differences in reported dimensions are expected because each source may refer to a different mapped boundary, geomorphic unit, or section of the coastal sabkha system. Inland systems are also regionally significant, especially Sabkhat Matti (Figure 2), which is described as the largest inland sabkha in the Arabian Peninsula, covering approximately 2950 km². It also represents an important discharge zone for regional groundwater systems associated with the Rub' al Khali basin [18]. These published values are summarized in Table 1.

Coastal sabkhas are a defining landform along the southern margin of the Arabian Gulf, distributed across the coastlines of the UAE, Saudi Arabia, Qatar, Kuwait, and Oman, yet they vary considerably in spatial extent, sedimentological character, and hydrological setting from one country to the next. Sabkha ecosystems extend along the shores of the Arabian Gulf and the Red Sea, occupying a combined area of approximately 2775 km² [20]. In Kuwait, coastal sabkhas are concentrated along elongated depressions parallel to the southern coastline, particularly in the Al-Jailaiha and Al-Khiran areas, while inland sabkhas in Al-Maqwa and Urafjan are siliciclastic rather than carbonate in character, reflecting the transitional tectonic setting between the stable Arabian Foreland and the Mesopotamian Plain [21]. Along the coastlines of Qatar, the UAE, and Saudi Arabia, stranded beach ridges and elevated sabkha deposits record a relative sea-level highstand of at least two metres between approximately 6000 and 4500 years ago [22], providing a common Holocene origin for sabkha systems across the region. In Qatar, comparison of two hydrological end-member regimes—a coastal sabkha in hydraulic continuity with marine water at Mesaieed and a continental sabkha within a closed basin at Dukhan, reveals considerable variability in the hydrological and geochemical processes controlling evaporite origins and spatial distribution [23]. Qatar's sabkhas are predominantly mixed siliciclastic-carbonate systems where dolomitization has been a primary research focus, but they lack the continuous barrier island and lagoonal architecture that distinguishes the Abu Dhabi system. Many major hydrocarbon reservoirs in Qatar and the broader Middle East, including the Permo-Triassic Khuff and Jurassic Arab formations, formed under conditions remarkably similar

to those shaping the Qatari coastline today [22,24]. In Oman, the Barr Al Hikman sabkhas on the eastern coast cover approximately 1400 km² of low-lying topography and develop within a thin sediment veneer over a complex geological substrate where recent sea-level fall and structural movement have produced emergent marine to lagoonal carbonate host sediments [25]. A classic carbonate-evaporite complex characterizes the coastal areas adjacent to the Arabian Gulf, whereas siliciclastics, minor carbonate sands, and local sabkhas characterize the coastal areas of the Gulf of Oman [26], underscoring the geochemical and depositional contrast between the Gulf-facing and Indian Ocean-facing coastlines of the Arabian Peninsula. Table 1 summarizes the key attributes of selected sabkha systems across the Arabian Gulf for comparative context.

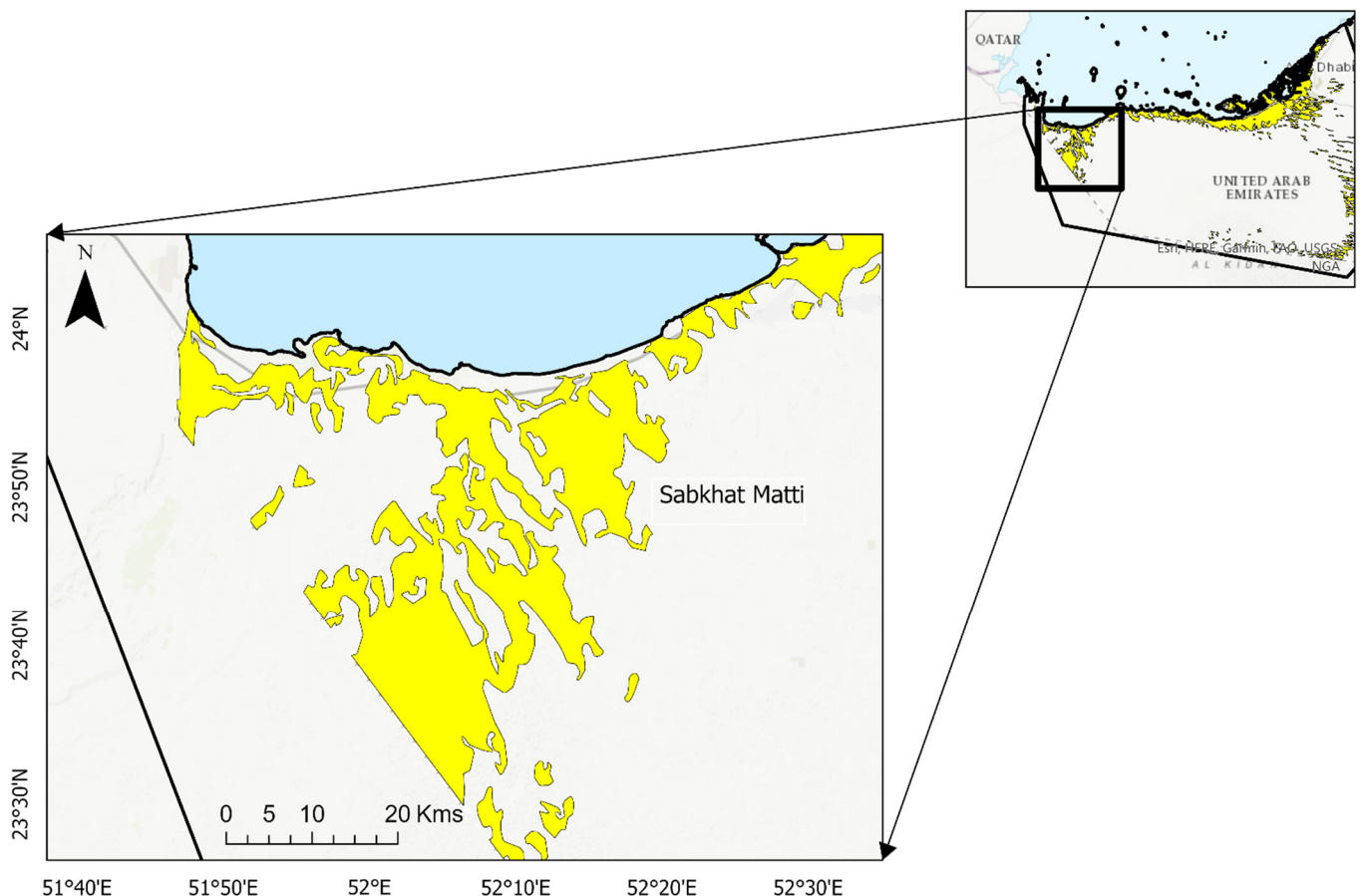


Figure 2. Location and spatial extent of Sabkhat Matti, the largest inland sabkha in the Arabian Peninsula, situated in the western part of Abu Dhabi Emirate along the UAE–Saudi Arabia border. Covering approximately 2950 km², the sabkha occupies a low-lying inland depression and represents a major discharge zone for regional groundwater systems associated with the Rub’ al Khali basin [18].

Within this regional picture, the Abu Dhabi coastal sabkha stands apart in several important respects. Regarded as the most extensive coastal sabkha in the Arabian Gulf, it spans approximately 150 km along the coastline from Ra’s Sadr to Tarif, west of Abu Dhabi Island, and reaches up to 15 km inland [27,28]. Its sedimentological record is correspondingly rich. Deposits of Abu Dhabi lagoons are mainly composed of burrowed skeletal-peloidal sands and lime-peloidal muds; intertidal deposits consist of laminated microbial mats in the upper zones, and supratidal deposits are characterized by a gypsum mush and anhydrite and/or gypsum nodules grown within a carbonate and siliciclastic matrix [29,30]. The microbial mat component is particularly distinctive. Dolomite formation along the Abu Dhabi coastline is interpreted to be linked to dolomite-mediating microbial organisms, with biopolymers of microbial origin referred to as Extracellular Polymeric

Substances (EPS) playing a key role in primary dolomite mineralization [10,11]. This active microbially mediated dolomite formation is not replicated at comparable scale or stratigraphic completeness in any other Arabian Gulf coastal sabkha system described in the peer-reviewed literature. The sabkha located south of Al Dhabaya and Abu Al Abyadh Islands is currently reported in UNESCO documentation as the only confirmed example to preserve all four main diagnostic layers such as lagoon mud, microbial mat, gypsum mud, and anhydrite nodules are together within a single coastal setting [9], a stratigraphic completeness that neither the Qatari, Kuwaiti, Saudi, nor Omani sabkha systems have been reported to possess.

This distinction is not simply a matter of scale. The protective geometry of Abu Dhabi's barrier island and lagoonal system creates a uniquely graduated progression from open marine to fully supratidal conditions over relatively short distances, preserving each depositional environment in a laterally continuous and vertically stacked sequence that is accessible, dateable, and actively forming today [13,14,31]. The modern intertidal microbial mat is separated from and partly overlaps the buried regressional microbial mat, representing a renewed eustatic transgression in response to global warming, while the mainland coastal sabkhas are simultaneously expanding seawards and extending landwards as a result of aeolian deflation [32]. Radiocarbon dating has confirmed that the coastal sabkha of Abu Dhabi formed over the last 7000 years, recording a continuous and dateable sedimentary history that underpins its scientific value [9,14]. Other Arabian Gulf sabkhas may offer insights into specific processes such as continental groundwater hydrology in Qatar's inland systems or halite-dominated evaporite accumulation in Kuwait's coastal depressions but none provide the same integration of lagoon, microbial, carbonate, and evaporite records within a single, spatially coherent, and stratigraphically complete system [26]. This is the scientific foundation of Abu Dhabi Sabkha's global geoheritage value and what ultimately differentiates it as a UNESCO Tentative List site rather than merely a regionally significant coastal feature [9,33].

2.5. Climatic Setting and Long-Term Climate Trends of the Abu Dhabi Coastal Sabkha Region

The climatic regime of the Abu Dhabi coastal sabkha region is not merely background context for this review; it is the primary mechanism through which the site's exceptional geological sequence is produced, maintained, and continuously extended. The evaporation that drives capillary brine rise, gypsum precipitation, anhydrite nodule formation, and microbial mat dynamics is directly controlled by temperature, humidity, solar radiation, wind, and the chronic water deficit that defines the Arabian Gulf coastal environment. To characterise these conditions quantitatively and to establish a long-term baseline against which future monitoring can be measured, monthly climate data were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) database for the period January 1981 to December 2025, covering the Abu Dhabi coastal sabkha region. Nine variables were extracted from MERRA-2 reanalysis and CERES SYN1deg satellite products: mean and maximum air temperature at 2 m (T_{2m} and T_{2m_max}), Earth skin temperature (T_s), relative humidity at 2 m (RH_{2m}), total precipitation (IMERG PRECTOT), surface soil wetness (GWETTOP), wind speed at 2 m (WS_{2m}), all-sky surface UV index, and all-sky surface albedo. Monthly values flagged as −999 were treated as missing and excluded from all calculations. UV index and albedo records begin from 2001; all other variables span the full 45-year record. Together these variables provide a comprehensive climatological portrait of the conditions under which the Abu Dhabi sabkha system operates (Figure 3), and a long-term record of the directional changes those conditions are undergoing (Figure 4).

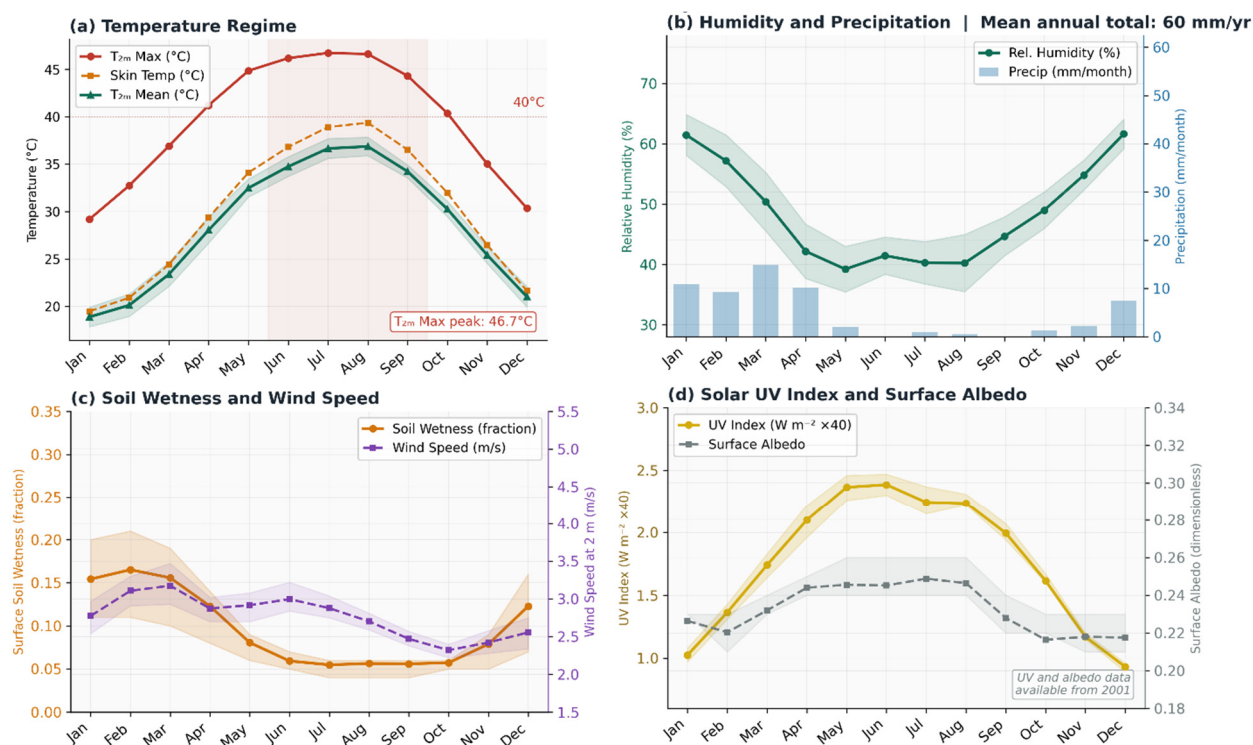


Figure 3. Monthly climatology of the Abu Dhabi coastal sabkha (1981–2025), based on NASA POWER MERRA-2 and CERES SYN1deg data. (a) Mean, maximum, and skin temperature, with the summer stress period (June–September) shaded. (b) Relative humidity and precipitation (mean annual total: 60 mm/year). (c) Soil wetness fraction and 2 m wind speed, showing the spring Shamal peak and persistent summer dryness. (d) All-sky UV index and surface albedo (2001–2025). Shaded bands represent the interquartile range (25th–75th percentile).

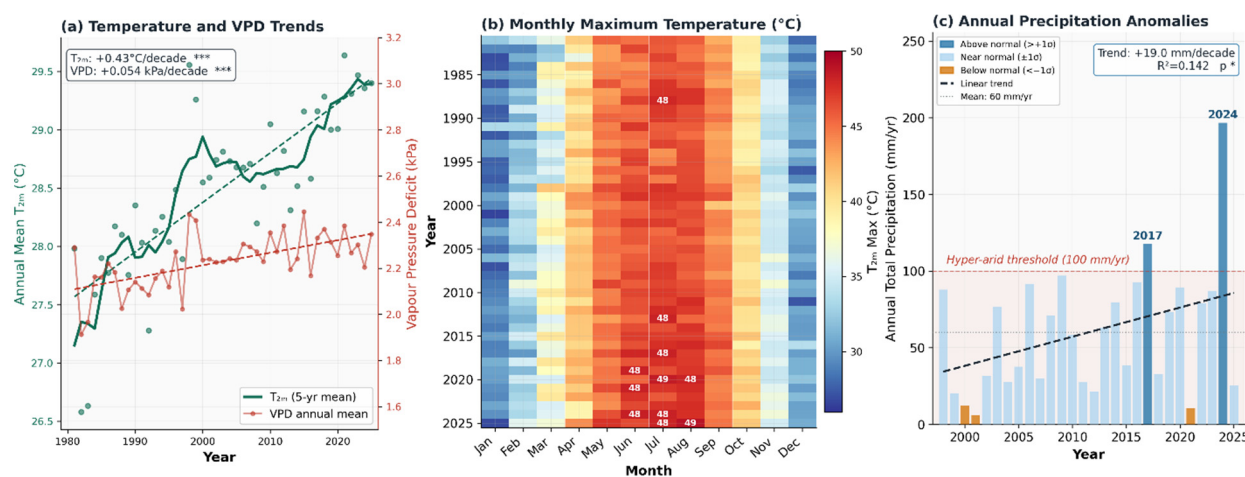


Figure 4. Long-term climate trends and aridity indicators for the Abu Dhabi coastal sabkha (1981–2025), based on NASA POWER MERRA-2 data. (a) Annual mean temperature (5-year running mean and trend) and vapour pressure deficit (VPD), both showing significant increases of $+0.43\text{ }^{\circ}\text{C}$ per decade and $+0.054\text{ kPa}$ per decade ($p < 0.001$), pointing to rising evaporative demand. (b) Monthly maximum temperature heatmap, with cells marked where $T_{2m_max} \geq 48\text{ }^{\circ}\text{C}$. (c) Annual precipitation anomalies relative to the long-term mean ($\pm 1\text{ SD}$), with the hyper-arid threshold (100 mm/year) marked; 2024 recorded the highest annual total in the record, at approximately 197 mm.

Table 1. Spatial extent, sedimentological character, stratigraphic completeness, and scientific significance of coastal and inland sabkha systems in Abu Dhabi and across the Arabian Gulf. Rows are organized into two blocks: Abu Dhabi sub-systems (upper block) and regional comparative sites (lower block). The Abu Dhabi coastal sabkha south of Al Dhabaya and Abu Al Abyadh Islands (highlighted in amber) is the reference site and the only sabkha in the world confirmed to preserve all four diagnostic layers—lagoon mud, microbial mat, gypsum mud, and anhydrite nodules—within a single coastal setting [9]. Stratigraphic completeness is assessed qualitatively against this four-layer benchmark. EPS = Extracellular Polymeric Substances. UAE = United Arab Emirates.

Country/Region	Sabkha/Location	Type	Approximate Reported Extent	Sedimentological Character	Stratigraphic Completeness	Scientific and Geoheritage Significance	Source
Abu Dhabi, United Arab Emirates							
UAE—Abu Dhabi	Coastal sabkha south of Al Dhabaya and Abu Al Abyadh Islands	Coastal	Up to ~16 km wide; covers 62% of the mainland coastal strip	Complete four-layer carbonate-evaporite sequence: lagoon mud, microbial mat, gypsum mud, and anhydrite nodules; active microbially mediated dolomite formation via EPS; halite crust at surface; anhydrite over 70 cm water table unique in occurrence	COMPLETE—all four diagnostic sabkha layers co-occur at a single coastal site; only confirmed example worldwide	UNESCO World Heritage Tentative List site (2018); globally referenced type section for Holocene carbonate-evaporite sedimentation; active dolomite formation at a scale unmatched elsewhere in the Arabian Gulf	[3,8,10]
UAE—Abu Dhabi	Abu Dhabi coastal sabkha sediment belt (mainland coast)	Coastal	~300 km long; ~15 km wide	Shoaling-upward cycles of lagoonal carbonates, cyanobacterial peats, gypsum mush, and displacive anhydrite; underlain by indurated carbonate crusts; formed over last 7000 years	Partial to complete—the full sequence is preserved at specific localities; overall belt lacks four-layer completeness at every point	Critical reference for groundwater-solute interaction, capillary evaporation, and evaporite mineral development in arid coastal settings; type locality for Holocene analogue studies	[13,14]
UAE—Abu Dhabi	Khor al Bazam coastal sabkha, western Abu Dhabi	Coastal	~320 km long; up to 24 km wide	Nine distinct sedimentary facies: coral-algal, oolitic, pellet-aggregate, molluscan, mangrove, algal mat, evaporite, and aeolian; cyanobacterial mats up to 2 km wide prograding northward over sandy micrites	Partial—most extensively facies-mapped zone in western Abu Dhabi; algal mat and evaporite zones documented but four-layer completeness not confirmed across full extent	One of the most extensively documented modern carbonate-evaporite sabkha belts in the Arabian Gulf; type locality for nine-facies Holocene carbonate model; analogues to ancient hydrocarbon-bearing formations	[26,34]
UAE—Abu Dhabi	Sabkhat Matti, western Abu Dhabi (UAE—Saudi Arabia border)	Inland	~2950 km ² ; ~150 km southward from coast	Siliciclastic inland sabkha grading coastward into a narrow carbonate-evaporite supratidal belt; surface halite crust; subsurface anhydrite and gypsum rosettes; water table at surface in winter; dune sands cemented by gypsum	Partial—inland evaporite sequence only; no lagoonal or microbial mat layers; controlled by continental groundwater rather than marine influence	Largest inland sabkha in the Arabian Peninsula; formed ~6000 years ago during post-glacial sea-level rise; major groundwater-discharge and solute-accumulation zone; important comparative site for coastal vs. continental sabkha hydrology	[18,26]

Table 1. Cont.

Country/Region	Sabkha/Location	Type	Approximate Reported Extent	Sedimentological Character	Stratigraphic Completeness	Scientific and Geoheritage Significance	Source
UAE—Abu Dhabi	Abu Dhabi Emirate sabkha landscapes (combined)	Coastal + inland	~7% of Abu Dhabi land mass; 8 major sub-classes	Mixed carbonate-evaporite supratidal flats, aeolian sands, storm washover deposits, and inland saline depressions; highest landform diversity in Abu Dhabi Emirate	Variable—composite landscape covering multiple completeness levels across sub-classes	Major land-cover and planning unit; foundational reference region for Holocene carbonate-evaporite research; eight sub-classes represent broadest sabkha landform diversity in the Arabian Peninsula	[19]
Arabian Gulf Region—Comparative Sites							
Qatar	Al-Kharayej sabkha, Gulf of Salwa, eastern Qatar	Coastal	~15 facies types over narrow coastal belt	Mixed siliciclastic-carbonate; pre-transgressive dune sands, open-coast to lagoonal facies, saline lake facies, and supratidal evaporites; dolomitization reported; lagoon closure triggering salina development	Partial—no confirmed four-layer completeness; microbial mat and anhydrite sequence less spatially developed than Abu Dhabi	Analogous to Permo-Triassic Khuff and Jurassic Arab formation reservoirs; important for dolomitization research; narrower barrier protection limits supratidal evaporite development	[22,24]
Qatar	Dukhan sabkha, western Qatar	Inland (continental)	Large inland basin; lowest point −7 m below sea level	Continental sabkha in a closed syncline; halite-dominated evaporites; no marine hydraulic continuity; brine entirely from continental groundwater; no carbonate lagoonal facies	Incomplete—continental end-member only; no marine-linked stratigraphic sequence	Represents hydrological end-member of continental sabkha development; useful for comparative groundwater-evaporite studies; no marine-microbial-evaporite linkage comparable to Abu Dhabi	[13,23]
Kuwait	Al-Jailaiha and Al-Khiran coastal sabkhas, southern Kuwait	Coastal	Elongated depressions parallel to southern coast	Coastal depression sabkhas; skeletal and oolitic fragments present; mixed siliciclastic input from Al-Dibdibbah fluvial system; transitional between Arabian Foreland and Mesopotamian Plain; halite and gypsum in shallow subsurface	Partial—mixed siliciclastic input and absence of well-developed barrier island protection limit sequence completeness	Transitional tectonic setting introduces siliciclastic input; no documented microbial mat component at Abu Dhabi scale; no four-layer completeness reported; useful for coastal process studies in mixed-input settings	[21]
Saudi Arabia	Eastern coastal plain sabkhas, Al-Hasa to Qatar border	Coastal + inland	Coastal plain ~610 km long; salt sabkhat and sandy areas	Flat, low-lying salt sabkha; halite surface crusts dominant; mixture of carbonate and siliciclastic sediment; groundwater near surface; continental and marine sediment fragments	Partial—greater regional extent than Abu Dhabi but no published documentation of four-layer completeness	Largest regional sabkha extent in the Arabian Gulf but lacks the protected lagoonal geometry and microbial mat development that characterize Abu Dhabi's complete sequence; important for regional groundwater and salinity mapping	[2,13]

Table 1. Cont.

Country/Region	Sabkha/Location	Type	Approximate Reported Extent	Sedimentological Character	Stratigraphic Completeness	Scientific and Geoheritage Significance	Source
Oman	Barr Al Hikman sabkhas, eastern Oman coast (Gulf of Oman)	Coastal + continental	~1400 km ² ; peninsula ~30 km wide	Thin sediment veneer over complex geological substrate; halite-dominated in low-lying coastal zones; gypsum layers in soft grainy host sediments; affected by sea-level fall and structural movement; Gulf of Oman siliciclastic influence	Partial—coastal and continental types present but system faces Gulf of Oman rather than Arabian Gulf; siliciclastic dominance limits carbonate-evaporite completeness	Gulf of Oman location means siliciclastic rather than carbonate sedimentation dominates; lacks the continuous lagoonal-to-supratidal carbonate-evaporite architecture of Abu Dhabi; valuable for sea-level and structural controls on sabkha development	[25,26]

2.6. Temperature Regime

The Abu Dhabi coastal sabkha region is characterised by an extreme and strongly seasonal temperature regime that is among the most intense of any coastal environment on Earth. As shown in Figure 3a, monthly mean air temperature (T_{2m}) rises from a winter minimum of approximately 20 °C in January to a summer maximum of approximately 34 °C in July–August, while monthly mean maximum temperature (T_{2m_max}) peaks at approximately 46.7 °C in the same period. Such temperatures may impose substantial thermal stress on exposed microbial and sedimentary surfaces. Earth skin temperature closely tracks T_{2m_max} with a slight lag, reflecting the high thermal inertia of the salt crust and mineral-rich sabkha surface. The summer period from June to September, shaded in Figure 3a, represents the interval of maximum evaporative intensity during which capillary brine rise is most vigorous, anhydrite formation is most rapid, and the sabkha surface is simultaneously at its most geochemically active and its most physically vulnerable to disturbance. The long-term warming trend, shown in Figure 4a, reveals a statistically significant increase in annual mean T_{2m} of +0.43 °C per decade over 1981–2025 ($R^2 = 0.639$, $p < 0.001$), equivalent to a total warming of approximately 1.9 °C across the record. The temperature heatmap in Figure 4b provides the most visually striking evidence of this trend: the deepening red saturation of the June–August columns from the 1980s to the 2020s is unambiguous, with monthly maximum temperatures at or above 48–49 °C appearing with markedly increasing frequency from 2010 onward and recurring every year from 2017 to 2025.

2.7. Precipitation, Humidity, and Aridity

Annual total precipitation in the Abu Dhabi coastal sabkha region averages approximately 60 mm/year, well below the 100 mm/year threshold that defines hyper-arid climates (Figure 3b). Precipitation is highly concentrated in the December–March period, when occasional frontal systems associated with the winter monsoon margin produce the majority of annual rainfall, while the summer months from June through September are effectively precipitation-free in most years. This seasonal structure is critically important for sabkha geochemistry: the coincidence of the dry summer with the period of maximum evaporation and highest temperatures creates the conditions under which capillary brine concentration, gypsum precipitation, and anhydrite formation are most intense. Relative humidity exhibits a pronounced inverse seasonal cycle, declining from a winter maximum of approximately 62% in January to a summer minimum of approximately 40% in May–June (Figure 3b), precisely when evaporative demand is at its peak. The combination of

minimum humidity, maximum temperature, and zero precipitation during summer creates the most extreme evaporative stress conditions of any season, and it is under these conditions that the upper sabkha layers, gypsum mud and anhydrite nodules, are most actively forming. Interannual variability in precipitation is high, as shown clearly in Figure 4c: most years cluster well below the hyper-arid threshold, but episodic anomalous years including 2017 and the exceptional April 2024 event, the highest annual total in the 45-year record at approximately 197 mm, stand out sharply. These rare high-rainfall events are geologically significant because they temporarily disrupt salt crust surfaces, dissolve near-surface halite, and can physically damage microbial mat integrity through sudden flooding and sediment transport [32]. Recovery from such disturbances operates over geological rather than human timescales, which is precisely why they represent a compounding risk when combined with the direct physical disturbances of coastal development and unmanaged access.

2.8. Evaporative Demand, Soil Conditions, and Radiation

Surface soil wetness remains persistently and extremely low throughout the year, with a long-term mean of approximately 0.097 (fraction of saturation) and a pronounced seasonal minimum during summer that mirrors the precipitation absence (Figure 3c). This chronic near-surface dryness is a fundamental condition for sustained capillary evaporation: a dry surface matrix draws saline groundwater upward continuously, concentrating brines and precipitating evaporite minerals in the upper sabkha sediment column. Wind speed shows a spring maximum in March–April, corresponding to the peak of the northwesterly Shamal season, when aeolian sediment transport onto the supratidal flat is most active and the cross-sabkha exchange of fine carbonate material most vigorous (Figure 3c). The annual VPD trend shown in Figure 4a integrates temperature and humidity into a single metric of evaporative demand and confirms a statistically significant increase of +0.054 kPa per decade ($p < 0.001$), driven by the warming trend. This means that the atmosphere above the sabkha is becoming progressively more capable of extracting moisture from the surface year on year, directly intensifying the evaporative processes that sustain the site's geological record. Solar UV loading peaks in June–July at an index value of approximately 2.4, reflecting the combination of low cloud cover, high solar elevation, and minimal atmospheric scattering under hyper-arid summer conditions (Figure 3d). The sustained high UV exposure is relevant to photodegradation of organic matter within the microbial mat and to the thermal loading of exposed evaporite surfaces, which contributes to the diurnal thermal expansion and contraction cycles that produce tepee structures and crack-fill cements in the near-surface sabkha [26].

2.9. Climate as the Engine of Sabkha Geoheritage

The 45-year instrumental climate record of the Abu Dhabi coastal sabkha region establishes unambiguously that the site operates under a hyper-arid, persistently extreme, and measurably intensifying climatic regime. Mean annual temperatures of 28.5 °C with summer maxima regularly exceeding 46–49 °C, annual precipitation averaging 60 mm/year with near-zero summer totals, peak vapour pressure deficit above 2.5 kPa in summer, and a warming trend of +0.43 °C per decade are the climatic foundations upon which the complete four-layer sabkha sequence is maintained and continuously extended. Two superimposed dynamics emerge from this record that carry direct implications for the conservation of the site. First, the documented warming trend and rising VPD confirm that the evaporative processes driving the sabkha's formative geology are intensifying with climate change, potentially accelerating the pace of supratidal diagenesis while simultaneously increasing the thermal stress on fragile surface features. Second, the episodic extreme precipitation events recorded in 2017 and 2024, both exceeding the hyper-arid threshold, introduce a countervailing disturbance dynamic whose cumulative effects on the sabkha's geological

integrity have not yet been systematically quantified and represent a priority gap for future field-based monitoring. Taken together, these findings confirm that Abu Dhabi Sabkha is not a static geological archive but an actively evolving system under an extreme and changing climate, one that simultaneously produces the features that justify its global significance and subjects them to increasing physical stress.

2.10. Land-Use and Land-Cover Changes Affecting Sabkha Environments

Land-use and land-cover (LULC) change is an increasing concern for sabkha and arid coastal systems in the Arabian Gulf. Rapid urban growth, reclamation, industrial activity, road networks, and shoreline modification have transformed many coastal landscapes. Recent regional studies show expansion of built-up areas, reclaimed land, inundated zones, and managed vegetation between 2001 and 2021 [35]. A 50-year review of Arabian Gulf remote-sensing research also confirms that coastal urbanization has altered natural habitats and increased environmental pressure across the region [12].

Remote sensing and GIS are now widely used to detect these changes. UAE-wide LULC mapping using Landsat imagery and machine-learning classification documented major land-cover transformation from 1972 to 2021, mainly linked to urban growth and development pressure [36]. Earlier work on the Abu Dhabi coastal zone also recorded rapid land-use change associated with industrialization and urban expansion [37]. These studies show the importance of repeated satellite-based assessment for tracking long-term change in sabkha-dominated coastal landscapes, especially in Abu Dhabi.

Recent sabkha-focused studies show that monitoring should go beyond broad land-cover classes. Along the Southern Red Sea coast of Egypt, Sentinel-2 imagery, digital elevation models, field observations, and GIS analysis were used to map sabkha distribution, salinity zones, topographic controls, and coastal facies [38]. In Qatar, spectral remote sensing was used to identify inland sabkha surfaces, evaporite minerals, salt crusts, gypsiferous soils, and soil-salinity patterns under land-use pressure [17]. These examples are relevant to Abu Dhabi because they show how satellite data can support mineralogical, hydrological, and geomorphic interpretation of sabkha sensitivity.

The choice of data resolution is important. Landsat imagery is suitable for long-term regional assessment because of its historical archive, but its 30 m resolution may not capture vehicle tracks, narrow access roads, localized crust damage, or disturbance to microbial mats. Sentinel-2 imagery, with 10–20 m resolution, provides better detail for mapping sabkha surfaces, salinity zones, shoreline change, and coastal facies. In highly sensitive zones, drone surveys, high-resolution commercial satellite imagery, field GPS mapping, groundwater monitoring, and soil-salinity measurements are needed to detect small-scale surface disturbance and hydrological change. These monitoring approaches are directly relevant to Abu Dhabi Sabkha because the site lies within a rapidly developing Arabian Gulf coastal setting.

Unmanaged urban expansion, road construction, reclamation, drainage modification, groundwater alteration, and infrastructure growth may affect salt crusts, microbial mats, evaporitic sediments, salinity gradients, and shallow groundwater pathways. Such impacts may reduce the geological integrity and geoheritage value of the complete sabkha sequence recognized in the UNESCO [9]. The sensitivity of Abu Dhabi sabkha soils to groundwater change, salinity increase, and infrastructure-related geotechnical problems further supports careful land-use planning [39].

For future assessment, Abu Dhabi Sabkha should be monitored at two scales. A Landsat-based LULC assessment every three to five years would help evaluate long-term urban expansion, reclamation, shoreline modification, and infrastructure growth. Annual Sentinel-2 or drone-based monitoring should be used for sensitive areas, especially after major development activity, extreme rainfall, flooding, or coastal modification. Change per-

centages should be reported separately for built-up area, reclaimed land, exposed sabkha surface, vegetation, water or inundation, roads, and disturbed crust. Published Gulf-scale studies provide useful regional evidence, but site-specific percentage change for Abu Dhabi Sabkha should be calculated through dedicated multi-temporal remote-sensing analysis rather than assumed from regional trends.

Accordingly, long-term LULC monitoring should be treated as a core component of sabkha conservation and sustainable coastal planning. Integrating satellite remote sensing, GIS analysis, drone surveys, field validation, groundwater monitoring, soil-salinity assessment, and geoheritage mapping can help identify early degradation and guide conservation-based land-use decisions. This approach is consistent with geoconservation principles that emphasize inventory, monitoring, protection, and active management of sensitive geological sites [33,40–42].

Table 2 summarizes selected international, regional, and local studies that used remote sensing, GIS, and machine-learning methods to assess LULC change in sabkha and arid coastal environments. Together, these studies show that saline coastal systems are increasingly affected by urbanization, reclamation, infrastructure growth, and shoreline modification. They also highlight the value of satellite-based monitoring for detecting salinity patterns, surface disturbance, shoreline change, and land-cover transformation. Although the study areas and methods differ, the evidence supports the need for regular monitoring and conservation-oriented land-use planning. This is directly relevant to Abu Dhabi Sabkha, where unmanaged coastal development may affect evaporitic surfaces, shallow groundwater processes, and geoheritage value.

Table 2. International evidence of land-use and land-cover changes affecting sabkha and arid coastal.

Region/Country	Sabkha or Related Coastal System	Period/Data Source	Main LULC Change Observed	Relevance to Abu Dhabi Sabkha	Citation
Southern Red Sea, Egypt	Coastal sabkhas	Sentinel-2 and DEM-based mapping	Land-cover classification identified sabkha distribution, salinity zones, topographic controls and coastal facies	Shows how modern satellite mapping can classify coastal sabkha units and support conservation mapping	[38]
Arabian Gulf region	Gulf coastal zone	2001–2021 Landsat and Random Forest classification	Urban areas expanded strongly, with coastal reclamation, inundation and urban vegetation expansion	Directly relevant because Abu Dhabi Sabkha is part of the Arabian Gulf coastal system	[35]
Arabian Gulf region	Coastal habitats and urbanized coast	50-year remote sensing review	Rapid coastal urbanization after the oil boom caused habitat modification, LULC change and environmental pressure	Supports the argument that Gulf sabkhas are exposed to development pressure	[12]
Qatar	Inland sabkha, Dukhan area	Remote sensing and spectral analysis	Mapping of salt crusts, gypsiferous soil flats, evaporite minerals and soil salinity under infrastructure and agriculture pressure	Useful comparison for inland sabkha sensitivity and land-use suitability	[17]
UAE	National LULC change	1972–2021 Landsat machine-learning classification	Long-term transformation of UAE land cover linked to urban growth and development	Provides national background for changing land use around Abu Dhabi sabkha landscapes	[36]
Abu Dhabi, UAE	Coastal zone	1972–2000 Landsat change detection	Coastal land-use/land-cover changes due to rapid industrialization and urbanization	Direct local support for discussing development pressure on Abu Dhabi coastal sabkhas	[37]
Saudi Arabia, Arabian Gulf coast	Al-Aba Oasis wetland near Ras Tanura	Remote sensing and GIS	Built-up and agricultural land increased by 2021 due to urbanization and anthropogenic influence	Useful regional comparison for LULC pressure on saline wetland/coastal environments	[43]

3. Review Methodology

This review followed a structured literature synthesis approach to evaluate Abu Dhabi Sabkha as a geological heritage system, covering its formation processes, UNESCO geoheritage significance, environmental sensitivity, and sustainable conservation needs. The methodology was designed to be systematic, transparent, and reproducible, drawing on peer-reviewed publications, UNESCO documentation, environmental authority reports, and regional geological studies (Figure 5).

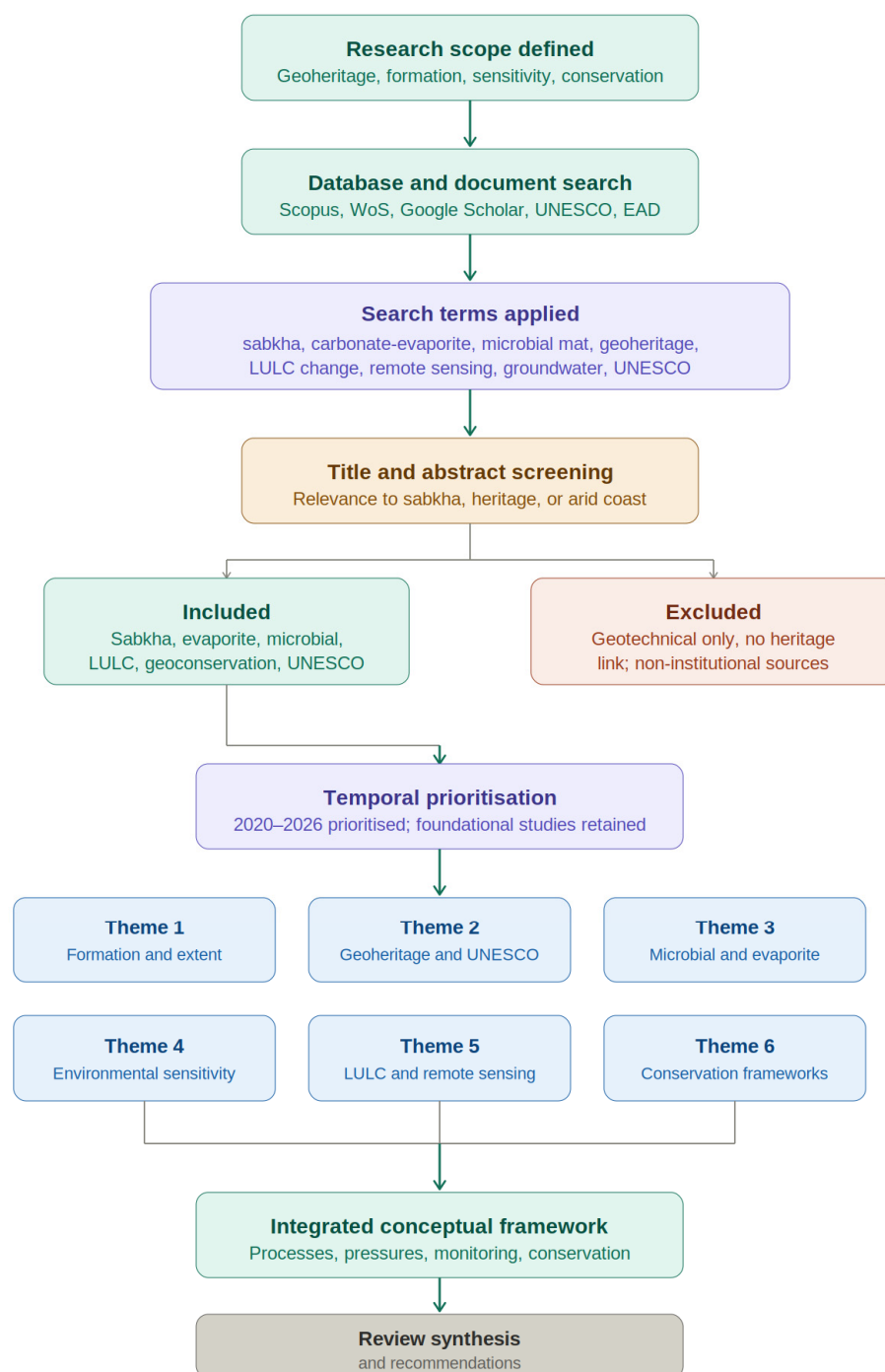


Figure 5. Flowchart summarizing the structured literature review methodology adopted in this study. The workflow proceeds from research scope definition and multi-database search through screening, temporal prioritization, and thematic synthesis across six categories, culminating in an integrated conceptual framework linking sabkha formation processes, UNESCO geoheritage significance, environmental pressures, and conservation-oriented management pathways.

3.1. Literature Search and Database Coverage

Literature was retrieved from Scopus, Web of Science, Google Scholar, and relevant grey literature repositories including UNESCO World Heritage Centre documents, the Environment Agency Abu Dhabi, and the IUCN geoconservation guidelines database. Search terms were applied in combination and included: sabkha, coastal sabkha, Abu Dhabi sabkha, carbonate-evaporite, microbial mat, dolomite formation, evaporite minerals, gypsum, anhydrite, Arabian Gulf sedimentation, geoheritage, geoconservation, UNESCO World Heritage, land-use land-cover change, remote sensing arid coast, groundwater sabkha, and sustainable coastal management. No strict start date was applied to the search in order to capture foundational studies from the 1960s onward, particularly the seminal Abu Dhabi sabkha investigations by [14,16,34], which remain scientifically essential for contextualizing modern sabkha research.

3.2. Inclusion and Exclusion Criteria

Studies were included if they addressed one or more of the following themes directly relevant to Abu Dhabi Sabkha: sabkha formation and coastal geomorphology, carbonate-evaporite sedimentation, microbial mat processes and dolomite formation, groundwater and hydrological controls, land-use and land-cover change in arid coastal settings, remote sensing and GIS applications for sabkha or saline environments, geoheritage assessment and geoconservation planning, and UNESCO World Heritage conservation frameworks. Studies were excluded if they addressed sabkha environments only in the context of geotechnical engineering problems without any connection to geological heritage, environmental sensitivity, or conservation. Non-peer-reviewed internet sources without institutional or scientific authority were also excluded.

3.3. Prioritization of Recent Literature

Publications from 2020 to 2026 were prioritized to capture updated remote sensing methodologies, machine-learning-based land-cover classification, climate-related impact assessments, and recent geoconservation frameworks [12,35,36,38,39,44]. Older foundational literature was retained where it provided irreplaceable field evidence or established the scientific basis for sabkha research in Abu Dhabi and the wider Arabian Gulf region [2,11,13].

3.4. Thematic Synthesis

The selected literature was organized thematically into six categories: (1) sabkha definition, formation, and spatial extent; (2) geological heritage value and the complete sabkha sequence; (3) microbial, carbonate, and evaporite processes; (4) environmental sensitivity and human-induced threats; (5) land-use and land-cover change monitoring; and (6) sustainable conservation and management frameworks. This thematic structure guided the organization of the review and ensured that geological, environmental, and heritage dimensions were addressed in an integrated manner rather than in isolation. A conceptual framework was developed from this synthesis to link natural sabkha processes with UNESCO geoheritage significance, environmental pressures, monitoring requirements, and conservation-oriented management pathways.

3.5. Scope and Limitations

This review is geographically focused on Abu Dhabi and the Arabian Gulf region, with selected international comparisons from Egypt, Qatar, Tunisia, and Oman used to contextualize the site within global sabkha and saline-flat research. Quantitative site-specific land-cover change data for Abu Dhabi Sabkha were not available from a single

dedicated multi-temporal study, and published regional estimates were therefore used with appropriate qualification. This limitation is identified as a priority gap for future research.

4. Abu Dhabi Sabkha and Its Significance

4.1. Location and Coastal Setting

Abu Dhabi Sabkha is located along the southern margin of the Arabian Gulf, within a low-gradient coastal landscape shaped by lagoons, tidal flats, channels, islands, shoals, and supratidal saline flats. This setting is significant because it allows different depositional environments to occur close to one another, ranging from shallow marine and lagoonal zones to intertidal microbial mats and supratidal evaporitic surfaces. UNESCO describes Abu Dhabi's coastal sabkha as reaching up to approximately 16 km in width in some areas and including channels, inlets, islands, and shoals [9].

Although Abu Dhabi also contains important inland sabkha systems, such as Sabkhat Matti (Figure 5), the UNESCO proposed inclusion significance discussed in this section is mainly associated with the coastal sabkha system. This system has strong geological and heritage value because it preserves closely linked sedimentary environments within a single arid coastal landscape. Earlier studies also highlighted that regions from the Abu Dhabi coast, like Khor Al Bazam and Mussafah Channel in equal importance due to the presence of Holocene carbonate and evaporite sedimentation in the Arabian Gulf [11,34].

4.2. UNESCO Tentative List Status

Abu Dhabi Sabkha was submitted by the United Arab Emirates to the UNESCO World Heritage Tentative List on 20 June 2018, indicating its potential heritage significance and eligibility for future nomination to the World Heritage List [9].

UNESCO Tentative List comparison (Table 3) also shows that the number of proposed criteria should not be interpreted as a direct measure of inscription potential. UNESCO requires a property to demonstrate Outstanding Universal Value and meet at least one selection criterion, together with integrity, protection and management requirements [45]. Therefore, Abu Dhabi Sabkha's proposal under criterion (viii) alone is not a weakness. Its strength lies in the focused geological justification of a rare coastal sabkha sequence that records lagoonal sedimentation, microbial mat development, evaporite formation and anhydrite nodule growth within one arid coastal system [9].

Table 3. UNESCO Tentative List comparison of sabkha and saline-flat related natural sites.

Site/System	Country	Year Submitted	UNESCO Criteria	Main Heritage Focus	Interpretation for Abu Dhabi Sabkha	Citation
Abu Dhabi Sabkha	United Arab Emirates	2018	(viii)	Coastal sabkha formation and carbonate-evaporite sequence	Strong focused geological argument with clear geoheritage identity	[9]
Khor Al-Adaid Natural Reserve	Qatar	2008	(vii), (viii)	Desert-coastal landscape, tidal embayment, dunes and sabkha processes	Broader landscape focus; not presented as a complete coastal sabkha sequence	[46]
Chott El Jerid	Tunisia	2008	(vii), (viii), (ix), (x)	Large inland saline-flat/chott system and arid landscape	Broader inland saline ecosystem rather than coastal carbonate-evaporite sabkha sequence	[47]
Bar Al Hakman Proposed Nature Reserve	Oman	2013	Natural site	Coastal wetland, shoreline geomorphology and saline-flat setting	Useful regional comparison, but not presented as a complete sabkha sequence	[48]

Successful nominations require strong evidence of geological integrity, legal protection, management effectiveness, monitoring capacity, and long-term conservation planning [8,45]. In this context, Abu Dhabi Sabkha represents a scientifically focused criterion (viii) geoheritage case because its significance is primarily linked to the preservation of a rare and well-developed coastal carbonate–evaporite sequence that records lagoonal sedimentation, microbial mat development, evaporite formation, and anhydrite nodule growth within a single arid coastal environment [9].

4.3. Geological Basis for Possible Outstanding Universal Value

The case for Outstanding Universal Value (OUV) of Abu Dhabi Sabkha rests on a convergence of geological attributes that, taken individually, are found in other arid coastal systems around the world, but in combination and at the spatial scale and stratigraphic completeness observed here, are not replicated elsewhere. UNESCO criteria for OUV under natural heritage require that a nominated site constitutes an outstanding example of major stages in Earth's history, including the record of significant ongoing geological processes and geomorphic or physiographic features [45]. Abu Dhabi Sabkha satisfies the geological dimension of this standard through four interconnected arguments: the completeness and integrity of its sedimentary sequence, the active and ongoing nature of the carbonate–evaporite processes it preserves, its value as a globally referenced modern analogue for ancient sedimentary formations of considerable economic importance, and the uniqueness of its microbially mediated mineral formation at a scale unmatched in any comparable coastal system.

The most widely cited geological attribute of the site is the complete sabkha sequence preserved south of Al Dhabaya and Abu Al Abyadh Islands, reported as the only location in the world where all four main diagnostic layers of a coastal sabkha system co-occur within a single site: lagoon mud, microbial mat, gypsum mud, and anhydrite nodules [9]. Each layer records a distinct stage in the progression from marine to continental conditions. The basal lagoon mud represents shallow subtidal sedimentation under open marine influence, dominated by burrowed skeletal-peloidal carbonates deposited in the protected lagoonal settings behind Abu Dhabi's barrier island system [14,26]. Overlying this, the microbial mat constitutes the most scientifically significant component of the sequence, formed by cyanobacterial communities in the upper intertidal zone where biological activity drives early diagenetic transformations including carbonate mineral precipitation [10,11]. The gypsum mud records the transition to supratidal conditions where intense evaporation draws hypersaline brines upward through capillary action, while the uppermost anhydrite nodule layer represents the most advanced stage of evaporitic development, forming as gypsum dehydrates under extreme surface temperatures and persistent aridity [2,13]. The anhydrite-rich soil developed over a 70 cm-deep water table has been described as unique in occurrence across Abu Dhabi Emirate [9], adding a further dimension of geological distinctiveness to the site.

The outstanding character of the site is further reinforced by the active and ongoing nature of the processes it records. Abu Dhabi Sabkha is not a relict system preserved from a geologically distant past; lagoon sedimentation, microbial mat growth, gypsum precipitation, and anhydrite nodule formation are all occurring simultaneously and are directly observable in the field today [11,14,26]. Radiocarbon dating has established that the coastal sabkha formed over the last 7000 years during the post-glacial Flandrian transgression [9,14], meaning the stratigraphic record at the site bridges Holocene sea-level change, progressive climate aridification, and evaporite mineral development within a single readable geological section. The modern intertidal microbial mat has also been found to partly overlap a buried regression mat beneath it, recording the signature of a

renewed eustatic transgression potentially linked to recent global warming [32], extending the scientific relevance of the site into contemporary Earth system dynamics.

The third and fourth pillars of the geological OUV argument are closely related and together represent perhaps the most compelling scientific case for global significance. The Holocene carbonate-evaporite sediments of Abu Dhabi have been cited for over six decades as type examples of the processes responsible for analogous ancient formations across the geologic record, including the Permian Khuff Formation, the Upper Jurassic Arab Formation, and the Hith Anhydrite of the Arabian Gulf subsurface, as well as Paleozoic carbonates of the USA, the Permian Zechstein Sea of the North Sea, and Mesozoic carbonate-evaporite systems of the Gulf of Mexico [26,34,49]. These ancient analogues include some of the most economically significant hydrocarbon reservoirs in the world, and the ability to study their formative processes in a modern, accessible, and active surface setting gives Abu Dhabi Sabkha a scientific utility extending far beyond its geographic boundaries. Building directly on this analogue value, the discovery of active microbially mediated dolomite formation within the sabkha's microbial mats addressed one of the longstanding unsolved problems in sedimentary geology, how dolomite forms under near-surface conditions at low temperatures [2]. Ref. [10] demonstrated that Extracellular Polymeric Substances secreted by sulfate-reducing bacteria and cyanobacteria within the Abu Dhabi microbial mats are actively facilitating dolomite precipitation today, a finding that positioned the site as the most important modern field laboratory for understanding low-temperature dolomite formation and its relevance to the ancient sedimentary record.

Taken together, these geological arguments constitute a well-grounded and defensible basis for recognizing Abu Dhabi Sabkha as possessing Outstanding Universal Value. The site records, within a single accessible coastal setting, both the processes and the products of one of the most scientifically important carbonate-evaporite systems on Earth's surface today, with a completeness and process-relevance that no comparable modern site has been demonstrated to match.

4.4. Scientific Importance of the Al Dhabaya and Abu Al Abyadh Sabkha Area

The sabkha environments south of Al Dhabaya and Abu Al Abyadh Islands are among the most distinctive coastal sabkha systems in Abu Dhabi and the wider Arabian Gulf region. Their significance is reflected in the inclusion of Abu Dhabi Sabkha on the UNESCO World Heritage Tentative List, mainly because the area has been reported to preserve a rare and well-developed sedimentary sequence within a single coastal setting. UNESCO identifies this sequence as lagoon mud, microbial mat, gypsum mud, and anhydrite nodules, representing subtidal, intertidal, and supratidal conditions [9]. The coexistence of these features makes Abu Dhabi Sabkha valuable for examining the environmental transition from shallow marine conditions to evaporite-dominated supratidal settings.

This geological setting is especially important because it occurs within a rapidly developing coastal region where sabkha surfaces are sensitive to disturbance from coastal development, road construction, industrial expansion, and off-road vehicle movement. Disturbance to these surfaces may affect fragile microbial mats, evaporite deposits, salt crusts, and sedimentary structures that are important for understanding coastal sabkha evolution. Studies of the Abu Dhabi coastal sabkha, particularly from Mussafah Channel, have shown that Holocene carbonates and sabkha evaporites preserve facies stacking patterns, microbial-mediated dolomite, and evaporite overprints, supporting the value of this system as a modern analogue for ancient carbonate-evaporite environments [3,11].

Among the main components of the sabkha sequence, the microbial mat layer is particularly important because microbial processes can influence sediment binding, carbonate precipitation, and dolomite formation. In addition, Ref. [50] examined microbial dolomites

from carbonate-evaporite sediments of the Abu Dhabi coastal sabkha and highlighted their exploration implications for interpreting ancient carbonate systems and dolomite reservoirs.

4.5. Relevance for Geoheritage and Sustainable Conservation

Abu Dhabi Sabkha is not simply a geological curiosity or a sedimentological reference section, it is a functioning natural system in which biological, chemical, and physical processes operate simultaneously and continuously at the Earth's surface. Its inclusion on the UNESCO World Heritage Tentative List formally recognizes this, but recognition alone does not constitute protection. Translating geoheritage significance into meaningful, long-term conservation requires a management framework that is scientifically grounded, institutionally supported, and responsive to the specific vulnerabilities of a hyper-arid coastal environment operating under increasing development pressure. Without such a framework, the features that make the site globally significant—including the intact four-layer sequence, active microbial mats, displacive evaporite structures and fragile salt-crust surfaces—may face irreversible degradation from disturbances that accumulate incrementally but whose consequences are permanent on any practical human timescale.

The sensitivity of the sabkha system to physical disturbance is well established in the literature and deserves to be stated plainly. Sabkha surfaces and their underlying sedimentary structures do not recover quickly from damage. Off-road vehicle movement, foot traffic, excavation, coastal reclamation, road construction, and groundwater extraction can destroy microbial mat integrity, disrupt evaporite crystal growth, collapse sedimentary layering, and alter the subsurface hydrological conditions that drive capillary brine movement and mineral precipitation [2,13,26]. The recovery of disturbed microbial mat communities and evaporite sequences operates over geological rather than human timescales, meaning that physical damage sustained today represents a permanent loss of scientific record. Land-use and land-cover change across the Abu Dhabi coastline documented through multi-temporal remote sensing as involving coastal reclamation, infrastructure expansion, and industrial development has already reduced the spatial extent and connectivity of intact sabkha surfaces in parts of the emirate [12,36]. The area south of Al Dhabaya and Abu Al Abyadh, which hosts the only confirmed four-layer complete sabkha sequence in the world, sits within a coastal zone subject to ongoing planning pressures, and its protection cannot be assumed to follow automatically from Tentative List status alone.

Geoheritage studies consistently demonstrate that scientifically valuable geosites require systematic inventory, condition assessment, protection zoning, regular monitoring, and explicit integration into land-use planning frameworks before significant degradation occurs rather than in response to it [33,40,42]. For Abu Dhabi Sabkha, this means treating the Al Dhabaya and Abu Al Abyadh area not as a passive saline landscape at the margins of coastal development decisions, but as an active geological heritage system requiring the same institutional seriousness afforded to archaeological or biodiversity heritage sites. Practically, this would involve establishing formally delineated protection zones around the complete sabkha sequence, enforcing access controls that distinguish scientific and educational use from unmanaged visitor or vehicle access, and developing a long-term monitoring programme that tracks the physical condition of the microbial mat, evaporite layers, and surface crust integrity at defined intervals. Environmental and heritage impact assessments should be mandatory for any development activity within or adjacent to the sabkha zone, and their findings should carry binding weight in coastal planning decisions.

The sustainable conservation of Abu Dhabi Sabkha also carries a dimension that extends beyond the site itself. As one of the most extensively studied modern analogues for ancient carbonate-evaporite systems globally, the site functions as an open-air scientific laboratory that has informed petroleum geology, sedimentology, geomicrobiology, and

palaeoclimate research across six decades of international scholarship. Protecting it is therefore not only an act of local environmental stewardship but a contribution to the global scientific commons. A site that trains researchers, validates geological models, and advances understanding of processes operating in the rock record over hundreds of millions of years represents a resource whose value is difficult to quantify but whose loss, once it occurs, cannot be undone. The argument for sustainable conservation is in this sense identical to the argument for OUV itself: Abu Dhabi Sabkha represents a geoheritage resource of exceptional scientific significance that warrants long-term protection.

4.6. Quantitative Geosite Assessment

To move beyond a qualitative description of geological heritage value, this section applies a semi-quantitative geosite assessment to Abu Dhabi Sabkha, following the criteria-based scoring approach commonly used in geoheritage evaluation [33]. Five criteria were scored on a four-point scale (1 = low, 2 = moderate, 3 = high, 4 = very high) based on evidence synthesized from the literature reviewed in this paper: representativeness of the carbonate-evaporite process record, rarity of the complete four-layer sequence, integrity of the site under current pressures, scientific knowledge and research use potential, and diversity of geological features present within a single setting. The results are summarized in Table 4.

Table 4. Semi-quantitative assessment of the scientific value of Abu Dhabi Sabkha (adapted from [33]).

Criterion	Score (1–4)	Justification	Key Supporting References
Representativeness	4	Records the full sequence of processes defining coastal sabkha development, from shallow marine sedimentation to evaporite-dominated diagenesis	[8,13]
Rarity	4	Reported as the only known site preserving all four diagnostic sabkha layers in one location	[8]
Integrity	3	Sequence remains largely intact, though coastal development, vehicle access, and groundwater change present ongoing risks	[13,39]
Scientific knowledge and research use potential	4	Sustained body of peer-reviewed research since 1969, used as a modern analogue for ancient carbonate-evaporite reservoirs	[3,11,50]
Diversity of geological features	4	Combines sedimentological, microbial, evaporitic, and hydrogeological features within a single coastal system	[10,13]
Total (out of 20)	19	Interpreted as very high scientific value (band: 17–20 very high, 13–16 high, 9–12 moderate, below 9 low)	

As a second, independent line of evidence, the temporal distribution of peer-reviewed studies specifically addressing the Abu Dhabi coastal sabkha was tabulated by decade of publication (Table 5). This offers a bibliometric proxy for sustained scientific interest and research value, complementing the criteria-based score in Table 4.

Table 5. Temporal distribution of peer-reviewed studies specifically addressing the Abu Dhabi coastal sabkha, cited in this review.

Decade	Number of Studies	Representative Studies (Reference Numbers)
1960s	3	[14,16,34]
2000s	1	[13]
2010s	6	[3,10,11,50]
2020s	1	[39]

The exploratory assessment in Table 4 places Abu Dhabi Sabkha within the very-high category under the adapted scoring scheme applied in this review [8,33]. This simplified

assessment is adapted from Brilha's criteria and is intended as a transparent literature-based screening exercise rather than a substitute for a formal field-based geosite inventory and quantitative assessment Table 5 shows that research attention has been uneven over time, with a strong concentration of studies in the 2010s and comparatively little dedicated process-based research published in the 2020s [39]. This gap is consistent with the knowledge gaps identified later in this review and supports the case for renewed, targeted research investment ahead of any future UNESCO nomination.

5. Geological Heritage Value: The Complete Sabkha Sequence

The geological heritage value of Abu Dhabi Sabkha is inseparable from a single, defining attribute: the preservation of a complete coastal sabkha sequence within one accessible, actively forming, and spatially continuous site. UNESCO highlights the sabkha south of Al Dhabaya and Abu Al Abyadh Islands because it contains all four characteristic layers of a fully developed coastal sabkha system of lagoon mud, microbial mat, gypsum mud, and anhydrite nodules are co-occurring together in one location [9]. Each layer records a distinct environmental stage in the progressive transition from open marine to hyper-arid supratidal conditions, and their co-occurrence has not yet been documented elsewhere in the published literature. Figure 6 illustrates this spatial and stratigraphic progression as a schematic coastal cross-section, showing how the four layers are distributed across the lagoonal, intertidal, and supratidal zones from the Arabian Gulf shoreline inland, with the groundwater table and capillary brine pathways that drive evaporite mineral formation also indicated. The scientific and heritage significance of this sequence lies not in any individual layer considered in isolation, but in the continuity and integrity of the complete record and what it reveals about the coupled interactions between marine sedimentation, biological activity, evaporation, groundwater dynamics, and evaporite mineral formation in arid coastal settings.

The basal lagoon mud layer represents the marine foundation of the sabkha system. Deposited under low-energy, shallow subtidal to restricted lagoonal conditions, it records the earliest phase of the Holocene coastal sequence in which fine carbonate mud and marine-derived sediments accumulated behind the protective screen of Abu Dhabi's barrier island and shoal system. The geochemical and sedimentological character of these lagoonal carbonates dominated by burrowed skeletal-peloidal sands, lime muds, and fine pelleted material reflects the highly restricted circulation, elevated salinity, and warm shallow-water conditions characteristic of the protected lagoons of western and eastern Abu Dhabi [14,34]. These lagoonal deposits are not merely a basal substrate; they are the sedimentary archive of the environmental conditions under which the sabkha system was initiated, and their preservation intact beneath the overlying sequence is essential to the interpretive completeness of the site.

Overlying the lagoonal carbonates, the microbial mat layer marks the transition to intertidal conditions and constitutes the most scientifically consequential component of the entire sequence. Formed by communities of cyanobacteria and associated microorganisms colonizing the upper intertidal zone, microbial mats bind and stabilize sediments, trap fine particles, accumulate organic matter, and exert significant control over early diagenetic mineral precipitation in the surrounding sediment [10,11]. The Abu Dhabi microbial mats are of particular global scientific interest because they have been demonstrated to be sites of active, low-temperature dolomite formation, with Extracellular Polymeric Substances (EPS) secreted by sulfate-reducing bacteria playing a direct facilitating role in dolomite mineralization [10]. This finding is scientifically significant because low-temperature dolomite formation under surface conditions has historically been one of the unresolved problems in sedimentary geology—the so-called dolomite problem—and the Abu Dhabi

microbial mats offer one of the clearest modern demonstrations of a plausible biological mechanism for its resolution [2]. No other coastal sabkha system in the Arabian Gulf has been shown to host microbially mediated dolomite formation at comparable spatial scale or with equivalent stratigraphic context.

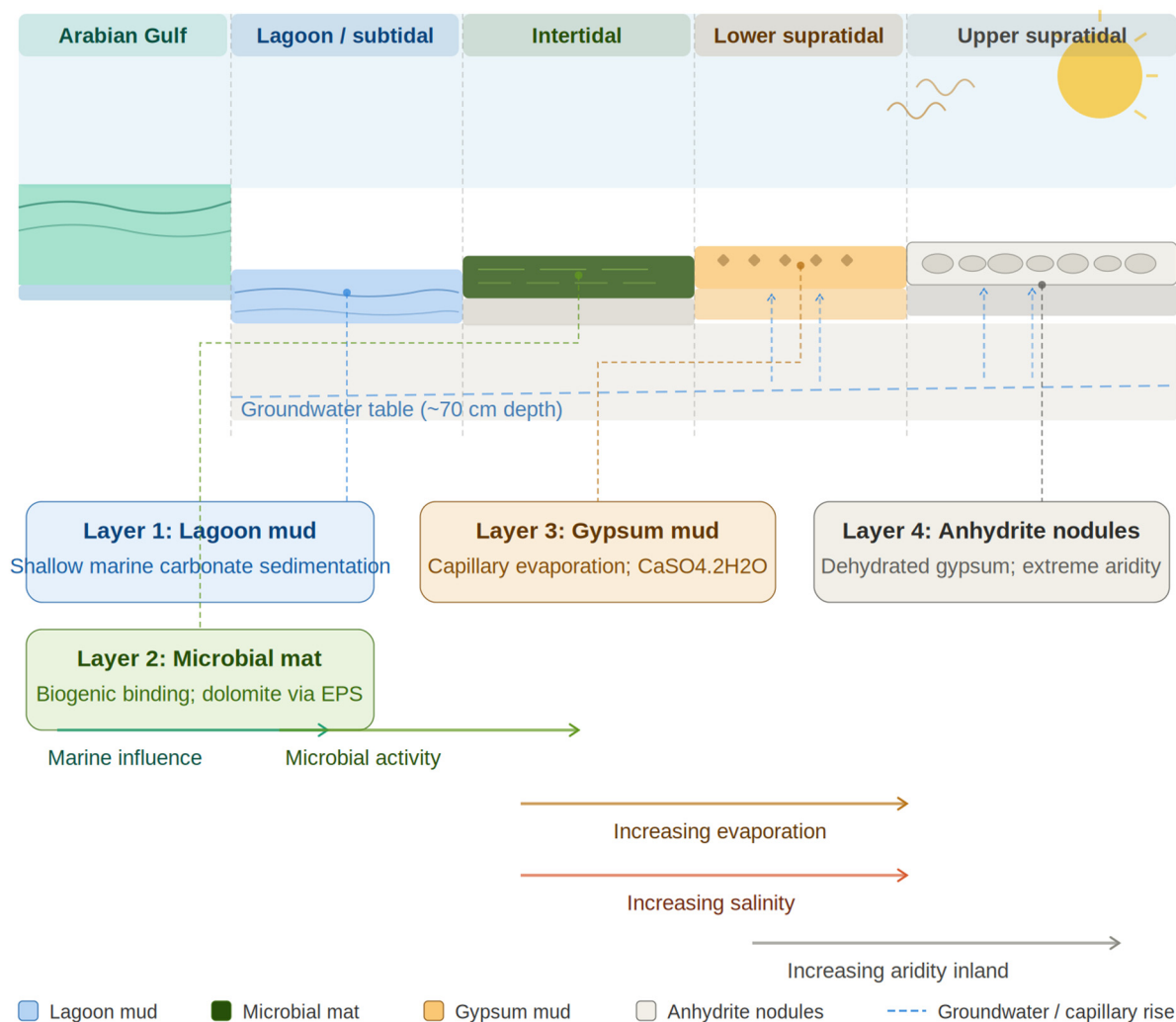


Figure 6. Schematic cross-section of the four-layer Abu Dhabi coastal sabkha sequence, from the Arabian Gulf (left) through lagoonal, intertidal, and supratidal zones to the inland surface (right), showing lagoon mud, microbial mat, gypsum mud, and anhydrite nodules in stratigraphic position. The dashed line marks the groundwater table (~70 cm depth); arrows show capillary brine rise driving evaporite precipitation. Adapted from [2,9,10,14].

The gypsum mud and anhydrite nodule layers together record the supratidal stage of sabkha evolution under conditions of intense evaporation, capillary brine rise, and hyper-saline groundwater interaction. Gypsum mud forms in the lower supratidal zone where surface moisture is still sufficient to maintain hydrated calcium sulfate, while anhydrite nodules develop landward where extreme aridity and elevated temperatures drive the dehydration of gypsum to anhydrite within a carbonate and siliciclastic matrix [2,11,13]. The anhydrite-rich soil developed over a 70 cm-deep water table across Abu Dhabi Emirate has been described as unique in character and occurrence [9], reflecting the specific combination of shallow groundwater, high evaporation rates, and persistent aridity that prevails along this coastline. These evaporite layers are not only indicators of present-day environmental conditions; they are also the primary reason Abu Dhabi Sabkha serves as a globally referenced modern analogue for ancient evaporite formations of considerable

economic importance, including the Permian Khuff Formation, the Upper Jurassic Arab Formation, and the Hith Anhydrite of the Arabian Gulf subsurface [26,49].

Considered as an integrated system rather than a succession of individual layers, the complete four-layer sequence of Abu Dhabi Sabkha provides an unbroken field record of coastal sabkha evolution from open marine sedimentation through biological mat colonization, evaporite mineral development, and advanced supratidal diagenesis are compressed within a single, spatially coherent coastal setting that formed over the last 7000 years [9,14]. This temporal and spatial completeness is what elevates the site above the many other coastal sabkha systems described in the Arabian Gulf literature. It is a record of process, not merely of product: a geological document in which the reader can trace, step by step across a few kilometres of coastline, the full sequence of environmental transitions that have shaped carbonate–evaporite systems throughout Earth history. That is the foundation of its geological heritage value, and it is the reason the scientific community’s investment in its documentation, protection, and formal UNESCO inscription may warrant further consideration based on the scientific evidence summarized here.

6. Microbial Mats, Evaporites, and Carbonate Processes

The importance of Abu Dhabi Sabkha is not limited to the presence of a complete sedimentary sequence. It also lies in the active processes that form, modify, and preserve this sequence. Microbial activity, carbonate sedimentation, evaporite precipitation, salinity variation, and groundwater movement operate together across the shallow marine, intertidal, and supratidal zones. These linked processes make the Abu Dhabi coastal sabkha an important modern analogue for understanding carbonate–evaporite systems in arid coastal environments [2,14,34].

Microbial mats are one of the most important biological components of this system. They commonly develop in intertidal areas where periodic tidal flooding, high salinity, fine sediment supply, and intense evaporation create suitable conditions for microbial growth. Their role in the Abu Dhabi sabkha is especially important because previous studies have linked microbial activity with dolomite formation under hypersaline conditions [10,11].

Evaporite formation represents the chemical response of the sabkha system to strong evaporation and increasing salinity in the supratidal zone, repeated wetting and drying, capillary rise, and evaporative concentration of porewater support the precipitation of gypsum and anhydrite. These minerals record groundwater movement, salinity evolution, and early diagenetic transformation within the sabkha profile [2]. In Abu Dhabi, the development of gypsum mud and anhydrite nodules reflects the progressive transition from intertidal microbial influence to more evaporite-dominated supratidal conditions [9,11].

Carbonate sedimentation is closely connected with both microbial and evaporitic processes. In the lower parts of the sabkha system, carbonate mud is deposited under shallow marine and lagoonal conditions. As the environment becomes more restricted, these sediments are progressively modified by microbial activity, salinity change, evaporite precipitation, and early diagenesis. This relationship between carbonate deposition and evaporite overprint is a defining feature of coastal sabkha development and provides valuable insight into ancient carbonate–evaporite successions [2,14,34].

Overall, microbial mats, evaporite minerals, and carbonate sediments explain the process-based significance of Abu Dhabi Sabkha. They show that the sabkha is not simply a saline coastal flat, but an active geological system shaped by biological, chemical, and physical interactions. Protecting this system therefore requires attention not only to the visible landform, but also to the natural processes that maintain its scientific value and long-term sustainability. So, the disturbance to microbial mats, evaporite surfaces, groundwater movement, or sedimentary layers can affect the natural processes that preserve the sabkha

sequence. Therefore, understanding the environmental sensitivity and human-induced threats to Abu Dhabi Sabkha is essential for developing sustainable conservation and management strategies.

7. Environmental Sensitivity and Human-Induced Threats

Sabkha system is environmentally sensitive due to its geological value, which mainly depends on fragile surface and near-surface processes. Evaporation, shallow groundwater movement, salinity variation, microbial activity, carbonate sedimentation, and evaporite mineral formation process together within a low-gradient coastal setting. Disturbance to any of these processes can affect microbial mats, salt crusts, evaporite layers, groundwater chemistry, and the preservation of the complete sabkha sequence. This is highly notable because the sabkha located south of Al Dhabaya and Abu Al Abyadh Islands is recognized on the UNESCO World Heritage Tentative List for preserving lagoon mud, microbial mat, gypsum mud, and anhydrite nodules within one coastal system [8].

Human activities are among the main pressures on sabkha environments. Urban expansion, road construction, land filling, infrastructure development, and coastal modification can fragment sabkha surfaces and disturb the natural transition from marine to intertidal and supratidal conditions. Sabkha sediments are also geotechnically sensitive because they are commonly saline, weak, moisture-dependent, and corrosive, creating risks for roads, foundations, buried pipelines, and reinforced structures [2]. Recent work from the Abu Dhabi Metropolitan Area shows that low-lying coastal sabkha soils are highly sensitive to sea-level rise and groundwater-related changes, with potential impacts including saltwater intrusion, increased groundwater salinity, soil weakening, and corrosion risks for infrastructure materials [39].

Coastal modification can further disturb the natural balance between tidal exchange, sediment supply, groundwater flow, carbonate deposition, microbial mat development, and evaporite precipitation. Activities such as dredging, reclamation, artificial drainage, and shoreline alteration may change inundation patterns, surface morphology, and shallow groundwater behaviour. Vehicle movement across exposed sabkha surfaces can also cause long-lasting damage by breaking salt crusts, compacting soft sediments, and disturbing microbial mats. Since microbial mats help stabilize sediments and influence carbonate mineralization, their disturbance can reduce both the biological and geological integrity of the sabkha system [2,10,11].

Field observations from the Abu Dhabi coastal sabkha confirm the fragility of these surfaces described above. Figure 7 shows the sabkha crust at close range and across its broader extent, illustrating both its natural texture and the visible marks of disturbance. The crust surface consists of fine, granular salt aggregates that form a continuous but thin cover over the underlying sediment (Figure 7a,e), and this layer breaks apart easily under direct pressure, exposing the softer, moisture-retaining sediment beneath. Vehicle tracks are clearly visible cutting across the crust (Figure 7c), showing how a single pass can leave a lasting scar on a surface that otherwise regenerates slowly under natural evaporative conditions. The broader view of the sabkha flat (Figure 7b) and its margin against the surrounding desert plain (Figure 7d) show how flat and exposed the terrain is, with little natural barrier to limit vehicle access or foot traffic across sensitive zones. These field conditions support the case for controlled access and marked routes discussed later in this review, since even limited, informal use of the surface leaves a visible and long-lasting imprint.

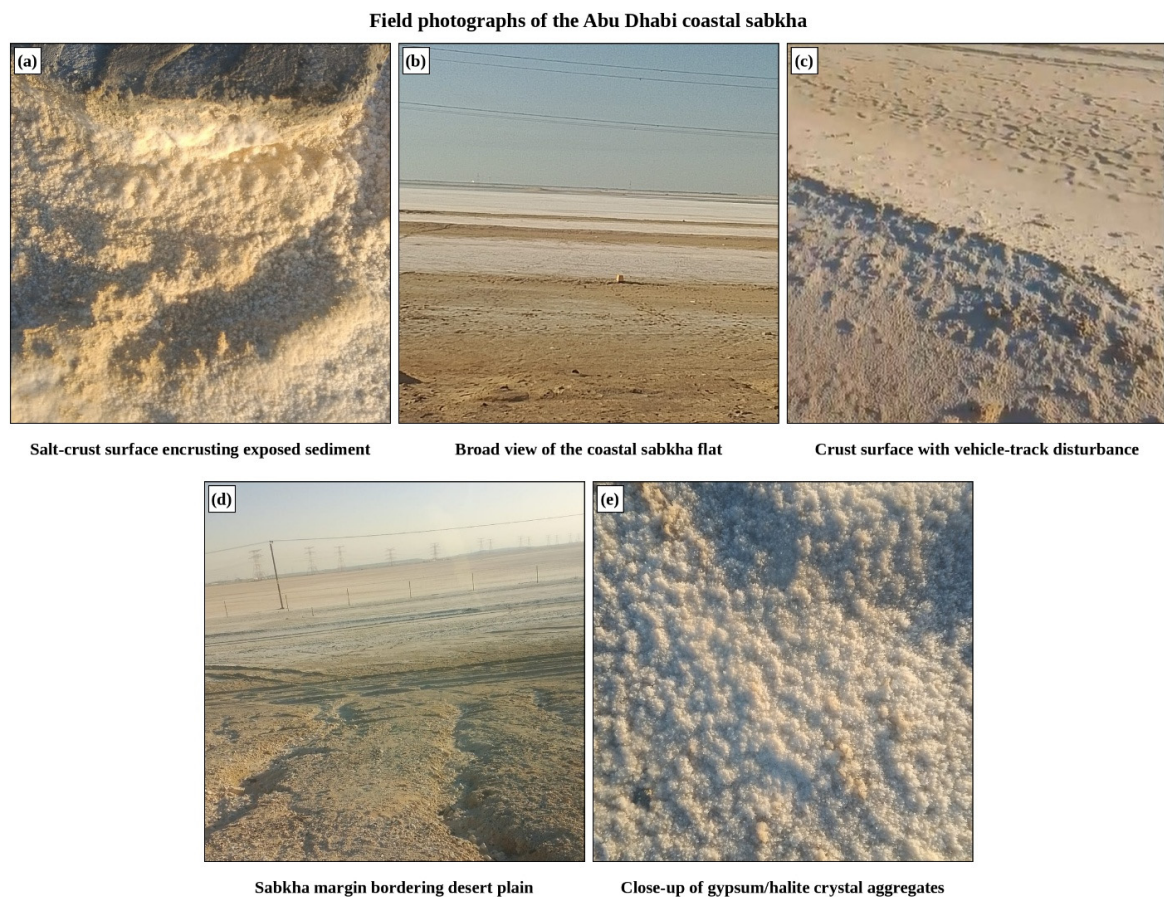


Figure 7. Field photographs of the Abu Dhabi coastal sabkha showing surface crust morphology and human-induced disturbance. (a) Salt-crust surface encrusting exposed sediment. (b) Broad view of the coastal sabkha flat. (c) Crust surface with vehicle-track disturbance. (d) Sabkha margin bordering the desert plain. (e) Close-up of gypsum/halite crystal aggregates. Photographs taken within the Abu Dhabi coastal sabkha field area (approx. 24°00′59.3″ N, 53°52′32.2″ E). (photo taken by the authors).

Groundwater alteration is another major concern because shallow groundwater directly controls many sabkha processes. Changes in groundwater level, flow direction, or salinity can affect capillary rise, salt crust formation, gypsum precipitation, anhydrite development, and near-surface diagenesis. In Abu Dhabi coastal sabkhas, solutes are closely linked to brines, groundwater movement, and evaporation, which makes the system sensitive to hydrological change [2,13]. Pollution should be discussed carefully as a potential pressure rather than a confirmed site-specific impact. Coastal sediment studies from Abu Dhabi have reported increasing heavy-metal contamination trends, with slight arsenic enrichment but generally low overall pollution load [51]. The Environment Agency–Abu Dhabi (EAD) also identifies groundwater salinity increase, declining water levels, and groundwater-quality deterioration as wider environmental challenges in the emirate. In sabkha settings, contaminants may become concentrated in shallow groundwater and surface sediments under strong evaporation, potentially affecting porewater chemistry, microbial communities, and mineral-forming processes [52].

Climate-related pressures should also be considered alongside with human disturbance, coastal modification and groundwater alteration. The 16 April 2024 UAE extreme rainfall event provides a recent example of the country’s exposure to hydrological extremes. This event caused severe flooding, infrastructure disruption, and widespread impacts across the UAE, and also recent studies have predicted that human-driven climate change may increase the likelihood of similar extreme rainfall events in the region [44,53]. For sabkha systems, intense rainfall followed by rapid drying may redistribute salts, disturb

surface crusts, affect microbial mats, and modify near-surface hydrological conditions on the existing surface.

Overall, the main threat to Abu Dhabi Sabkha is not only the physical loss of land surface, but also the disturbance of the natural processes that preserve its geological record. If microbial mats, evaporite crusts, shallow groundwater systems, or sedimentary layers are damaged, the site may lose part of its value as a natural archive of arid coastal evolution. Geoheritage conservation frameworks also emphasize that scientifically valuable geological sites require inventory, assessment, protection, and management rather than passive recognition alone [33,54]. Therefore, future planning around sabkha environments should include environmental impact assessment, geoheritage mapping, groundwater monitoring, climate-risk screening, controlled access, and conservation-based land-use decisions.

8. Sustainable Conservation and Management Pathways

The conservation of Abu Dhabi Sabkha requires a geoheritage management approach because its scientific value depends on fragile surface and near-surface structures. Microbial mats, salt crusts, gypsum mud, anhydrite nodules, shallow groundwater pathways, and carbonate sediments collectively preserve the complete sabkha sequence that supports the site's UNESCO Tentative List significance [2,8]. Damage to these structures through vehicle movement, trampling, construction, drainage alteration, or uncontrolled access may disturb the natural processes responsible for sediment stability, evaporite formation, and long-term geological preservation.

Protection zoning should therefore be considered a key conservation requirement by local authorities. Areas containing well-preserved microbial mats, evaporite crusts, anhydrite nodules, and exposed sedimentary layers should be classified as strict conservation zones with restricted access. Clear signage, visible boundary markers, and site-information boards should be installed to identify sensitive zones and guide visitors away from fragile surfaces. Surrounding areas can serve as buffer zones for research, monitoring, and controlled educational activities. This approach is consistent with geoheritage conservation principles, which emphasize identifying valuable geological features, assessing vulnerability, and managing human access according to site sensitivity [33,40,41].

Controlled access is especially important because many sabkha features are exposed at the surface and can be easily damaged. Vehicle tracks can break salt crusts, compact soft sediments, and disturb microbial mats, while unmanaged access may affect shallow sedimentary layers and evaporite structures. For this reason, marked routes, restricted vehicle entry, boardwalks, designated research access points, and clear warning signs should be installed across sensitive sabkha areas to reduce direct physical disturbance. These measures would help protect the biological and geological integrity of the sabkha while still allowing scientific study and education [10,11,40].

Environmental and heritage impact assessments should also be strengthened for sabkha environments. Environmental impact assessment should consider land-cover change, groundwater level, salinity, tidal influence, surface crust condition, microbial mat integrity, sediment disturbance, and climate-related risks such as flooding and sea-level rise. Heritage impact assessment is also important because it evaluates both direct and indirect effects on heritage values before development decisions are made [55]. This is particularly relevant for Abu Dhabi sabkha environments, where coastal planning must increasingly consider climate risks, including sea-level rise, extreme rainfall, and flooding [44,56].

A long-term monitoring system should be established using remote sensing, drone surveys, field observations, groundwater monitoring, and soil-salinity measurements. These methods can help track vehicle scars, surface crust damage, moisture changes, salt redistribution, microbial mat condition, and coastal change. Monitoring should be

directly linked with management action so that areas showing early signs of disturbance can be protected through access restriction, restoration planning, or revised zoning. This is consistent with wider geoconservation guidance, which treats monitoring as a core requirement for protecting sensitive geological sites [40,41].

Carefully managed educational access can support conservation, but only if protection remains the main priority. Abu Dhabi Sabkha has high educational value because it shows how arid coastal systems form through the interaction of seawater, evaporation, groundwater, microbial activity, carbonate sedimentation, and evaporite precipitation. Guided visits, interpretation panels, digital mapping, virtual tours, and university-led field learning can increase awareness without exposing fragile sabkha surfaces to uncontrolled disturbance. Geoheritage studies also show that education and interpretation can strengthen conservation when they are linked with site vulnerability and visitor management [40,54].

Finally, Abu Dhabi Sabkha should be integrated into coastal planning as a sensitive geoheritage system rather than vacant or marginal land. Site-specific measures such as protection zoning, controlled access, monitoring, and visitor management remain essential for preventing damage to fragile sabkha structures. Integrating these measures into Abu Dhabi coastal planning would help protect the site's geological record while supporting responsible development, research, education, and long-term sustainability.

Figure 8 summarizes the focused methodology of sabkha formation processes, UNESCO geoheritage significance, environmental pressures, monitoring approaches, conservation planning, and future research priorities for Abu Dhabi Sabkha. The framework highlights the required scientific monitoring, field validation, and conservation management for supporting long-term protection of sensitive sabkha environments.

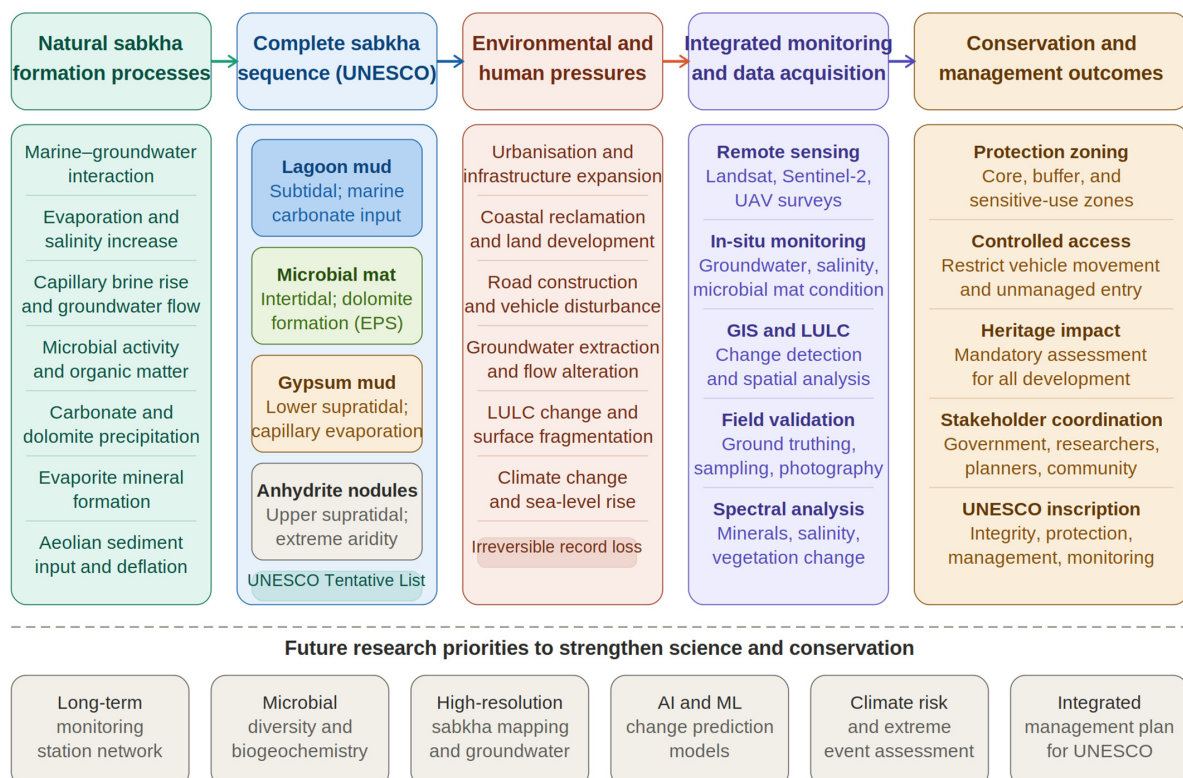


Figure 8. Integrated conceptual framework for the sustainable conservation and management of Abu Dhabi Sabkha, organized across five thematic columns from natural formation processes and the four-layer UNESCO sequence, through environmental pressures, to monitoring and management outcomes. A sixth tier identifies priority research gaps supporting the case for UNESCO inscription. EPS = extracellular polymeric substances; LULC = land-use and land-cover change; ML = machine learning; UAV = unmanned aerial vehicle.

9. Knowledge Gaps and Future Research Needs

Despite the strong scientific and geoheritage value of Abu Dhabi Sabkha, important knowledge gaps remain in relation to long-term monitoring, conservation planning, and future UNESCO nomination readiness. Existing studies have documented the sedimentological, hydrogeological, microbial, and land-cover characteristics of sabkha systems, but these findings have not yet been integrated into a single applied framework for conservation and sustainable coastal management [2,3,11,13]. Future research should therefore connect geology, groundwater behaviour, microbial processes, land-use change, climate risk, and geoheritage protection through a systematic monitoring and management approach.

Abu Dhabi Sabkha is highly sensitive to rapid surface and near-surface changes, including salt-crust breakage, microbial mat disturbance, groundwater-level fluctuation, salinity change, sediment compaction, and evaporite alteration. Such changes may occur after vehicle movement, construction activity, drainage modification, tidal flooding, coastal reclamation, or extreme rainfall. Recent UAE flood studies show that extreme rainfall can cause sudden hydrological impacts, disturb saline surfaces, redistribute salts, and modify shallow groundwater conditions in sabkha environments [44,53]. Therefore, monitoring should be strengthened through regular site observation, continuous instrument-based monitoring, and event-based data collection.

Considering the recent extreme rainfall events in the UAE, a permanent or semi-permanent monitoring station should be established near the sensitive Al Dhabaya and Abu Al Abyadh sabkha area. This station should support regular data acquisition on groundwater level, groundwater salinity, soil salinity, surface moisture, crust stability, microbial mat condition, evaporite mineral changes, sediment compaction, surface temperature, rainfall, tidal influence, vehicle tracks, land-cover change, and shoreline movement. These parameters would help identify both gradual degradation and immediate disturbance after natural or human-induced events.

To support long-term conservation and future UNESCO-oriented management, monitoring should be based on measurable environmental and geoheritage indicators rather than occasional site observations alone. International sabkha studies and UNESCO conservation frameworks show that effective management requires continuous environmental reporting, field validation, spatial monitoring, and documentation of both gradual and immediate disturbance. A government-supported sabkha monitoring programme would provide reliable evidence for conservation planning and management decisions. Such a programme should involve environmental authorities, universities, research centers, coastal planners, geologists, microbiologists, remote-sensing specialists, and heritage managers. Table 6 summarizes recommended monitoring parameters for Abu Dhabi Sabkha based on international sabkha studies, geoheritage principles, and UNESCO management requirements.

Landsat data can support long-term regional monitoring, while Sentinel-2 imagery, drone surveys, high-resolution commercial satellite data, and spectral analysis can help identify smaller changes in sabkha surfaces, salinity zones, shoreline position, and disturbed areas. Recent studies from the Arabian Gulf, UAE, Egypt, and Qatar show that remote sensing, GIS, machine learning, and spectral approaches are effective for mapping LULC change, sabkha distribution, evaporite minerals, soil salinity, and coastal environmental pressure [12,17,35,36,38]. For Abu Dhabi Sabkha, future studies should calculate site-specific change percentages to evaluate monitoring effectiveness and avoid relying only on regional trends.

Microbial mat and carbon-related studies also require greater attention. Previous Abu Dhabi studies have shown the importance of microbial mats in sediment binding, carbonate precipitation, and dolomite formation [10,11]. However, limited work has examined microbial diversity, organic-carbon preservation, carbon cycling, greenhouse-gas

exchange, and possible blue-carbon relevance in coastal sabkha environments. Such studies could improve understanding of how microbial communities support carbonate–evaporite formation and whether sabkha systems contribute to carbon storage under hyper-arid coastal conditions.

Table 6. Recommended monitoring parameters for Abu Dhabi Sabkha based on international sabkha studies, geoheritage conservation principles, and UNESCO-related management requirements.

Monitoring Theme	Recommended Parameters for Abu Dhabi Sabkha	Purpose for Conservation and UNESCO Readiness	Suggested Method	Supporting Citation
Geoheritage integrity	Lagoon mud, microbial mat, gypsum mud, anhydrite nodules, exposed sedimentary layers	To protect the complete sabkha sequence that supports the site’s geological value	Field mapping, photographic records, drone survey, geoheritage inventory	[9,33,40]
Surface condition	Salt crust stability, crust breakage, vehicle tracks, trampling marks, sediment compaction	To detect direct physical disturbance and identify high-risk zones	Drone survey, field GPS mapping, repeat photography, high-resolution imagery	[3,40,41]
Groundwater system	Groundwater level, groundwater salinity, flow direction, capillary rise indicators	To understand hydrological controls on salt formation, evaporite development, and soil stability	Monitoring wells, dataloggers, EC/TDS measurement, groundwater sampling	[13,18,39]
Soil and salinity	Soil salinity, surface moisture, gypsum-rich flats, evaporite mineral distribution	To track salinity change, evaporite behaviour, and sabkha surface sensitivity	Soil sampling, spectral remote sensing, Sentinel-2, field EC measurement	[17,38]
Microbial systems	Microbial mat extent, thickness, colour change, moisture condition, visible damage	To protect microbial processes linked with sediment binding and carbonate transformation	Field survey, close-range photography, drone mapping, laboratory microbial analysis	[10,11]
Carbon and biogeochemistry	Organic carbon, carbonate precipitation, dolomite formation, possible carbon storage indicators	To assess the role of sabkha microbial and carbonate processes in carbon cycling	Sediment sampling, geochemical analysis, microbial and carbonate studies	[2,10,11]
LULC change	Built-up area, roads, reclaimed land, vegetation, water/inundation, exposed sabkha surface	To quantify land-cover transformation and development pressure	Landsat, Sentinel-2, GIS, Random Forest or other machine-learning classification	[35–37]
Coastal dynamics	Shoreline movement, tidal influence, inundation frequency, coastal modification	To assess changes in marine influence and coastal setting	Sentinel-2, Landsat, DEM analysis, tide records, field validation	[12,35,38]
Climate and extreme events	Rainfall, flooding extent, surface ponding, salt redistribution, post-event crust damage	To document immediate effects after extreme rainfall or flooding events	Rain gauges, satellite images, drone survey, rapid field assessment	[44,53,56]
Management pressure	Access routes, visitor movement, construction activity, nearby infrastructure, illegal dumping	To support zoning, controlled access, and impact assessment	Field inspection, drone survey, GIS buffer analysis, annual reporting	[40,41,55]
Reporting and governance	Annual monitoring reports, rapid post-event reports, updated GIS database, risk maps	To provide evidence for government decision-making and future UNESCO nomination preparation	Central database, technical reporting, stakeholder review, public authority coordination	[55]

Future research should also produce high-sensitivity maps for conservation planning. These maps should identify areas with well-preserved microbial mats, fragile salt crusts, gypsum mud, anhydrite nodules, shallow groundwater influence, vehicle disturbance, and high development pressure. Such mapping would support conservation zoning, controlled access, environmental impact assessment, restoration priorities, and visitor management. Proper reporting is also needed. Monitoring results should be compiled into annual technical reports showing changes in LULC, groundwater level, salinity, surface disturbance, microbial mat condition, and climate-related impacts. After major rainfall, flooding, construction, or coastal modification, rapid assessment reports should be prepared to document immediate effects and recommend management action. These reports

would provide transparent evidence for government agencies, researchers, planners, and UNESCO-related conservation planning.

Abu Dhabi Sabkha needs an integrated conservation-management framework that links scientific monitoring with policy action. UNESCO Tentative List status confirms potential heritage value, but future nomination strength depends on integrity, protection, management planning, monitoring, and evidence-based conservation [8,55]. This would help move Abu Dhabi Sabkha from scientific recognition toward stronger conservation readiness and possible future UNESCO consideration.

10. Conclusions

Abu Dhabi Sabkha occupies a singular position in the Earth sciences, not as a marginal saline landscape or a geotechnical constraint on coastal development, but as one of the most scientifically consequential arid coastal systems on Earth's present-day surface. This review has demonstrated that the site preserves, within a single spatially coherent and actively forming coastal setting, the complete progression from shallow marine sedimentation through intertidal microbial colonization to evaporite-dominated supratidal diagenesis under hyper-arid conditions. The co-occurrence of lagoon mud, microbial mat, gypsum mud, and anhydrite nodules in an unbroken stratigraphic sequence at the sabkha south of Al Dhabaya and Abu Al Abyadh Islands reported, as currently recognized, constitutes the only documented example of this completeness, constitutes a geological record of outstanding scientific value and establishes a defensible basis for its recognition as a site of Outstanding Universal Value under UNESCO's natural heritage criteria [9].

The scientific significance of the site extends well beyond its stratigraphic completeness. The discovery of active, microbially mediated dolomite formation within the intertidal mat community, facilitated by Extracellular Polymeric Substances secreted by sulfate-reducing bacteria, has positioned Abu Dhabi Sabkha as the most important modern field laboratory for investigating low-temperature carbonate mineralisation, a process of direct relevance to understanding ancient hydrocarbon-bearing formations across the Arabian Gulf subsurface and beyond [2,10,11]. The site's six decades of continuous scientific investigation, its role as a type locality for Holocene carbonate-evaporite analogue studies, and its recognised relevance to the interpretation of ancient formations including the Permian Khuff, Upper Jurassic Arab, and Hith Anhydrite collectively place it among the most globally referenced coastal geological systems in the literature [26,49,57].

Against this background of exceptional scientific value, this review has documented a set of threats that are neither hypothetical nor distant. Urban expansion, coastal reclamation, road construction, off-road vehicle access, groundwater extraction, and land-use change have already reduced the spatial extent and connectivity of intact sabkha surfaces along the Abu Dhabi coastline, as confirmed by multi-temporal remote sensing analyses [12,36]. The physical sensitivity of sabkha surfaces to disturbance is well established: microbial mat integrity, evaporite crystal growth, sedimentary layering, and subsurface hydrological pathways do not recover on human timescales once disrupted, meaning that incremental damage accumulating under current management conditions represents a permanent and irreversible reduction in the site's scientific and heritage integrity [13,39,44]. The interval between Tentative List recognition and the establishment of comprehensive national protection and management arrangements is particularly important, because degradation during this period may be difficult to reverse.

The conservation pathway this review advocates is therefore not passive stewardship but active, science-based management integrated into the coastal planning framework of Abu Dhabi Emirate. This requires formally delineated protection and buffer zones around the complete sabkha sequence, mandatory heritage and environmental impact assessments

binding on all adjacent development activities, a long-term multi-parameter monitoring programme covering microbial mat condition, evaporite surface integrity, groundwater dynamics, and land-cover change at defined intervals, and sustained coordination among research institutions, environmental authorities, urban planners, and heritage agencies at both national and international levels. These are not precautionary measures in excess of what the evidence demands and they are the minimum response proportionate to the irreplaceable scientific and heritage value the evidence confirms.

Abu Dhabi Sabkha has informed geological science for more than six decades, has shaped the conceptual frameworks used to interpret ancient carbonate-evaporite systems across diverse sedimentary basins worldwide, and continues to generate scientifically significant findings that could not be obtained from any other accessible modern surface site. Protecting it is simultaneously an act of environmental stewardship, a contribution to the global scientific commons, and a recognition that some geological records, once lost, cannot be reconstructed from any other source. The available scientific evidence provides strong support for continued evaluation of Abu Dhabi Sabkha for future World Heritage consideration, subject to UNESCO requirements regarding integrity, protection, management, and monitoring.

Given the pace of urban expansion around Abu Dhabi and the pressures this places on the sabkha, local and regional urban planning strategies need to be brought into closer alignment with UNESCO's guidelines for World Heritage properties, particularly those governing impact assessment and the protection of sites under Tentative List consideration [45,55]. Embedding sabkha protection directly into emirate-level planning frameworks, rather than treating it as a separate conservation exercise, would give Abu Dhabi Sabkha a stronger and more defensible basis for eventual nomination to the World Heritage List [19,40].

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