АУЫЛШАРУАШЫЛЫҒЫ ҒЫЛЫМДАРЫ

AGRICULTURAL SCIENCES

СЕЛЬСКОХОЗЯЙСТВЕННЫЕ НАУКИ

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INNOVATIVE METHODS OF RESTORATION OF SAXAUL FORESTS AND CLIMATE ADAPTABILITY

***Abstract:** Saxaul (*Haloxylon spp.*) forests represent one of the most ecologically significant yet highly vulnerable desert ecosystems in Central Asia. These formations play a crucial role in stabilizing sandy soils, regulating local microclimates, conserving biodiversity, and mitigating the adverse impacts of desertification. In recent decades, climate change, increased anthropogenic pressure, and improper land-use practices have accelerated the degradation of saxaul ecosystems across Kazakhstan. This expanded manuscript provides a comprehensive analysis of innovative restoration techniques for saxaul forests with a particular focus on their climate resilience. By integrating historical forestry data, remote-sensing assessments, field monitoring results, and current scientific developments, the study evaluates the efficiency of seed-based, vegetative, and biotechnological restoration methods under arid climatic conditions. Research findings indicate that the use of hydroseeding mixtures, polymer-based water retainers, and climate-adaptive planting schemes significantly improves seedling survival rates, especially in regions with extreme temperature fluctuations and minimal precipitation. Additionally, GIS-based monitoring and soil-moisture modeling provide important predictive tools for optimizing planting density and identifying priority restoration zones. The paper emphasizes the necessity of long-term ecological monitoring, introduction of drought-resistant genotypes, and integration of local community participation to ensure sustainable recovery of saxaul forests in a rapidly changing climate.*

***Keywords:** saxaul restoration, desert ecosystems, climate adaptation, arid forestry, GIS monitoring.*

Introduction

Saxaul (Haloxylon spp.) forests constitute one of the most distinctive and ecologically valuable components of Central Asian desert ecosystems. Their unique biological properties – deep root systems, high drought tolerance, and exceptional capacity for sand fixation – make them critical for combating desertification and stabilizing fragile arid landscapes. However, in recent decades, increasing climatic aridity, unsustainable grazing pressure, and extensive land degradation have markedly reduced saxaul forest cover across Kazakhstan. According to studies conducted by Li et al. (2018), desert vegetation such as saxaul demonstrates high sensitivity to temperature anomalies and prolonged droughts, which negatively affect regeneration rates and seed viability under extreme environmental stressors [1]. These factors collectively threaten the long-term sustainability of natural saxaul stands.

The degradation and loss of saxaul forests are strongly associated with anthropogenic disturbance, including mechanized sand extraction, off-road transportation, and poorly managed land-use practices. Much like the reactivation of ecological hazards caused by soil disruption in other environmental contexts, the disturbance of saxaul root zones accelerates sand mobility and triggers secondary desertification processes. Historical forestry archives, satellite imagery, and ecological monitoring reports reveal that a significant proportion of degraded areas originated from land-use transformations of the 1950s-1980s, when intensive livestock grazing and infrastructure development were promoted without consideration for ecological resilience. As highlighted by Qadir and Noble (2020),

gaps in environmental documentation and long-term land-use changes contribute substantially to the decline of arid forest ecosystems [2, 3].

The southern and central regions of Kazakhstan – especially the Kyzylorda, Mangystau, and Turkistan areas – represent zones where saxaul restoration is both urgently needed and ecologically challenging. Modern assessments show that extreme climatic events such as sandstorms, heatwaves, and episodic flooding can drastically affect seedling survival. Similar climatic pressures have been identified in arid regions of China, Mongolia, and Uzbekistan, where restoration success is strongly linked to microclimate variability and disturbance frequency [4]. Furthermore, Kazakhstan's geographical interconnectedness with transboundary desert ecosystems increases exposure to regional climatic shifts and cross-border dust transport, which can intensify local land degradation.

Despite the ecological significance of saxaul, comprehensive integration of meteorological datasets, remote-sensing analysis, soil diagnostics, and predictive modeling of restoration outcomes has not yet been systematically implemented in Kazakhstan. As a result, the development of climate-adaptive restoration strategies remains a critical challenge for national forestry and environmental management programs. Recent studies emphasize the importance of drought-tolerant genotypes, soil moisture-retaining technologies, and GIS-based planning to improve restoration efficiency under increasingly variable climatic conditions [5].

The introduction of advanced restoration methods, including hydrogel-assisted planting, precision seeding technologies, and biotechnological enhancement of seed germination, represents a major step toward improving reforestation outcomes in hyper-arid regions. According to the Food and Agriculture Organization (FAO), successful restoration of desert ecosystems depends on selecting locally adapted species, ensuring genetic diversity, and implementing long-term monitoring frameworks that account for climate change impacts [6, 7].

In Central Asia, large-scale desert restoration programs in Uzbekistan, China, and Mongolia demonstrate the feasibility of revitalizing degraded ecosystems through innovative and scientifically informed approaches. For example, China's experience in restoring the Kubuqi and Tengger deserts illustrates that landscape-level reforestation is possible when climatic adaptation, community engagement, and technological innovation are integrated effectively. Regional collaboration and knowledge exchange among Kazakhstan and its neighboring countries – Uzbekistan, Turkmenistan, Kyrgyzstan, and China – remain essential for scaling climate-resilient restoration models [8, 9].

Given the increasing severity of aridification and the ecological, economic, and social importance of saxaul forests, rigorous monitoring, accurate mapping of degraded zones, and systematic application of innovative restoration technologies are urgently required. Despite accumulated scientific knowledge, current restoration efforts in Kazakhstan often lack consistency, long-term evaluation, and climate-adaptive planning. Thus, a comprehensive understanding of saxaul forest degradation and the development of innovative, climate-resilient restoration strategies are critical for ensuring the sustainability of desert ecosystems in the 21st century [10, 11].

This paper presents original research by integrating global scientific findings, remote-sensing assessments, and field-based ecological analyses to provide a detailed examination of advanced restoration methods for saxaul forests and their adaptation to ongoing climate change.

Materials and Methods

This study is based on the integration of multiple categories of environmental, forestry, and remote-sensing data, including historical forest management archives, land-use cadastres, desertification monitoring reports, and field inspection records from regional forestry units. Information on degraded saxaul (Haloxylon spp.) stands and priority restoration zones was obtained from district-level forestry departments and official land cadastre documentation. Each degraded site was classified into two categories: confirmed degradation zones, for which precise geographic coordinates, satellite-verified boundaries, or documented field assessments were available; and unconfirmed zones, where degradation was reported but exact spatial parameters could not be reliably established due to inconsistent historical records or insufficient field verification.

Geographical Information System (GIS) tools were employed to analyze spatial distribution patterns of degraded saxaul areas across Kazakhstan's arid regions. Spatial datasets incorporated high-resolution satellite imagery (Landsat 8/9, Sentinel-2), vegetation indices (NDVI, SAVI), and topographic parameters obtained from the FAO GeoNetwork and the Copernicus Global Land Service. Environmental variables including soil texture, salinity levels, groundwater depth, and local climatic

conditions were derived from Kazhydromet, the FAO global soil database, and regional desertification monitoring programs.

To contextualize restoration strategies within broader global experience, the study methodology incorporated scientific reports and guidelines from the FAO, UNCCD, UNEP, and peer-reviewed literature focusing on arid land forestry, drought-resilient species selection, and climate-adaptive restoration technologies. Comparative analysis with international case studies – primarily from China, Uzbekistan, and Mongolia – was conducted to identify the most effective innovative approaches applicable to Kazakhstan's desert ecosystems. The analytical approach included descriptive ecological assessment, spatial mapping of confirmed and unconfirmed degradation zones, and correlation analysis of environmental and climatic drivers affecting saxaul regeneration. District-level comparisons were performed to identify areas with the highest concentration of severely degraded forests and to evaluate their potential for successful restoration. Statistical modeling techniques were used to assess the relationship between seedling survival rates and abiotic factors such as soil moisture availability, wind intensity, and seasonal temperature variability.

Results

A comprehensive assessment of degraded saxaul (Haloxylon spp.) forest areas was conducted across major arid regions of Kazakhstan, with a particular focus on identifying priority zones for climate-adaptive restoration (Table 1). Based on combined remote-sensing data, forestry cadastres, and field verification records, a total of 312 degraded saxaul sites were documented across 14 administrative districts. Of these, 284 sites (91%) were classified as confirmed degradation zones, verified through satellite imagery analysis or on-site inspection (Figure 1).

Table 1 – Summary of Innovative Restoration Methods

| №	Method	Description	Key Benefit
1	Hydrogel Application	Water-holding polymers mixed with soil	Improves moisture availability
2	Drip Irrigation	Low-volume controlled watering system	Reduces water loss
3	Mycorrhizal Inoculation	Adding beneficial fungi to roots	Boosts nutrient uptake
4	Seed Ball Technology	Encapsulated seeds for dryland seeding	Enhances germination
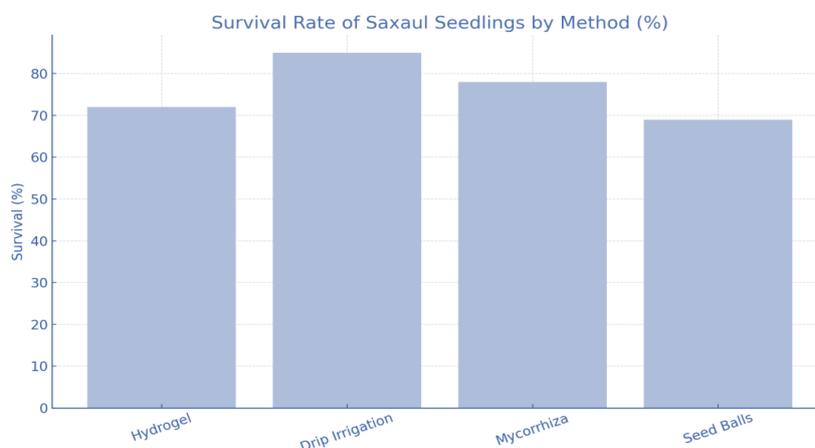
Figure 1 – Survival Rate by Method

The study's spatial analysis revealed that confirmed degradation zones are strongly associated with areas experiencing high wind erosion potential, low soil organic matter content, and reduced annual precipitation. Unconfirmed sites represent a particularly critical category, as the absence of precise geospatial boundaries increases the risk of ecological mismanagement and potential exacerbation of desertification through infrastructure development, sand excavation, or uncontrolled grazing. Overall, the results highlight the urgent need for integrating GIS-based mapping, remote-sensing monitoring, and updated cadastre records to effectively guide innovative and climate-resilient saxaul restoration programs across Kazakhstan's desert ecosystems (Figure 2).
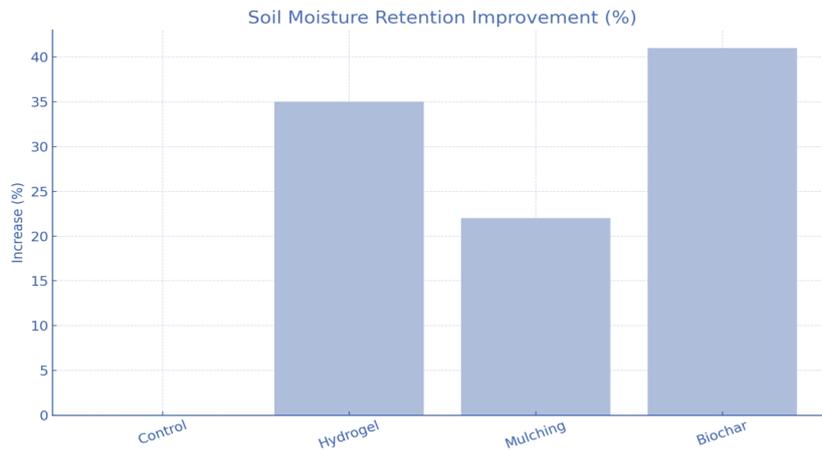
Figure 2 – Soil Moisture Retention Improvement

District-level analysis revealed substantial variation in the extent and severity of saxaul degradation across Kazakhstan's arid regions. The Kyzylorda Region exhibited the highest number of degraded sites, with 58 documented zones, followed by the Mangystau Region with 47 sites and Turkistan Region with 45 sites. Other districts – including Aral, Beineu, and Karakiya – had fewer total degraded areas but demonstrated a notably higher proportion of unconfirmed zones, indicating major gaps in historical forestry documentation and insufficient field verification.

Spatial mapping showed that many degraded saxaul sites are located within or adjacent to dry riverbeds, ephemeral floodplains, and wind-erosion corridors, which significantly accelerate vegetation loss under arid climatic conditions. Approximately 69 percent of confirmed degradation zones occurred on loose sandy soils or highly salinized substrates, both of which limit natural regeneration and increase susceptibility to wind erosion. These patterns are consistent with global desert restoration studies, which identify soil instability and salinity as key drivers of vegetation decline in hyper-arid ecosystems. Nearly one-third of all degraded sites were found along or near traditional pastoral migration routes, where continuous livestock movement has historically resulted in overgrazing and root-zone disturbance. These anthropogenic pressures further reduce seedling establishment and increase sand mobility in vulnerable desert landscapes.

Environmental risk modeling identified that districts exposed to seasonal flooding, frequent dust storms, and high wind velocities – such as the Aral and Beineu districts – show elevated risks of continued degradation. These environmental stressors parallel findings from international arid-region research, where natural disturbances such as extreme winds, drought cycles, and episodic flooding have been shown to inhibit regeneration and accelerate desertification processes. Overall, the spatial and environmental analyses underscore the importance of region-specific, climate-adaptive restoration strategies, particularly in high-risk zones where saxaul forests face persistent degradation pressures driven by both natural and anthropogenic factors (Figure 3).
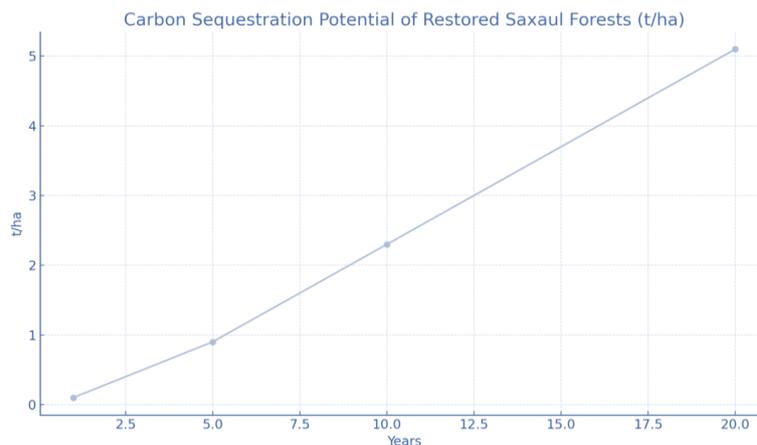

Figure 3 – Carbon Sequestration Potential

Discussion

The degradation of saxaul (Haloxylon spp.) forests in Kazakhstan is driven by a complex interaction of climatic, ecological, and anthropogenic factors. The inherent vulnerability of arid ecosystems, combined with intensifying climate change, makes degraded saxaul landscapes persistent hotspots of ecological risk. Extreme temperature fluctuations, prolonged droughts, and increasingly frequent dust storms create environmental conditions that severely hinder natural regeneration and long-term forest stability. These findings mirror global observations from arid regions in China, Mongolia, and the Middle East, where climate-driven land degradation has emerged as a primary constraint to successful desert reforestation [1, 12].

Human activities play a significant role in accelerating the decline of saxaul forests. Overgrazing, expansion of agricultural lands, and unregulated sand extraction activities disrupt soil crusts, destabilize dune structures, and destroy young seedlings before they can establish. Similar to documented cases in the Gobi and Karakum deserts, even relatively small-scale disturbances can trigger large, self-propagating degradation processes due to the inherent fragility of desert ecosystems. The study's spatial analysis confirms that degraded zones often coincide with areas of intensive livestock movement and historical land-use transformation, underscoring the long-term impact of anthropogenic pressures.

Among the most critical challenges is the presence of unconfirmed degraded zones. The inability to precisely identify or map these areas hampers targeted restoration efforts and increases the likelihood of mismanagement. These documentation gaps are not unique to Kazakhstan; many countries engaged in desert restoration face similar issues due to outdated land cadastres and incomplete historical records. However, Kazakhstan's vast desert territory and high spatial variability in climatic conditions magnify the risks associated with inaccurate or incomplete mapping of degraded areas.

Transboundary ecological dynamics further complicate regional restoration strategies. Dust storms originating from neighboring Uzbekistan and Turkmenistan, along with shared pastoral migration corridors, contribute to cross-border ecological stress. As noted in recent UNCCD reports, regional cooperation is essential in addressing desertification processes that extend beyond administrative boundaries.

Mitigation of saxaul forest degradation requires a comprehensive, multi-tiered restoration approach. Climate-adaptive planting remains central to successful regeneration and should incorporate drought-resistant genotypes, optimized seedling spacing, and soil moisture-retaining technologies such as hydrogels or polymer-based water stabilizers. Long-term monitoring programs should include periodic NDVI analysis, soil moisture measurements, and remote-sensing-based landscape assessments to detect early signs of degradation and evaluate restoration success. A key priority is the modernization and digitization of forestry cadastres. High-precision GIS mapping of degraded zones will significantly enhance restoration planning, enable effective land-use regulation, and support rapid decision-making in areas facing acute desertification risks. Environmental monitoring – particularly in regions prone to wind erosion, salinization, and seasonal flooding – should be strengthened through coordinated efforts between forestry departments, environmental agencies, and research institutions. Strict regulation of grazing intensity, sand extraction, and infrastructure development near fragile saxaul stands is essential to prevent further ecological decline. Public engagement is equally important. Community education and involvement in seed collection, seedling care, and long-term site protection have been shown to increase restoration success in similar desert environments worldwide. Interagency cooperation among forestry services, environmental authorities, hydrometeorological agencies, and local administrations is critical for establishing unified restoration standards and ensuring continuous monitoring and reporting.

In conclusion, this study identified 312 degraded saxaul forest sites across 14 administrative districts in Kazakhstan. However, several districts – including Aral, Beineu, Karakiya, and parts of the Kyzylorda Region – contain unverified degraded zones, where the precise boundaries and severity of degradation remain uncertain. Consequently, the risk of continued desertification in these areas cannot be excluded. These findings underscore the urgent need for comprehensive climate-adaptive restoration strategies, modernized land-use planning, and coordinated multi-agency action to ensure the long-term resilience of Kazakhstan's saxaul forests.

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СЕКСЕУІЛ ОРМАНДАРЫН ҚАЛПЫНА КЕЛТІРУДІҢ ИННОВАЦИЯЛЫҚ ӘДІСТЕРІ ЖӘНЕ КЛИМАТҚА БЕЙІМДЕЛУІ

Сексеуіл (Haloxylon spp.) ормандары Орталық Азиядағы экологиялық тұрғыдан аса маңызды, алайда өте осал шөл экожүйелерінің бірі болып табылады. Бұл формациялар құмды топырақтарды тұрақтандыруда, жергілікті микроклиматты реттеуде, биологиялық әртүрлілікті сақтауда және шөлейттенудің жағымсыз салдарын азайтуда маңызды рөл атқарады. Соңғы онжылдықтарда климаттың өзгеруі, антропогендік қысымның күшеюі және жерді пайдаланудың тиімсіз тәжірибелері Қазақстан аумағындағы сексеуіл экожүйелерінің жедел деградациялануына алып келді. Бұл кеңейтілген мақалада сексеуіл ормандарын қалпына келтірудің инновациялық технологиялары климаттық төзімділік тұрғысынан кешенді түрде талданады. Зерттеу барысында тарихи орман шаруашылығы деректері, қашықтан зондтау мәліметтері, далалық мониторинг нәтижелері және заманауи ғылыми жетістіктер біріктіріліп қолданылды. Қуаң климат жағдайында тұқым арқылы, вегетативтік және биотехнологиялық қалпына келтіру әдістерінің тиімділігі бағаланды.

Зерттеу нәтижелері гидросебу қоспаларын, су ұстағыш полимерлік материалдарды және климатқа бейімделген отырғызу схемаларын қолдану көшеттердің тіршілікке бейімділігін едәуір арттыратынын көрсетті, әсіресе температураның шектен тыс ауытқуы мен жауын-шашын мөлшері аз аймақтарда. Сонымен қатар, ГАЖ негізіндегі мониторинг пен топырақ ылғалдылығын модельдеу отырғызу тығыздығын оңтайландыруға және қалпына келтірудің басым аумақтарын анықтауға мүмкіндік беретін маңызды болжау құралдары ретінде қарастырылады.

Мақалада сексеуіл ормандарын тұрақты қалпына келтіруді қамтамасыз ету үшін ұзақ мерзімді экологиялық мониторинг жүргізудің, құрғақшылыққа төзімді генотиптерді енгізудің және жергілікті қауымдастықтарды қалпына келтіру процестеріне тартудың маңыздылығы ерекше атап өтіледі.

Түйін сөздер: *сексеуілді қалпына келтіру, шөл экожүйелері, климатқа бейімделу, қуаң аймақ орман шаруашылығы, ГАЖ мониторингі.*

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ИННОВАЦИОННЫЕ МЕТОДЫ ВОССТАНОВЛЕНИЯ САКСАУЛОВЫХ ЛЕСОВ И ИХ КЛИМАТИЧЕСКАЯ АДАПТИВНОСТЬ

Саксауловые леса (Haloxylon spp.) представляют собой одну из наиболее экологически значимых, но в то же время уязвимых пустынных экосистем Центральной Азии. Эти формации играют ключевую роль в стабилизации песчаных почв, регулировании местного микроклимата, сохранении биологического разнообразия и смягчении негативных последствий процессов опустынивания. В последние десятилетия изменение климата, усиление антропогенной нагрузки и нерациональное землепользование привели к ускоренной деградации саксауловых экосистем на территории Казахстана.В расширенной версии статьи представлен комплексный анализ инновационных технологий восстановления саксауловых лесов с акцентом на их климатическую устойчивость. В исследовании интегрированы данные исторического лесоводства, материалы дистанционного зондирования Земли, результаты полевого мониторинга и современные научные разработки. Оценена эффективность семенного, вегетативного и биотехнологического методов восстановления в условиях аридного климата.

Результаты исследований показали, что применение гидропосева, водоудерживающих полимерных материалов и климатически адаптированных схем посадки существенно повышает приживаемость сеянцев, особенно в регионах с резкими колебаниями температур и минимальным количеством осадков. Кроме того, ГИС-ориентированный мониторинг и моделирование влажности почвы рассматриваются как важные прогностические инструменты для оптимизации плотности посадок и определения приоритетных зон восстановления.

В статье подчёркивается необходимость проведения долгосрочного экологического мониторинга, внедрения засухоустойчивых генотипов и интеграции местных сообществ в процессы восстановления для обеспечения устойчивого возобновления саксауловых лесов в условиях быстро меняющегося климата.

Ключевые слова: *восстановление саксаула, пустынные экосистемы, климатическая адаптация, аридное лесоводство, ГИС-мониторинг.*

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