



Geotechnical Suitability Assessment of Sabkha Soils for Renewable Energy Infrastructure in Eastern Saudi Arabia

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Abstract: Sabkha soils along the Arabian Gulf coast of Eastern Saudi Arabia form one of the most difficult ground environments for renewable energy infrastructure because evaporite cementation, shallow brine, high salinity, variable fabric, and wetting-induced collapse interact over short distances. This review evaluates the geotechnical suitability of these soils for photovoltaic parks, concentrating solar plants, wind farm pads, substations, and transmission corridors. The aim is to synthesise recent evidence from 2020 to 2025 and translate it into a practical decision framework for screening, design, improvement, and operation. A structured narrative methodology was used, drawing on peer-reviewed studies, Saudi case evidence, regional renewable-energy reports, and recent standards-oriented infrastructure literature. The review shows that sabkha suitability cannot be inferred from bearing capacity alone. A defensible assessment must combine stratigraphy, groundwater level, pore-water chemistry, collapsibility, corrosion potential, dynamic response, trafficability, and dust-generation susceptibility. The most critical hazards are loss of salt bonding during freshwater intrusion, differential settlement under lightly loaded but spatially extensive arrays, corrosive attack on steel and reinforced concrete, rutting of maintenance roads, and dust supply from disturbed saline crusts. The paper proposes a tiered suitability model that classifies ground as suitable, conditional, or unsuitable according to coupled hydro-chemo-mechanical indicators. The synthesis supports early avoidance of high-risk sabkha where possible, targeted ground improvement where development is necessary, and monitoring systems that link moisture, salinity, settlement, and soiling to maintenance triggers.

Keywords: Sabkha, Eastern Saudi Arabia, geotechnical suitability, renewable energy infrastructure, solar photovoltaic, wind energy, salinity, ground improvement.

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1. INTRODUCTION

Eastern Saudi Arabia is central to the Kingdom's industrial and energy transition because its coastal and inland corridors host petrochemical cities, ports, grid nodes, and expanding renewable-energy projects. These corridors also contain extensive sabkha terrains, particularly near Al

Khobar, Dammam, Jubail, Ras Al-Khair, and low-lying coastal flats. Sabkha is not a single uniform soil type. It is a saline, evaporitic ground system composed of sands, silts, clays, gypsum, anhydrite, halite, carbonate fragments, shallow brine, and alternating cemented and loose layers. Recent regional reviews describe these soils as highly variable, often weak,

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compressible, corrosive, and sensitive to water chemistry [1].

Renewable-energy assets impose a different demand pattern from conventional buildings. Photovoltaic arrays and electrical yards apply relatively small loads, but they cover very large footprints and depend on strict alignment, cable integrity, and all-weather access. Wind turbines impose larger cyclic and dynamic loads through pads, crane hardstands, and deep foundations. Transmission lines introduce isolated tower reactions across long corridors. In each case, localised weak zones can govern serviceability even when average ground parameters appear acceptable. Studies on reclaimed and coastal land in Eastern Saudi Arabia show that groundwater fluctuation, inappropriate earthwork, heterogeneous fill, and insufficient geotechnical control can compromise infrastructure performance [2].

The topic has become more urgent because national energy policy is accelerating solar and wind deployment, while land-degradation and extreme-weather risks are receiving stronger attention in infrastructure planning [13-18]. At the same time, dust soiling is a measurable operating loss for solar plants in Saudi Arabia and the wider MENA region [9-12]. Sabkha soils sit at the intersection of these concerns: they can supply dust after crust disturbance, they can collapse or soften after wetting, and their salts can corrode foundations and electrical grounding systems. This review therefore asks how sabkha ground should be assessed before renewable-energy development and what mitigation logic is most appropriate for Eastern Saudi Arabia.

2. AIM AND OBJECTIVES OF THE REVIEW

The aim of this review is to develop a publishable, evidence-based synthesis of geotechnical suitability assessment for sabkha soils supporting renewable-energy infrastructure in Eastern Saudi Arabia. The first objective is to identify the dominant geological, chemical, hydraulic, and mechanical properties that control sabkha behaviour. The second objective is to connect these properties to the serviceability requirements of photovoltaic, concentrating solar, wind, substation, and transmission assets. The third objective is to propose a practical indicator framework that can be used during desk study, field investigation, laboratory testing, design, and operation. The fourth objective is to identify risk-reduction measures that are technically appropriate, sustainable, and adaptable to site-specific constraints.

This review is deliberately framed as a practice-oriented review rather than a laboratory study. It does not claim that one improvement

method suits all sabkha formations. Instead, it recognises that saline crusts, clayey pockets, calcareous sand, reclaimed layers, and shallow brine produce different failure mechanisms. The value of the review lies in integrating recent sabkha research, renewable-energy performance studies, salinity mapping, and geotechnical monitoring into a coherent suitability logic.

3. METHODOLOGY

A structured narrative review method was adopted. Searches were organised around four domains: sabkha soil properties, renewable-energy infrastructure requirements, Saudi and Gulf coastal ground conditions, and modern ground-improvement or monitoring tools. The principal search terms included sabkha, saline soil, Eastern Saudi Arabia, Ras Al-Khair, Al-Khobar, Jubail, geotechnical behaviour, collapse, salinity, sodicity, photovoltaic soiling, wind foundations, ground improvement, deep soil mixing, geopolymer treatment, remote sensing, and infrastructure resilience. Priority was given to publications and reports from 2020 to 2025, with older foundational concepts used only indirectly where recent papers relied on them.

The inclusion criteria were: relevance to sabkha or saline arid ground; explicit connection to strength, compressibility, chemistry, monitoring, or infrastructure performance; availability of interpretable methods or design implications; and publication within the requested date range. Exclusion criteria were: purely agricultural salinity studies without engineering interpretation, construction papers without ground data, papers outside the time range, and materials that offered no traceable technical basis. Data were extracted under six headings: site context, soil fabric, pore-water chemistry, geotechnical response, infrastructure implication, and suitability or mitigation recommendation. This approach allowed evidence from different disciplines to be compared without forcing a single statistical model onto heterogeneous studies.

3.1. Evidence Appraisal and Synthesis Logic

The evidence was appraised using a relevance and applicability lens. Laboratory studies were considered stronger when they reported sampling condition, salinity state, compaction procedure, curing period, wetting path, and measured deformation. Numerical studies were treated as useful when model calibration was described and when the simulated boundary conditions resembled construction practice. Policy and renewable-energy reports were used for context, not for deriving geotechnical thresholds. Where findings differed, the review placed more weight on

mechanisms that were repeated across studies: dissolution of evaporite bonds, compressibility under wetting, chemical aggressiveness, and deterioration of working platforms after traffic or storm events. This appraisal prevents the review from converting isolated test values into universal design rules.

The synthesis followed a mechanism-to-decision sequence. Each hazard was first linked to a controlling driver, such as fresh-water intrusion, shallow groundwater, high soluble salts, fine-particle dispersion, cyclic traffic, or wind exposure. The driver

was then linked to a measurable indicator and finally to a design or operational decision. For example, wetting-induced collapse is linked to collapse potential, groundwater fluctuation, and salt content; the decision may be avoidance, deep foundations, prewetting, replacement, or improvement. Dust soiling is linked to crust integrity, surface disturbance, and wind exposure; the decision may be road surfacing, restricted traffic, stabilised shoulders, robotic cleaning, or adjusted cleaning triggers. This chain is the core contribution of the review.

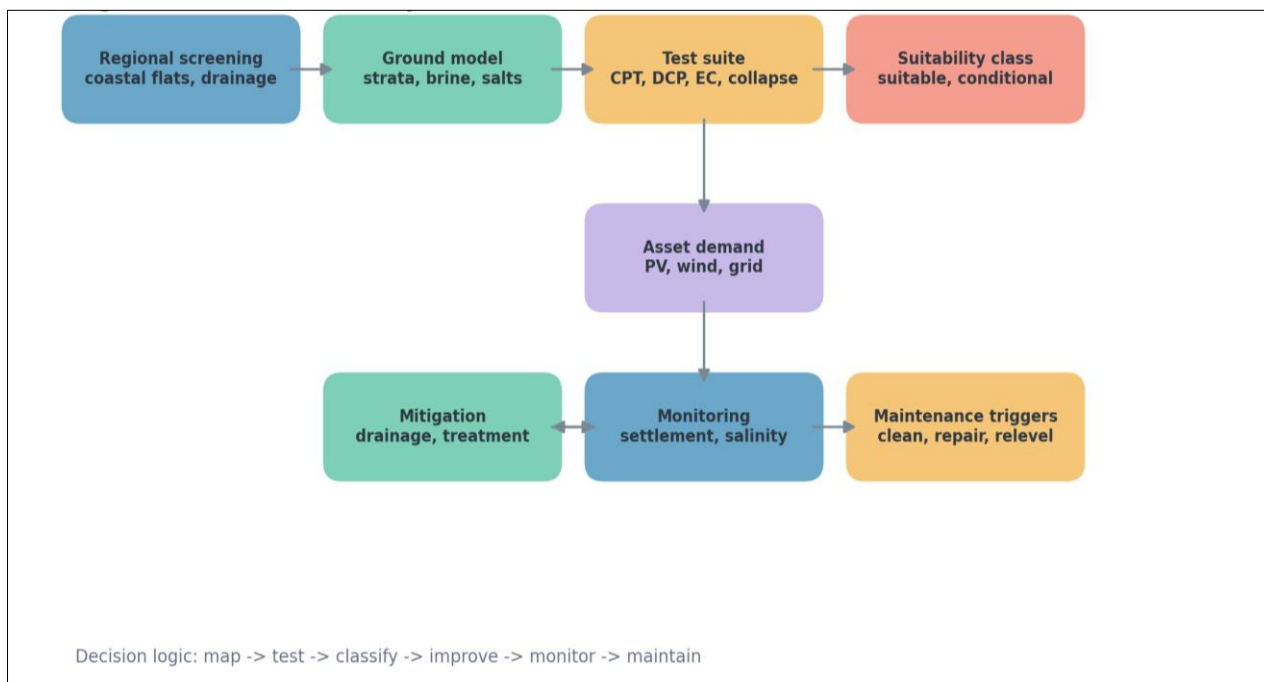


Figure 1: Conceptual workflow linking sabkha screening, field testing, suitability classification, mitigation, monitoring, and maintenance triggers

Table 1: Review method and evidence extraction structure

Review element	Specification	Purpose
Scope	Sabkha soils, Eastern Saudi Arabia, renewable-energy assets, and associated infrastructure corridors.	Keeps the review focused on engineering suitability rather than general soil salinity.
Evidence window	Studies, reports, and technical evidence published from 2020 to 2025.	Matches the requested contemporary citation range.
Core variables	Stratigraphy, groundwater, EC, chloride, sulfate, SAR, collapse potential, CBR, DCP, CPT, settlement, and corrosion exposure.	Links soil state to asset performance.
Outputs	Suitability classes, hazard mechanisms, investigation requirements, and mitigation options.	Translates the review into design and operation decisions.

4. Geological and Engineering Character of Sabkha in Eastern Saudi Arabia

Eastern Saudi sabkha forms through interaction between low relief, high evaporation, saline groundwater, marine transgression history, and aeolian sediment supply. The resulting ground profile may contain a brittle salt crust at the surface,

loose silty sand below, clayey lenses, evaporite-rich horizons, and shallow saline water. The soil may show apparent strength when dry because salt and carbonate bonds create temporary cementation. However, this apparent strength is not equivalent to durable engineering strength. When fresh water, storm runoff, leaking utilities, or construction water

dissolves evaporite bonds, the soil fabric can loosen and settlement can accelerate [1-3].

The most important feature is heterogeneity. Boreholes only a short distance apart may encounter different proportions of sand, silt, clay, gypsum, and halite. This spatial variation is critical for renewable-energy sites because large arrays depend on repeatable pile or anchor performance across thousands of support points. A micro-zonation study from Ras Al-Khair confirms that saline sabkha may show anomalous seismic and dynamic behaviour and therefore requires site-specific zoning rather than transfer of generic parameters [6].

A second defining feature is the coupling between chemistry and mechanics. High electrical conductivity indicates saline pore fluid; sodium adsorption and exchangeable sodium influence dispersion; sulfates and chlorides influence corrosion and cement performance. Studies of sandy sabkha also indicate that compaction can improve shear strength and bearing response, but improvement may be lost if wetting, leaching, or capillary rise changes the salt structure [3]. Consequently, investigation programmes must sample and test soil with field brine conditions wherever possible, not only with distilled water or fully remoulded specimens.

5. Infrastructure Demand from Renewable-Energy Assets

Photovoltaic arrays typically use driven piles, screw anchors, shallow pads, or ballast systems. Their individual loads are modest, but settlement tolerances are tight because row alignment affects tracker operation, cable strain, drainage, and maintenance access. Concentrating solar systems are even more alignment-sensitive because mirrors or heliostats require accurate orientation and clean reflective surfaces. Wind turbines have higher bearing, overturning, fatigue, and dynamic requirements; crane platforms and heavy transport roads may govern the geotechnical design as much as the turbine foundation. Substations and transmission corridors introduce corrosion, grounding resistance, cable trench stability, and service road performance as additional suitability concerns.

These asset classes also create ground disturbance. Grading, trenching, repeated vehicle movements, drainage concentration, and vegetation removal can break the saline crust and expose fine particles. This creates a feedback loop: disturbed sabkha may supply dust, dust reduces solar output, more cleaning traffic increases surface disturbance, and surface disturbance increases rutting and erosion. Saudi photovoltaic soiling studies show that dust accumulation can materially reduce module

performance and that mitigation requires both cleaning strategy and environmental understanding [9]. Regional reviews similarly identify dust accumulation as a persistent constraint in dryland photovoltaic development [10, 11].

5.1. Asset-Specific Design Interpretation

For fixed-tilt photovoltaic fields, geotechnical design is often governed by constructability and repeated small tolerances rather than ultimate bearing failure. Pile refusal in cemented crust, loss of lateral resistance in loose wet sand, and variable pull-out capacity can all occur within one array block. A rational design should therefore group pile test zones by geomorphic unit and chemical condition, not merely by project boundary. Trial installation, axial tension testing, lateral testing, and post-wetting checks should be considered before full production piling. Where ballast blocks are used, the designer should evaluate bearing stress, scour, uplift stability, and the risk of salt crystallisation or dissolution below shallow slabs.

For single-axis trackers and concentrating solar systems, differential movement deserves additional attention. Even small angular changes can reduce tracking accuracy, increase actuator loads, and damage drive components. The ground solution should therefore limit both total and differential settlement. In conditional sabkha, a uniform granular working layer may reduce short-term variability but may not prevent collapse below the improved zone. Where the weak layer is shallow, replacement and compaction may be adequate; where it is deep or saturated, pile solutions, geosynthetic-reinforced platforms, or soil mixing may offer better lifecycle performance.

For wind infrastructure, foundation suitability must consider cyclic stiffness, damping, resonance avoidance, and construction logistics. Heavy crane movements can be more damaging than operational turbine loads because they occur during construction when drainage may be incomplete and traffic is concentrated. Crane pads and access roads should be designed as engineered pavements with moisture control, not temporary tracks. Where sabkha is interbedded with dense calcareous sand, differential stiffness can also create uneven stress transfer. Dynamic response parameters from local geophysical and laboratory testing should therefore support the final foundation model [6].

Transmission and substation works are especially sensitive to corrosion and shallow excavations. Tower pads can be moved slightly to avoid the worst ground, but substations require a compact site with strict tolerance for slabs, ducts, grounding grids, transformer rails, and drainage.

Salinity, sulfate, chloride, and resistivity measurements should be mapped in three dimensions. The design should also consider accidental water release, firefighting water, and storm ponding. These events may convert a stable crusted surface into a softened or collapsing subgrade within a short period.

6. Hydro-Chemo-Mechanical Hazards Controlling Suitability

The first hazard is wetting-induced collapse. In dry conditions, salt, carbonate, and gypsum bonds hold an open structure. Once dissolved, the skeleton loses support and particles rearrange. This can produce differential settlement under foundations, pile groups, inverter slabs, and cable trenches. Eco-friendly lime and geopolymer studies demonstrate that the bearing and deformation behaviour of collapsible sabkha can be improved, but they also show that treatment geometry, binder dosage, and treated depth must match the load path [4-7].

The second hazard is low bearing capacity and high compressibility. Natural sabkha may appear competent at the surface while containing soft layers below. This is especially problematic for wind farms and substations because load concentration and long service life amplify small errors in site characterisation. A recent geopolymer study showed that treated layers can improve ultimate bearing capacity, but inappropriate treated diameter or thickness may still limit performance [7]. Deep soil mixing studies also indicate that improved walls or columns can support excavations and foundations if excavation depth, stiffness contrast, and reinforcement are accounted for [5].

The third hazard is corrosion. Chlorides, sulfates, high total dissolved solids, and shallow brine can attack steel piles, reinforcement, grounding grids, and buried connections. Corrosion risk is not merely a durability issue; it can also affect electrical safety and maintenance reliability. Suitability assessment should therefore include chemical testing, resistivity, groundwater depth, and materials design. Protective measures may include corrosion-resistant alloys, coatings, cathodic protection, sulfate-resistant concrete, pozzolanic binders, geomembranes, capillary breaks, and drainage control.

The fourth hazard is erosion, crust breakage, and dust supply. Sabkha crusts may reduce dust emission while intact but become fragile after construction traffic or wetting-drying cycles. Solar

developments are particularly exposed because the economic penalty of soiling can be continuous rather than episodic. Saudi and regional studies show that dust storms, dry deposition, tilt angle, rainfall absence, and cleaning frequency strongly influence energy yield [9-12]. Thus, geotechnical suitability should include not only subgrade strength but also surface stability, access-road design, and dust-control planning.

7. Suitability Indicators and Investigation Strategy

A suitable investigation strategy should progress from regional screening to asset-specific confirmation. Remote sensing and available geological mapping help identify low-lying sabkha, drainage paths, salt crusts, reclaimed land, and disturbed surfaces. Recent work on salinity mapping in Jubail demonstrates that combining field electrical conductivity with spatial modelling can support hazard identification in Eastern Province settings [20]. Such methods should not replace boreholes or in-situ testing, but they improve the targeting of intrusive investigations.

Field testing should include boreholes, trial pits, cone penetration testing where access permits, dynamic cone penetration for roads, plate-load testing for pads, groundwater monitoring, and electrical resistivity for salinity and corrosion mapping. Laboratory testing should include gradation, Atterberg limits, sulfate and chloride content, EC, pH, organic content where relevant, compaction, CBR, direct shear or triaxial strength, consolidation, collapse potential, swell potential, permeability, and chemical compatibility with proposed binders. Dynamic and geophysical assessment is recommended for wind turbines, major substations, and sites near reclaimed industrial zones because weak saline strata may not respond like ordinary sands under cyclic loading [6].

The interpretation should classify land into three geotechnical suitability categories. Suitable areas have low salinity influence, deeper groundwater, limited collapsibility, adequate density, low corrosion exposure, and manageable dust risk. Conditional areas require improvement, drainage, monitoring, or asset-specific foundation design. Unsuitable areas include highly compressible or wet sabkha, zones with shallow aggressive brine, active flooding, severe collapse potential, and areas where mitigation would exceed the economic or environmental value of development.

Table 2: Suitability indicators for renewable-energy development on sabkha soils

Indicator group	High-risk signal	Design implication
Groundwater and salinity	Shallow brine, high EC, high sulfate or chloride, low resistivity.	Raise platforms, control drainage, protect concrete and steel, and monitor chemistry.
Compressibility and collapse	Open fabric, high void ratio, collapse upon wetting, weak cemented crust.	Use avoidance, replacement, prewetting, piles, soil mixing, or geopolymer treatment.
Strength and trafficability	Low CBR, high DCP penetration, soft lenses, rutting after wetting.	Reinforce access roads, add geosynthetics, improve base layers, restrict wet-weather traffic.
Surface stability and dust	Broken salt crust, exposed fines, wind corridors, repeated cleaning traffic.	Stabilise roads, protect crusts, use targeted cleaning, and reduce unnecessary disturbance.
Asset sensitivity	Trackers, mirrors, turbine pads, substations, or cable trenches with tight tolerance.	Adopt asset-specific limits for settlement, rotation, corrosion, alignment, and access.



Figure 2: Asset-hazard screening matrix showing relative risks for common renewable-energy and grid assets on sabkha terrain

7.1. Proposed Suitability Scoring Logic

The proposed suitability model uses five weighted groups rather than one global score. The first group is geological reliability, covering thickness of sabkha, stratigraphic continuity, variability between boreholes, and presence of buried soft lenses. The second group is hydrochemical aggressiveness, covering groundwater depth, seasonal fluctuation, EC, sulfate, chloride, SAR, and resistivity. The third group is mechanical serviceability, covering CBR, DCP index, cone resistance, compressibility, collapse potential, and cyclic stiffness where relevant. The fourth group is surface process risk, covering flooding, erosion, crust fragility, dust source potential, and maintenance-road disturbance. The fifth group is constructability, covering equipment access, availability of brine-

compatible testing, feasibility of compaction, and ability to maintain drainage after commissioning.

A site should not be upgraded to a more favourable class simply because one group performs well. For example, a dense crust with good penetration resistance remains conditional or unsuitable if aggressive groundwater lies near foundation depth. Similarly, a low-salinity inland site may be conditional if collapse potential is high or if access roads cross wet depressions. The scoring logic is therefore conservative: the poorest critical group controls the preliminary classification unless design evidence demonstrates that the mechanism has been neutralised. This approach is appropriate for renewable-energy assets because serviceability problems may interrupt operation even when collapse or structural failure does not occur.

The model also encourages staged decision-making. At feasibility stage, developers can use geological maps, satellite images, drainage information, and limited testing to avoid obvious high-risk zones. At preliminary design, targeted boreholes, geophysics, and laboratory chemistry refine the zoning. At detailed design, load tests, improvement trials, corrosion design, and drainage modelling confirm treatment. During operation, settlement, moisture, salinity, dust, and rutting data are fed back into the maintenance plan. This staged process reduces uncertainty progressively and avoids late discovery of unsuitable ground after procurement commitments have been made.

8. Ground-Improvement and Design Options

Mitigation should follow a hierarchy: avoid, minimise, improve, protect, and monitor. Avoidance is preferable where sabkha is thick, saturated, chemically aggressive, or environmentally sensitive. If development must proceed, the first design priority is water control. Positive drainage, lined channels, raised platforms, capillary breaks, and controlled construction water reduce the risk of salt dissolution and collapse. Drainage design must avoid simply transferring saline runoff to adjacent foundations or cable trenches.

For lightly loaded solar arrays, improvement may involve shallow replacement, controlled compaction, geogrid-reinforced working platforms, granular capillary breaks, screw piles extending beyond weak crusts, or micropiles in highly variable zones. For access roads, stabilised base layers, geotextiles, geocells, and drainage shoulders can reduce rutting and fines pumping. For wind turbines and substations, deeper solutions may be needed. Deep soil mixing, stone columns, preloading, surcharging, grouting, and geopolymer or lime stabilisation are possible, but their use must be validated against saline chemistry and wetting cycles [4-29].

Sustainability considerations should be explicit. Cement-rich treatment can improve strength but carries carbon cost. Geopolymer and recycled aggregate options may reduce embodied emissions where local supply chains are reliable and durability is verified [7, 8]. Renewable-energy projects should avoid treating the entire site uniformly when only roads, inverter pads, pile lines, and drainage nodes control risk. Targeted improvement reduces cost, emissions, and unnecessary ground disturbance.

8.1. Sustainability and Land-Management Implications

The geotechnical solution should not be separated from land stewardship. Renewable-energy projects are intended to reduce carbon intensity, but

poorly located projects can increase erosion, dust, brine migration, and material consumption. Recent land-management guidance emphasises that renewable-energy siting should avoid unnecessary degradation and should prefer already modified or low-impact land where feasible [14]. In sabkha terrain, this means that engineering feasibility should be considered alongside hydrological connectivity, coastal sensitivity, construction water demand, access-road density, and the possibility of restoring disturbed areas after construction.

Water is a critical constraint. Cleaning solar panels with water may improve energy yield but can also add moisture to saline ground, dissolve salts, and create local softening if runoff is poorly controlled. Dry or robotic cleaning can reduce water demand, but it may change maintenance traffic and abrasion patterns. The optimal choice is therefore site-specific. On highly collapsible sabkha, the design may favour waterless cleaning, lined collection points, and controlled discharge. On better-drained sandy sabkha, periodic washing may be acceptable if drainage and salt movement are managed.

Material selection also has sustainability implications. Conventional cement stabilisation is familiar and effective, yet cement production has high embodied carbon. Geopolymer binders, recycled aggregates, industrial by-products, and targeted geosynthetic solutions may reduce emissions, but only where local quality control and durability are demonstrated [7, 8]. A low-carbon treatment that fails under saline wetting is not sustainable; it simply transfers cost and emissions to future repairs. The preferred design is the least intrusive treatment that reliably satisfies the asset's performance requirement.

9. Monitoring, Maintenance, and Operational Control

Long-term performance on sabkha depends on monitoring because risk changes with groundwater, rainfall, leakage, traffic, and dust events. A practical monitoring plan should record settlement at representative foundations, moisture and groundwater level, salinity or resistivity at corrosion-sensitive zones, rut depth on access roads, dust deposition on modules, and the condition of drainage paths. Renewable-energy resilience guidance increasingly emphasises quality infrastructure, weather readiness, and continuous operation under extreme events [13-16].

Monitoring should be linked to triggers. For example, settlement beyond tracker tolerance should require survey verification and foundation adjustment. Rising groundwater or falling resistivity should trigger corrosion inspection and drainage

review. Rutting beyond maintenance thresholds should prompt road reinforcement before heavy component transport. Dust deposition after storms should trigger cleaning only where expected energy recovery justifies water or robotic cleaning costs. Such trigger-based operation is more defensible than fixed maintenance intervals because sabkha behaviour is controlled by episodic wetting, brine movement, and surface disturbance.

10. DISCUSSION

The review indicates that sabkha suitability for renewable-energy infrastructure is a multi-criteria problem rather than a single bearing-capacity question. The same site may be suitable for fixed-tilt photovoltaic piles after shallow improvement but unsuitable for a substation without deep treatment and corrosion protection. Conversely, a site with difficult chemistry may still be manageable if groundwater is deep, drainage is well controlled, and assets are lightly loaded. This reinforces the need for asset-specific suitability classes.

The main evidence gap is the limited availability of long-term field performance data from Saudi renewable-energy assets built directly on sabkha. Laboratory and numerical studies provide valuable guidance, but real projects involve construction traffic, material variability, seasonal salt movement, and evolving maintenance practices. Future studies should combine instrumented pilot foundations, remote sensing, dust monitoring, and lifecycle cost data. Artificial intelligence may assist zonation and predictive maintenance, but it should remain interpretable and grounded in geotechnical testing rather than replacing site investigation [22].

10.1. Procurement and Risk Allocation

A further practical issue is procurement. Renewable-energy projects are commonly delivered through fast engineering, procurement, and construction schedules, and geotechnical investigation may be compressed to protect programme milestones. Sabkha conditions make this approach risky because early unit rates for piles, roads, drainage, and corrosion protection may be based on incomplete ground models. Tender documents should therefore require minimum investigation densities, chemical testing methods, groundwater observation periods, trial improvement panels, and acceptance criteria for treated ground. They should also allocate responsibility for changes caused by saline groundwater, collapse during wetting, or unexpected soft lenses. Without these clauses, contractors may optimise for short-term installation speed rather than long-term serviceability. A suitability assessment is therefore not only a technical study; it is a risk allocation tool. It converts uncertain ground behaviour into

measurable requirements that can be priced, verified, and monitored. For developers, this reduces the chance that renewable-energy infrastructure inherits the same problems historically observed in reclaimed coastal construction, where serviceability defects often appear after handover and are expensive to correct.

The same requirement applies to operation. If the owner receives only as-built drawings and no geotechnical monitoring baseline, later settlement, salinity, or dust problems become difficult to diagnose. Handover should include baseline settlement markers, road condition surveys, groundwater readings, salinity maps, drainage inspection points, and a schedule for repeating critical measurements during the first two years of service. This information allows maintenance teams to distinguish between isolated construction damage and progressive geotechnical deterioration. It also supports transparent reporting to lenders and regulators because observed ground performance can be compared against the assumptions used at financial close and commissioning. Such continuity is especially valuable in sabkha, where water, salts, traffic, and wind can alter risk after construction appears complete. It protects performance, safety, capital, credibility, and durability.

10.1. Research Agenda for Eastern Saudi Arabia

A focused research agenda is needed for the next generation of Saudi renewable-energy projects on difficult ground. First, full-scale pile and anchor tests should be performed in representative sabkha units before and after controlled wetting. These tests would show how installation disturbance, brine chemistry, and lateral cyclic loading affect pull-out and serviceability. Second, long-term test sections of access roads should compare granular replacement, geocells, geogrids, stabilised bases, and capillary-break layers under repeated maintenance traffic. Third, corrosion exposure stations should measure steel loss, concrete durability, grounding resistance, and coating performance under local salinity and temperature cycles.

Fourth, dust-generation research should connect geotechnical surface indicators with photovoltaic soiling. Measuring crust shear strength, fine-particle content, wind exposure, and module deposition at the same site would allow operators to target road surfacing and cleaning more intelligently. Fifth, remote sensing and geophysical datasets should be calibrated with boreholes, chemistry, and settlement observations so that hazard maps express uncertainty rather than simple colour classes. Finally, lifecycle assessment should compare avoidance, shallow improvement, deep foundations, and binder-intensive stabilisation in terms of cost, carbon, water

demand, energy availability, and maintenance interruption. This evidence would help regulators and developers choose solutions that are both technically reliable and environmentally defensible.

11. CONCLUSIONS

Sabkha soils in Eastern Saudi Arabia can support renewable-energy infrastructure only when their coupled geological, chemical, hydraulic, and mechanical behaviour is properly assessed. The key risks are wetting-induced collapse, variable bearing capacity, aggressive salinity, corrosion, crust disturbance, access-road rutting, and dust generation. A robust suitability assessment should combine regional mapping, intrusive investigation, chemical testing, collapse and swell evaluation, geophysical or dynamic assessment where needed, and asset-specific performance criteria.

The proposed framework classifies sites as suitable, conditional, or unsuitable based on measurable indicators rather than generic soil names. For suitable sites, standard foundations with drainage and corrosion detailing may be adequate. For conditional sites, targeted improvement, capillary control, geosynthetics, deep soil mixing, geopolymer treatment, or reinforced platforms may be justified. For unsuitable sites, avoidance or relocation is more sustainable than excessive treatment. This conclusion is consistent with recent renewable-energy land-management guidance, which argues that the energy transition should not create new land degradation where better siting and design are available [14]. In Eastern Saudi Arabia, the most successful renewable-energy projects on sabkha will be those that treat ground performance as an operational variable, not a one-time construction assumption.

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