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Original Research Paper

Agricultural Utilization of Sand Dunes in South Kuwait: A Review of Soil Reclamation Techniques and Sustainable Practices

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Abstract

The southern area of Kuwait experiences its extreme dry climate through its desert environment which features active sand dunes as its main ecological challenge. The extreme environmental conditions which include less than 120 millimeters of yearly rainfall and summer temperatures that reach above 45 degrees Celsius and the presence of calcareous soils with no organic matter and gravelly texture have resulted in growing interest to convert these damaged dune areas into agricultural fields which people consider necessary for food security. The study presents current and past research on soil reclamation methods that researchers use to restore south Kuwait's sandy dune areas. The study investigates four main techniques which include biochar application and organic and composite material use and mechanical and biological dune stabilization and windbreak installation and halophyte planting and bio-saline agricultural methods. The Kuwait Institute for Scientific Research (KISR) trials show that biochar-based soil conditioners increase crop yield by 50% and decrease irrigation water needs by 25% and lower fertilizer requirements by 40% in Kuwait's sandy soils. Research studies from around the world show that using composite amendments in sandy soils results in a 92% increase in crop yield and a 59% increase in soil organic carbon (SOC) content. Salicornia bigelovii and Atriplex species serve as valuable native halophytes which enable bio-saline agriculture through brackish-water irrigation systems. The most effective sustainable agricultural methods combine soil amendment with dune stabilization and water-efficient irrigation and salt-tolerant crop selection. The research paper develops an evidence-based framework which supports policymakers and agricultural scientists and land managers who work on food security and land rehabilitation initiatives in Kuwait and the wider region.

Keywords: sand dune reclamation; arid agriculture; Kuwait; biochar; halophytes; soil amendment; bio-saline agriculture; desertification; food security; Wafra

1. Introduction

The State of Kuwait faces ongoing food security problems because its population depends on international food imports for 90 percent of their food needs which results from the country's limited agricultural land and freshwater resources (Food and Agriculture Organization [FAO], 1967). Kuwait consists of desert areas that contain sandy and calcareous soils which lack the clay and organic material and nutrient content required for sustainable agricultural production (Kuwait Foundation for the Advancement of Sciences [KFAS], 2024). The southern regions of Kuwait—encompassing the Jal Al-Liyah area and the Wafra agricultural zone—are especially susceptible to active sand dune encroachment, a geomorphic process driven primarily by prevailing northeasterly winds locally known as Al-Shamal (Al-Dousari et al., 2025). The sand dunes located in southern Kuwait function as mobile landforms which move across the landscape. Remote sensing studies spanning 1993 to 2023 document migration rates ranging from 4 to 60 meters per year in the Jal Al-Liyah region, with dramatic changes in dune shape, size, and number over the monitoring period (Al-Dousari et al., 2025). The movement of this material creates direct dangers to nearby farmland which results in damage to irrigation systems and prevents agricultural development in the future. The Arabian Peninsula faces desertification threats that endanger 70 to 90 percent of its agricultural land which makes restoring sand dune soils for productive use an

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urgent environmental and economic mission (Desert Control, 2024).

Kuwait's food supply system faces special risks because worldwide supply chains operate under unstable conditions which makes Kuwaiti authorities focus on enhancing local agricultural production and soil restoration efforts. KISR has dedicated its resources to soil improvement studies because the organization discovered that Kuwait's basic sandy soil needs special scientific methods for successful enhancement (KISR, 2022). The research on bio-saline agriculture has demonstrated new agricultural methods which can be used in Kuwait's saline soil areas that lack adequate freshwater resources (Kuwait Institute for Scientific Research [KISR], 2003).[5][6]

The current study combines existing research about soil reclamation methods and the agricultural use of sand dunes which exist in southern Kuwait. The research aims to achieve three main objectives which include: (1) creating a complete description of the pedological and climatic restrictions that affect south Kuwait's sand dune systems and (2) analyzing how well existing soil reclamation methods work and (3) finding sustainable agricultural development solutions that match Kuwait's unique environmental conditions.

2. Agro-ecological Profile of South Kuwait

2.1 Climatic Conditions

Kuwait experiences a hyper-arid desert climate (Köppen BWh classification), with mean annual rainfall of about 115 millimeters which falls during short winter rain showers (Al-Dousari et al., 2025). The country experiences southward arid conditions which create an aridity index below 0.05 because summer temperatures reach 45 to 50 degrees Celsius and potential evapotranspiration exceeds rainfall (Al-Dousari et al., 2025). The extreme weather conditions create serious physical challenges for traditional agricultural plants while the only sustainable farming approach becomes irrigation-based agriculture. The northwest Al-Shamal winds which reach their strongest point during June and July create frequent sandstorms that result in ongoing aeolian sand movement throughout Kuwait's desert regions (Al-Dousari et al., 2025).

2.2 Soil Characteristics

Kuwait's soils mainly consist of sandy calcareous materials which have loose structure and possess minimal ability to retain nutrients and water (KFAS, 2024). Soil organic carbon (SOC) content typically falls below 0.5%, and cation exchange capacity (CEC) is negligible without amendment input (Musei et al., 2024). The FAO reconnaissance soil survey of Kuwait found approximately 200,000 hectares of irrigable land which suffered from surface salinization due to extended brackish groundwater irrigation practices (FAO, 1967). Agricultural soils in Kuwait are described by KISR as sandy, calcareous, and deficient in clay and organic matter, making them inherently infertile for sustainable crop production without continuous external inputs (KFAS, 2024). The high-permeability sandy matrix allows nutrients to leach which creates significant risks for both environmental quality and farmer profits (KISR, 2022).

2.3 Sand Dune Morphology and Mineralogy

Sand dunes in Kuwait are distributed across several fields, with the Jal Al-Liyah region in the western part of the country encompassing the major Al-Huwaimiliyah dune field which extends through its northwest-southeast axis for approximately 220 square kilometers (Al-Dousari et al., 2025). Dune types include barchan and barchanoid and domal and nabkha forms, with barchan dunes demonstrating the most consistent unidirectional migration under Al-Shamal forcing (Al-Dousari et al., 2025). The Normalized Difference Sand Dune Index and ASTER spectral mapping and Fe^{3+}-based remote sensing analysis demonstrate that Kuwait's sand dunes primarily consist of quartz and carbonate minerals which exist in different ratios (Al-Dousari et al., 2025). The sands that contain quartz as the main component exhibit strong mechanical strength together with low cohesion and little capacity to hold water, which results in enhanced dune movement and hinders agricultural development (Al-Dousari et al., 2025). The Gulf War destroyed natural desert pavements and redirected Tigris River floods into Mesopotamian marshes, which resulted in greater sediment availability for aeolian transport and accelerated dune formation in Kuwait (Al-Dousari et al., 2025).[2]

3. Challenges to Sand Dune Agriculture

3.1 Soil Fertility and Structural Constraints

The agricultural advancement process in southern Kuwait faces multiple soil problems which exist as interconnected issues. The high sand permeability causes water and nutrients to leach out of the root zone which makes conventional fertilization and irrigation methods too expensive and environmentally harmful to implement (Musei et al., 2024). The KISR research institute observed that Sandy soils in Kuwait require continuous water and fertilizer application because their nutrients move out of the root zone area to contaminate nearby shallow groundwater (KISR, 2022). The soil's low cation exchange capacity and extremely low soil organic carbon content prevent plants from absorbing nutrients which results in a high nutrient loss from the topsoil which leads to soil productivity decline.[7][5]

3.2 Water Scarcity and Salinity

The most important factor which limits Kuwaiti agriculture operations stands as water scarcity. The

agricultural sector in Kuwait depends mainly on energy-consuming desalinated seawater for producing high-quality irrigation water while its main water supply comes from brackish groundwater which contains total dissolved salts of 3 to 8 g/L (KISR, 2003). The salinity level of this water exceeds the tolerance limits of most conventional food crops which forces farmers to use desalination methods that become too expensive for large-scale farming operations or to select salt-tolerant plant types (Abdal, 2009). The soil degradation process intensifies when brackish water irrigation creates secondary salinization because salts build up in the upper soil layer which decreases agricultural output over time (FAO, 1967).[8][6][1]

3.3 Wind Erosion and Dune Encroachment

Active sand encroachment remains a persistent structural threat to agricultural zones in south Kuwait. The documented migration rates of 4–60 meters per year in Jal Al-Liyah area lead to field boundaries being flooded and drip irrigation systems getting damaged and new crops being buried during a single growing season according to research by Al-Dousari and colleagues in 2025. The period from 2013 until 2023 shows dune morphological evolution through which individual barchan dunes develop into bigger barchanoid structures or divide into multiple secondary dunes which create unpredictable spatial patterns for dune migration corridors according to Al-Dousari and colleagues in 2025. The southern Kuwaiti Wafra agricultural project which serves as a primary agricultural zone in Kuwait faces severe sand encroachment threats from active dune fields that move toward the area under northwest wind conditions.[2]

3.4 Institutional and Economic Constraints

The hydrocarbon-based economy of Kuwait has created a system that lessens investment interest in local agricultural development which leads to reduced funding for agricultural research through institutional and financial restrictions (KFAS, 2024). The recent food supply disruptions combined with national food security initiatives have created changes in the situation which led KISR to receive additional responsibilities for soil development and bio-saline agricultural research according to KISR report from 2022. Small-scale Kuwaiti farmers face challenges in adopting soil amendment technologies because they need to pay high initial costs for biochar production and distribution which shows the requirement for subsidized demonstration programs that should receive public funding.[3][5]

4. Soil Reclamation Techniques

4.1 Biochar Application

Biochar stands as one of the top soil amendments that improve sandy soils in dry desert areas. The Kuwait Biochar Initiative (KBI) developed bioorganic soil conditioners which KISR has tested in Kuwait's sandy agricultural fields to show better water retention and nutrient availability and increased crop production (KISR, 2021). KBI's patented Bioorganic Soil Conditioner is reported to increase crop production by 50%, reduce irrigation water demand by 25%, decrease fertilizer use by 40%, and control soil erosion in Kuwait's sandy agricultural settings (KISR, 2022).[9][5]

The worldwide use of biochar improves the water-related physical characteristics of sandy soils because it decreases water evaporation and enhances the soil's ability to hold water which plants can use especially in dry regions between arid and semi-arid climates where water shortages prevent crops from growing (Kaur et al., 2024). The systematic review by Musei et al. (2024) assessed 42 technologies for sandy soil reclamation which researchers from 27 countries published in 144 studies and found that biochar emerged as one of the most reliable methods to raise both soil moisture levels and SOC in sandy soils around the globe. The application rate and feedstock type and soil pH serve as the primary factors that determine biochar effectiveness because higher application rates result in stronger nutrient cycling effects (Bashir et al., 2024).[10][11][7]

Biochar amendments improve CEC and decrease bulk density and increase microbial biomass and plant-available nitrogen and phosphorus fractions in calcareous sandy soils that exist in Kuwait(Bashir et al., 2024). The study meta-regression results show that soils with high pH levels which need more biochar application show the strongest soil nutrient improvements(Bashir et al., 2024). The combination of biochar and organic compost as a composite amendment strategy produces the highest crop yield increases in sandy soils worldwide which reach 92% above control plots because it outperforms both biochar and compost when used separately(Zhang et al., 2025).

4.2 Organic and Composite Amendments

The application of organic amendments such as compost and farmyard manure and processed municipal organic waste leads to significant enhancements in soil structure and microbial diversity and nutrient cycling processes in degraded sandy dune soils. The global meta-analysis which examined 843 independent observations from 151 field-based studies showed that both organic and inorganic amendments together produced a 39% increase in crop yield and a 62% rise in soil organic carbon (SOC) for sandy soils while composite amendments delivered the highest yield enhancement of 92% and inorganic amendments resulted in the most substantial SOC gain of 133% according to Zhang et al. 2025.

The Kuwait Institute for Scientific Research has discovered that locally sourced clay functions as an economical soil conditioner which achieves better results when combined with sulfur and compost into pelleted form for sandy agricultural soils in Kuwait

according to KFAS 2024. The KISR testing facilities have proven that clay-sulfur-compost composite amendments enable alfalfa Medicago sativa and barley Hordeum vulgare and maize Zea mays to achieve better water use efficiency while minimizing irrigation drainage losses according to KFAS 2024.

The practice of using locally obtained amendment materials serves as an effective circular economy solution which decreases expenses and reduces environmental impact for soil enhancement initiatives in Kuwait.3. The studies conducted in arid Tunisia demonstrate that organic residue amendments lead to permanent increases in exchangeable cation content which benefits crop productivity during multiple harvest cycles according to Oueriemmi et al. 2021 as cited in Frontiers in Soil Science.

4.3 Mechanical and Biological Sand Dune Stabilization

The stabilization of active sand dunes must occur before any agricultural activities can begin because dune stabilization protects developing plants and construction materials from unanticipated dune movement. The Gulf region has used mechanical stabilization methods which include petroleum-based mulches for binding sand surface particles together according to a technique that originated in Iran and spread to Kuwait and the UAE as a solution for stabilizing moving dune fronts which Al-Huwaimiliyah Dune Management Program presents (Al-Dousari et al., 2025). The short-term effectiveness of petroleum-based mulches in sand immobilization faces environmental challenges because the products create hydrocarbon contamination that affects soil microbiological activity and this factor must be assessed against their effectiveness in preparing land for agricultural use.[2]The use of drought-resistant pioneer vegetation for biological stabilization constitutes an environmentally suitable solution which provides long-lasting benefits for ecosystems. Research shows that using native desert plant species Haloxylon persicum, Tamarix spp., Calligonum polygonoides, and Atriplex canescens throughTheir planting on actively migrating dunes leads to reduced sand movement and the establishment of organic matter through pedogenic processes which improve surface microclimate conditions over time (Musei et al., 2024). The initial stage of succession begins when pioneer species establish plant roots which bind loose sand while they generate surface litter that draws soil organisms to create nutrient recycling systems. KISR's environmental restoration studies confirm that native species can successfully establish on degraded Kuwaiti dune soils when protected from grazing pressure which remains a primary disturbance factor in restored areas (KFAS, 2024).[3][7]

4.4 Windbreaks and Shelterbelts

Establishing windbreaks which consist of tree and shrub plantings that grow in lines which extend across the main wind directions will help farmers safeguard their fields against Al-Shamal sandstorms while decreasing the water needs of their crops. The Gulf region uses windbreak systems that utilize Prosopis juliflora Acacia species Casuarina equisetifolia and Tamarix stricta to defend agricultural fields against destructive winds which move at high speeds (Environmental Research Group, 1983, as reviewed in regional literature). Windbreaks that designers construct effectively generate their leeward areas with wind speed reductions ranging from 50% to 70%. This process creates better microclimatic conditions which support plant survival and development (Al-Dousari et al., 2025).The agricultural zones in southern Kuwait demand integrated windbreak systems which need to handle both Al-Shamal wind path changes and dune field movement patterns. The protection of agricultural land in hyper-arid areas needs permanent sand dune protection which can be achieved through the use of surface stabilizers together with living windbreaks that protect against sand movement through their structural and biological defensive capabilities (Environmental Research Group, 1983). The FAO requires non-cultivated areas near Kuwait's agricultural zones to establish experimental forestry and grazing protection units as the first step toward developing successful afforestation methods for Kuwaiti desert environments (FAO, 1967).

4.5 Bio-saline Agriculture and Halophyte Cultivation

Kuwait relies on brackish and saline groundwater to provide its main irrigation sources. Bio-saline agriculture demonstrates its suitability as a practical solution which enables salt-tolerant crop farming under low-quality water conditions to flourish in south Kuwait's sand dune agricultural regions. The Kuwait Institute for Scientific Research created a bio-saline agricultural research framework in the 1980s to develop salt-tolerant crop varieties through traditional plant breeding together with advanced biotechnology methods which included tissue culture and recombinant DNA techniques (KISR, 2003).[6]

The KISR Medairah agricultural research site in Kuwait produced profitable Salicornia bigelovii yields through experimental cultivation of this obligate halophyte which tolerates seawater-equivalent salinity (Abdal, 2009). Salicornia offers multiple agronomic benefits through its seed content which provides 30% protein and 26-33% oil that can be extracted for biodiesel or food-grade purposes while its remaining biomass functions as livestock feed thus enabling multiple income sources from a single crop which grows on unproductive saline sandy soils (Abdal, 2009). The University of Arizona and KISR research collaboration confirmed that Salicornia can complete

its entire growth cycle in Kuwait's sandy soils while using seawater-level salinity irrigation which shows that bio-saline cultivation works in actual field conditions (Abdal, 2009).[8]

Researchers tested several native and non-native halophyte plants to see whether they could restore salt-damaged soils while generating usable plant material. The plants Atriplex nummularia and Sesuvium portulacastrum and Tamarix aphylla serve as phytoremediators because they remove soluble salts from the ground by taking in ions which accumulate in their above-ground parts that people can collect (Manousaki & Kalogerakis, 2014). The process of salt extraction leads to decreasing soil salinity which continues through multiple growing seasons until it establishes conditions that enable less salt-tolerant crop species to thrive thus expanding the agricultural capabilities of restored dune soils (Manousaki & Kalogerakis, 2014). Dune reclamation programs that start with halophyte cultivation before introducing traditional agricultural plants achieve three objectives which include stabilizing sand, decreasing soil salinity, and creating biomass that generates financial benefits.[14]

5. Water Management Strategies

The agricultural activities of south Kuwait require farmers to use water resources in the most efficient way because pan evaporation rates exceed 3500 millimeters per year and irrigation costs represent the highest expenses for agricultural operations. The agricultural method of subsurface drip irrigation, which delivers water directly to the root zone beneath the surface area, effectively decreases water losses when compared to sprinkler and surface irrigation systems and has gained increasing acceptance throughout Kuwait's protected fields and open agricultural fields since its introduction (KISR, 2003). Drip systems function as superior solutions for sandy soils because sandy soils drain quickly which causes water to flow away from plants before they can absorb it; when emitters are positioned at root depth more water becomes accessible for plants to use (Musei et al., 2024).[6][7]

The combination of biochar soil amendments with subsurface drip irrigation creates a synergistic relationship because biochar enhances water retention in sandy soil, which allows drip irrigation to apply water exactly to the biochar-treated area that shows maximum water retention (Kaur et al., 2024). KISR's biochar field trials demonstrated a 25% reduction in irrigation water demand under biochar amendment, a finding with significant practical implications for water budget planning in a country where desalinated water costs represent a major share of agricultural production expenses (KISR, 2022).[10][5]

Rainwater harvesting through micro-catchment construction and contour earthworks and detention bunds building exists as an extra method which increases soil moisture levels in south Kuwait's intermittent rain pattern. The region receives only small amounts of rainfall throughout the year yet heavy rainstorms create street runoff which designed landscape systems can capture to use as irrigation during cooler months and to assist with establishing windbreak and dune stabilization plantings. Treated agricultural wastewater and municipal greywater reuse for non-food crop irrigation and halophyte cultivation on reclaimed dune soils represents an underutilized water resource option in Kuwait's agricultural planning system.

6. Integrated Approaches and Policy Framework

6.1 Integrated Reclamation Strategies

No single reclamation technology is sufficient to transform south Kuwait's sand dune systems into sustainably productive agricultural land. The scientific literature demonstrates that integrated methods which use multiple complementary solutions to solve problems show better results than exclusive use of single solutions (Musei et al., 2024). South Kuwait requires an integrated strategy which will implement six sequential steps. The first step of the process involves using mechanical methods to stabilize active dune fronts which lie next to agricultural areas. The second step requires establishing pioneer vegetation to stabilize the area. The third step involves planting windbreaks to create protection for developing agricultural regions. The fourth step requires applying composite biochar-compost amendments to enhance soil water and nutrient retention capabilities. The fifth step includes implementing subsurface drip irrigation systems which water the agricultural fields based on the modified soil's better hydraulic characteristics. The sixth step involves starting agricultural activities through halophyte and bio-saline crop cultivation which will later progress to growing more valuable crops after the soil achieves better conditions.[7]

The circular economy dimension of this integrated approach is particularly relevant for Kuwait. The agricultural sector together with municipal organic waste streams and food processing operations produce biomass feedstocks which can be used to produce both compost and biochar through industrial production methods (KISR, 2022). The strategic value of using local clay and sulfur as supplementary soil amendments demonstrates how KISR uses domestic materials to lower costs and decrease Kuwait's need for imported materials in its soil improvement initiatives (KFAS, 2024). Closed-loop nutrient cycling which transforms organic waste into soil amendments will decrease

fertilizer imports to Kuwait while supporting the country's Vision 2035 sustainability objectives and food security goals.[5][3]

6.2 Policy and Institutional Recommendations

Kuwait's Vision 2035 national development plan provides a supportive institutional framework for investment in soil reclamation research and agricultural development, which focuses on food security and environmental sustainability and economic development that does not depend on fossil fuels (Desert Control, 2024). The implementation of this policy through which the government plans to establish operational programs needs particular institutional operational requirements which must be fulfilled. The first step to establish an evidence base for scaling proven technologies requires KISR to expand its Aridland Agriculture Department operations by launching systematic multi-year soil reclamation pilot projects in Wafra and Abdally agricultural zones. The establishment of subsidized demonstration farms which implement biochar and composite amendment and bio-saline techniques in integrated systems will reduce the technology adoption barrier for private farmers.[4]

The development of best practices that meet Kuwait's specific pedological and climatic conditions requires scientists to conduct international research with institutions in Israel and the UAE and Saudi Arabia and Australia that possess expertise in arid zone agriculture. The Gulf Cooperation Council (GCC) framework provides an effective platform for regional agricultural research consortia which address common research needs in arid zone environments. The existing regulatory frameworks which control treated wastewater usage in agriculture must undergo revisions to enable greywater and tertiary-treated effluent use as irrigation resources for halophyte and bio-energy crop cultivation on reclaimed dune soils which will help achieve both municipal water management and agricultural production goals.

7. Conclusion

The sand dune areas of South Kuwait present major difficulties which farmers can overcome through their agricultural work. The combination of extreme drought conditions together with sandy unproductive ground and salty irrigation water and moving sand dunes creates a unique environmental challenge which requires scientists to develop local-based reclamation solutions that use multiple technologies. The literature reviewed herein demonstrates that biochar-based soil conditioners, organic and composite amendments, halophyte cultivation, windbreak systems, and bio-saline agriculture each contribute meaningfully to the rehabilitation of sandy dune soils when applied within an integrated framework (Musei et al., 2024; KISR, 2022; Zhang et al., 2025).[12][5][7]

The Kuwait Biochar Initiative and bio-saline agricultural programs which KISR conducts serve as research platforms that enable scientists to create effective agricultural solutions for southern Kuwait's farming regions (KISR, 2021; KISR, 2003). Research groups should focus their efforts on conducting field trials that evaluate different amendment solutions for extended periods in Kuwaiti weather conditions and using remote sensing technology to track dune stabilization success during several decades and on performing detailed cost-benefit evaluations of different reclamation options which will support decision-making for limited resource investment. The process of changing Kuwait's sand dunes into productive agricultural land functions as an agricultural obstacle which supports Kuwait's national strategy for achieving food independence and environmental protection and sustainable development.[9][6]

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