

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)

**NEWS OF THE NATIONAL ACADEMY
OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF
GEOLOGY AND TECHNICAL SCIENCES**

№5

2026

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)



N E W S
OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN,
SERIES OF GEOLOGY AND TECHNICAL
SCIENCES

5 (479)

September – Oktober 2026

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2026

The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Owner: «Central Asian Academic Research Center» LLP (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.

<http://www.geolog-technical.kz/index.php/en/>

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).

Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік. Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

<http://www.geolog-technical.kz/index.php/en/>

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

ISSN 2224-5278

Volume 5.

Number 479 (2026), 273–289

<https://doi.org/10.32014/2026.2518-170X.703>

UDC: 502.521:631.6(574.11)

IRSTI: 87.21.00

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GEOECOLOGICAL ASSESSMENT AND PHYTOMELIORATIVE RESTORATION OF DEGRADED ARID LANDS IN THE ATYRAU REGION OF WESTERN KAZAKHSTAN

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Abstract. Relevance. The arid lands of the northern Caspian Lowland are losing their productive function under the combined action of climatic aridisation, profile salinity, deflation and the thinning of vegetation cover. Phytomelioration with salt- and drought-tolerant semi-shrubs of the local flora is the only reclamation option available at the scale of the problem, yet its outcome on heavy-textured saline soils is governed by edaphic and microtopographic conditions that are rarely quantified. **Objective.** To assess the geoecological potential of adaptive arid species for the reclamation of degraded lands of the Atyrau Region and to identify the soil and terrain conditions that control their establishment. **Methods.** Field experiments were carried out in 2024–2025 on moderately saline brown alluvial medium-loamy soils, on 30 m² plots in four replications, with *Kochia prostrata*, *Camphorosma monspeliaca*, *Ceratocarpus arenarius*, *Salsola orientalis* and a *Kochia*–*Camphorosma* mixture.

Field emergence, plant density, retention, height, weed competition, biomass and forage value were compared under contrasting precipitation regimes of 268.3 and 147.2 mm. *Results.* *Kochia prostrata*, *Camphorosma monspeliaca* and their mixture proved the most adapted, with plant retention of 83.7, 78.9 and 88.7% respectively. The mixture gave the highest biomass (22.0 c ha⁻¹), feed units (4.75 c ha⁻¹), digestible protein (1.10 c ha⁻¹) and metabolizable energy (6.77 GJ ha⁻¹). *Salsola orientalis* did not emerge and *Ceratocarpus arenarius* established very unevenly. Field emergence was controlled by surface crusting and by hardening of the layer beneath the seed, both functions of soil texture and microrelief. *Conclusion.* *Kochia prostrata* and *Camphorosma monspeliaca*, particularly in mixture, have a high geocological potential for reclaiming degraded arid lands, provided that soil texture and microrelief are used as site-selection criteria.

Keywords: geocological assessment, land degradation, soil salinity, soil crust, phytomelioration, desertification, *Kochia prostrata* (L.) Schrad., *Camphorosma monspeliaca*

Funding: This research has been funded by the Ministry of Agriculture of the Republic of Kazakhstan Grant No. BR22883585 "Development of effective technologies to increase productive potential and rational use of pastures".

For citations: Mukhambetov B., Nasiyev B., Kanat T., Zhumin B. Geocological Assessment and Phytomeliorative Restoration of Degraded Arid Lands in the Atyrau Region of Western Kazakhstan. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences.* 2026. No.5. Pp. 273–289. DOI: <https://doi.org/10.32014/2026.2518-170X.703>

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БАТЫС ҚАЗАҚСТАННЫҢ АТЫРАУ ОБЛЫСЫНДАҒЫ ДЕГРАДАЦИЯҒА ҰШЫРАҒАН АРИДТІ ЖЕРЛЕРДІ ГЕОЭКОЛОГИЯЛЫҚ БАҒАЛАУ ЖӘНЕ ФИТОМЕЛИОРАЦИЯЛЫҚ ҚАЛПЫНА КЕЛТІРУ

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Аннотация. *Өзектілігі.* Солтүстік Каспий маңының аридті жерлері климаттың құрғақтануы, топырақ профиілінің тұздануы, дефляция және өсімдік жамылғысының сиреуі салдарынан өнімді қызметін жоғалтуда. Жергілікті флораның тұзға және құрғақшылыққа төзімді жартылай бұталарымен жүргізілетін фитомелиорация — мәселенің ауқымына сай келетін бірден-бір мелиорациялық тәсіл, алайда оның ауыр механикалық құрамды тұзданған топырақтардағы нәтижесі сирек сандық бағаланатын эдафикалық және микрорельефтік жағдайлармен айқындалады. *Мақсаты.* Атырау облысының деградацияға ұшыраған жерлерін қалпына келтіру үшін бейімделгіш аридті түрлердің геоэкологиялық әлеуетін бағалау және олардың қалыптасуын айқындайтын топырақ пен бедер жағдайларын анықтау. *Материалдар мен әдістері.* 2024–2025 жылдары орташа тұзданған қоңыр аллювийлі орташа саздақ топырақтарда, ауданы 30 м² төрт қайталамалы делянкаларда *Kochia prostrata*, *Camphorosma monspeliaca*, *Ceratocarpus arenarius*, *Salsola orientalis* және *Kochia–Camphorosma* қоспасы зерттелді. Далалық өңгіштік, өсімдік тығыздығы, сақталуы, биіктігі, арамшөптенуі, биомасса өнімділігі және азықтық құндылығы 268,3 және 147,2 мм контрастты ылғалдану жағдайында салыстырылды. *Нәтижелері.* Ең бейімделгіш түрлер — *Kochia prostrata*, *Camphorosma monspeliaca* және олардың қоспасы: өсімдіктердің сақталуы тиісінше 83,7, 78,9 және 88,7% құрады. Қоспа биомассаның (22,0 ц/га), азықтық бірліктің (4,75 ц/га), қорытылатын протеиннің (1,10 ц/га) және алмасу энергиясының (6,77 ГДж/га) ең жоғары көрсеткіштерін берді. *Salsola orientalis* өнбеді, *Ceratocarpus arenarius* біркелкі емес өнді. Далалық өңгіштікті топырақ қабыршағының түзілуі және тұқым астындағы қабаттың тығыздалуы айқындады, бұл топырақтың механикалық құрамы мен микрорельефтің функциясы болып табылады. *Қорытынды.* *Kochia prostrata* және *Camphorosma monspeliaca*, әсіресе қоспа құрамында, учаске таңдау кезінде топырақтың механикалық құрамы мен микрорельефі ескерілген жағдайда, деградацияға ұшыраған аридті жерлерді қалпына келтіру үшін жоғары геоэкологиялық әлеуетке ие.

Түйін сөздер: геоэкологиялық бағалау, жер деградациясы, топырақ тұздануы, топырақ қабыршағы, фитомелиорация, шөлейттену, *Kochia prostrata* (L.) Schrad., *Camphorosma monspeliaca*

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ГЕОЭКОЛОГИЧЕСКАЯ ОЦЕНКА И ФИТОМЕЛИОРАТИВНОЕ ВОССТАНОВЛЕНИЕ ДЕГРАДИРОВАННЫХ АРИДНЫХ ЗЕМЕЛЬ АТЫРАУСКОЙ ОБЛАСТИ ЗАПАДНОГО КАЗАХСТАНА

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Аннотация. *Актуальность.* Аридные земли Северного Прикаспия постепенно утрачивают свою продуктивность под воздействием комплекса природных и антропогенных факторов, включая усиление засушливости климата, засоление почвенного профиля, дефляционные процессы и сокращение растительного покрова. Одним из перспективных способов восстановления деградированных территорий является фитомелиорация с использованием солеустойчивых и засухоустойчивых полукустарничков местной флоры. Однако эффективность данного подхода на засоленных почвах тяжелого гранулометрического состава в значительной степени зависит от почвенных характеристик и особенностей микрорельефа, влияние которых требует количественной оценки. *Цель.* Оценить геоэкологический потенциал адаптированных к аридным условиям видов растений для восстановления деградированных земель Атырауской области, а также выявить почвенные и микрорельефные факторы, определяющие их всхожесть, приживаемость и продуктивность. *Методы.* В 2024–2025 гг. проведены полевые исследования на средnezасоленных бурых аллювиальных среднесуглинистых почвах. Эксперименты выполнялись на делянках площадью 30 м² в четырех повторностях. Изучались виды *Kochia prostrata*, *Camphorosma monspeliaca*, *Ceratocarpus arenarius*, *Salsola orientalis*, а также травосмесь *Kochia prostrata* и *Camphorosma monspeliaca*. Оценивали полевую всхожесть, густоту стояния, сохранность, высоту растений, засоренность

посевов, продуктивность биомассы и питательную ценность корма. Сравнительный анализ проводился при различающихся условиях увлажнения, характеризовавшихся количеством осадков 268,3 и 147,2 мм. *Результаты.* Наиболее высокую адаптивность к исследованным почвенно-климатическим условиям продемонстрировали *Kochia prostrata*, *Camphorosma monspeliaca* и их травосмесь. Сохранность растений составила 83,7 %, 78,9 % и 88,7 % соответственно. Наибольшая продуктивность установлена для травосмеси: урожайность биомассы достигла 22,0 ц/га, выход кормовых единиц - 4,75 ц/га, переваримого протеина - 1,10 ц/га, а обменной энергии - 6,77 ГДж/га. В исследованных условиях всходы *Salsola orientalis* отсутствовали, тогда как *Ceratocarpus arenarius* характеризовался крайне неравномерным появлением всходов. Установлено, что формирование почвенной корки и уплотнение подсеменного слоя ограничивали полевую всхожесть растений. Выявленные особенности могут быть связаны с гранулометрическим составом почвы и условиями микрорельефа. *Заключение.* Результаты исследования свидетельствуют о высоком потенциале *Kochia prostrata* и *Camphorosma monspeliaca* для фитомелиоративного восстановления деградированных аридных земель Атырауской области. Наиболее перспективным вариантом является совместное выращивание указанных видов в составе травосмеси, обеспечивающее повышенную сохранность растений, продуктивность биомассы и кормовую ценность. При выборе участков для фитомелиорации необходимо учитывать гранулометрический состав почв, степень их засоления, вероятность образования почвенной корки и особенности микрорельефа. Полученные результаты могут использоваться при разработке мероприятий по восстановлению деградированных пастбищных угодий в аридных условиях Северного Прикаспия.

Ключевые слова: геоэкологическая оценка, деградация земель, засоление почв, почвенная корка, фитомелиорация, опустынивание, *Kochia prostrata* (L.) Schrad., *Camphorosma monspeliaca*

Introduction. The arid lands of the northern Caspian Lowland are among the most degradation-prone territories of Kazakhstan. Their soil–vegetation cover has formed on young alluvial and alluvial-deltaic deposits, is saline through most of the profile, and carries a sparse xerophytic cover whose loss exposes fine-textured material to deflation. In the Atyrau Region this combination of lithological, hydrogeological and climatic conditions, reinforced by prolonged grazing pressure, has produced a progressive loss of vegetation cover, a decline in the productive function of the land, and an expansion of deflation-prone surfaces. Reclaiming such land calls for measures that work at low cost over large areas and depend on neither irrigation nor drainage, neither of which is available here. Phytomelioration — the deliberate re-establishment of a self-sustaining cover of salt- and drought-tolerant native semi-shrubs — is the principal option, but its success is governed less by the

choice of species than by the soil-physical and microtopographic conditions met at the moment of germination.

The adaptive potential of halophytic semi-shrubs under such conditions has been established in a series of regional studies. Mukhambetov et al. (2024) demonstrated stable growth of *Kochia prostrata* (L.) Schrad. and *Camphorosma monspeliaca* on saline land of the northern Caspian desert, and Mukhambetov et al. (2023) quantified the effect of soil and climatic conditions on the chemical composition of *K. prostrata* forage. Kadasheva et al. (2025) reported that *C. monspeliaca* raises vegetation diversity and productivity on degraded land in the arid regions of Kazakhstan, while Nasiyev et al. (2019) established the fodder potential of Sudan grass under the conditions of Western Kazakhstan. Shamsutdinova et al. (2022) related the adaptation of fodder halophytes to their root architecture in saline and dry soils, and Meldebekova et al. (2024) addressed the breeding improvement of *K. prostrata*.

Despite this body of work, the reclamation of degraded arid land in the Atyrau Region has not been assessed within a single geoecological framework linking soil salinity and texture, surface condition, climatic variability and the resulting vegetation response. The aim of the study was to assess the geoecological potential of salt-, solonetz- and drought-tolerant species of the local flora for the reclamation and productive use of degraded arid land in the northern desert of Western Kazakhstan, with explicit account of heterogeneous soil and landform conditions. The objectives were: (1) to determine the biometric establishment and growth parameters of the selected species under contrasting soil-moisture regimes; (2) to identify the soil-physical and microtopographic conditions that control field emergence; and (3) to compare the biomass, hay and fruit-forage productivity and the forage value of the resulting cover as a measure of the productive capacity recovered by the land.

Literature review. The outcome of dryland reclamation is largely decided in the first weeks after sowing. Shackelford et al. (2021), analysing a large set of dryland restoration efforts, showed that seedling establishment is controlled by site-specific environmental and biotic drivers rather than by species choice alone - a conclusion of direct relevance to saline and solonchic land, where establishment is constrained simultaneously by salinity, surface hardening and moisture deficit. Water availability at that stage is decisive: Tatsumi et al. (2021) found that micro-catchment water harvesting on a degraded dryland improved soil microbial abundance, diversity and function, indicating that measures directed at the soil water regime also act on belowground processes. Garbowski et al. (2021) showed that an invasive annual grass interacts with drought to modify both community composition and soil moisture, so that competition for a limited water store must be weighed alongside the establishment of the target species.

Surface and soil management provides a second lever. Leger et al. (2022) found mulch more effective than compost in improving soil health during vegetation re-

establishment on semiarid rangeland, and Kimmell et al. (2023), in a global meta-analysis, established that soil restoration practices improve soil-health indicators across drylands, with a magnitude set by environmental context. Taken together, these studies indicate that the reclamation of degraded arid land requires seedling establishment, water availability, soil physical condition, plant competition and site-specific terrain conditions to be treated simultaneously. Their application to mixed stands of *K. prostrata* and *C. monspeliaca* on the saline and solonchic soils of the Atyrau Region has not been tested, which defines the object of the present study.

Materials and Methods. The study was based on field experiments conducted in space and time on degraded land of the semi-desert and desert zones of the Atyrau Region, Western Kazakhstan. The experimental soils are moderately saline brown alluvial soils of medium loamy texture; the moderately saline layer extends to about 60 cm and is underlain by very strongly saline material. Available nitrogen and phosphorus are low and exchangeable potassium is very high. Plots were 30 m² and were laid out in four replications. Seed of all species was collected within the Atyrau Region, so that the tested material is of local provenance and adapted to the regional salinity and moisture regime.

Field trials were established by pre-winter sowing on 16–18 November 2023 and 2024, using the species and the grass mixture listed in Table 1.

Table 1. Plant species and grass mixtures used in the field experiments.

№	Name of species and grass mixtures
1	<i>Kochia prostrata</i> (L.) Schrad
2	<i>Camphorosma monspeliaca</i>
3	<i>Ceratocarpus arenarius</i>
4	<i>Salsola orientalis</i>
5	Grass mixtures (<i>Kochia prostrata</i> + <i>Camphorosma monspeliaca</i>)

Field emergence was assessed by counting established seedlings in each plot after the end of the emergence period. Plant density was determined at the beginning and at the end of the growing season and expressed in plants m⁻²; the ratio of the two characterises the completeness of establishment and the loss of plants during the season. Spatial uniformity of emergence was recorded separately, because *Ceratocarpus arenarius* emerged unevenly and *Salsola orientalis* did not emerge at all under the experimental conditions. Plant height was measured from the soil surface to the apex of the main shoot at the beginning and at the end of the season. For second-year plants the biometric observations were supplemented by the principal phenological stages - emergence, stem formation, budding, flowering, fruiting and full fruit maturity - which allowed the rate of development to be related to the seasonal course of temperature and precipitation.

Weed infestation was counted as the number of weed plants per square metre at the beginning of the growing season and used to compare the competitive performance of the single-species stands and of the *K. prostrata*–*C. monspeliaca* mixture; a lower

weed density in the mixture was interpreted as more complete occupation of the available growing space. Biomass and hay yield were determined for second-year plants at the harvesting stage, recalculated per hectare and expressed in centners per hectare (c ha⁻¹). For each variant, pasture mass, hay yield, feed units, digestible protein and metabolizable energy were determined, which links the establishment indicators to the productive capacity recovered by the reclaimed land.

The forage value of the restored cover was characterised through the chemical composition of the dry matter - crude protein, crude fat, crude fibre, nitrogen-free extractive substances, starch, sugar, ash, calcium, phosphorus and carotene - from which feed units, digestible protein, metabolizable energy and energy feed units were calculated. The geoeological component of the methodology rested on comparing the plant response under contrasting annual moisture conditions. Total precipitation, its distribution during the emergence period, the seasonal temperature regime and the soil properties of each plot were treated as environmental factors acting on establishment and subsequent productivity, and the 2023–2024 and 2024–2025 agricultural years were therefore treated as two contrasting environments rather than as replicates. Differences in emergence date, plant density, retention, height and productivity were interpreted against the recorded differences in precipitation and temperature. Species combining stability of establishment with higher productive characteristics were considered more suitable for the reclamation of degraded arid land.

Agronomic practices. The arid species were sown at 4–10 kg ha⁻¹ after autumn ploughing to 20–22 cm. The field was disked twice before ploughing to control weeds and harrowed in two passes afterwards. No further operations were carried out in the year of sowing.

Weather conditions. By total precipitation the 2023–2024 agricultural year was relatively favourable, with 268.3 mm against a long-term mean of 189.8 mm. The 2024–2025 year was dry, with 147.2 mm, a deficit of 42.6 mm against the mean. The two years were therefore used as contrasting moisture environments in the interpretation of establishment and productivity.

Feed analysis. Feed quality was assessed by zootechnical and chemical analysis after preliminary sample preparation, using an INFRAXACN 7500 feed analyser (Sweden). Protein, fat, fibre, ash, sugar, starch, carotene, calcium and phosphorus were determined on an Inframac instrument (Denmark).

A full zootechnical analysis was carried out at the Feed Quality Analysis Laboratory of the Kazakh Research Institute of Livestock and Fodder Production and covered 18 parameters: initial, hygroscopic and total moisture, dry matter, crude protein, crude fat, crude fibre, nitrogen-free extractive substances (NFES), starch, sugar, ash, calcium, phosphorus, carotene, feed units, digestible protein, metabolizable energy and energy feed units.

Initial moisture content was determined by drying feed samples to constant weight at 65–70°C. Hygroscopic moisture was determined by drying a 2-g sample to constant weight at 100–105°C. Total moisture content was calculated as:

$$TM = IM + GM (100 - IM)/100, \quad (1)$$

where TM is total moisture, IM is initial moisture, GM is hygroscopic moisture. Dry matter was determined using the formula:

$$DM = 100 - TM \quad (2)$$

where DM is dry matter and TM is total moisture.

Data analysis

Feed unit, digestible protein, metabolizable energy, energy feed unit were determined by the following formulas:

$$FU = (1.176 \cdot CP + 1.953 \cdot CFat + 0.903 \cdot NFES) / 100, \quad (3)$$

where FU is feed units per kg, CP is crude protein, CFat is crude fat and NFES is nitrogen-free extractive substances, all expressed as a percentage of the natural-moisture sample.

$$DP = CP \cdot Kd, \quad (4)$$

where DP is digestible protein (g kg^{-1}), CP is crude protein (g kg^{-1}) and Kd is the protein digestibility coefficient of the feed, which for the samples analysed here lies between 0.76 and 0.77.

$$ME = 17.71 \cdot dCP + 37.89 \cdot dCFat + 13.44 \cdot dCFib + 14.78 \cdot dNFES, \quad (5)$$

where ME is metabolizable energy and dCP, dCFat, dCFib and dNFES are the digestible crude protein, crude fat, crude fibre and nitrogen-free extractive substances respectively.

$$EFU = ME / 10 \quad (6)$$

where EFU is energy feed units and ME is metabolizable energy.

Assessment of establishment and retention. The persistence of the restored cover was expressed as plant retention, the percentage of plants surviving to the end of the growing season:

$$PR = De / Di \cdot 100, \quad (7)$$

Where PR is plant retention (%), (De) is plant density at the end of the growing season (plants m^{-2}), and (Di) is plant density at the beginning of the growing season (plants m^{-2}).

Higher retention indicates a more persistent cover and, in geoeological terms, a longer period over which the soil surface is protected from deflation and from the

kinetic energy of rainfall. Biometric parameters were determined on 1 m² sampling frames in each variant, within which cultivated plants and weeds were counted and plant height was measured with a ruler from the soil surface to the stem apex; the values were averaged by variant.

Results and Discussions. Degraded arid land is treated here as a coupled soil–vegetation system in which the recovery of cover and the recovery of soil properties are mutually dependent. Zhou et al. (2023) showed for the arid and semi-arid regions of China that vegetation restoration alters soil organic matter, nutrient availability and biomass, with the magnitude depending on the restoration pathway; the assessment of reclamation therefore cannot rest on aboveground biomass alone. Wiethase et al. (2023) further showed that degraded rangeland loses resistance to environmental pressure while retaining a capacity for recovery once the controlling ecological conditions are re-established. In the Atyrau Region aridity, profile salinity, irregular precipitation and grazing pressure act jointly, so the reclamation potential of a species has to be judged by its ability to establish and persist under the combination rather than under any single factor.

The limiting step is germination and early root growth, and it is controlled by the physical state of the uppermost soil layer rather than by the annual water balance. Eldridge and Ding (2023) found that microtopographic treatments such as pitting do not by themselves sustain improvements in ecosystem structure, their effect depending on site conditions. The same dependence governs the establishment of *K. prostrata* and *C. monspeliaca* on the medium-loamy saline soils of the study area, where uneven drying of the surface, crust formation and compaction of the upper layer act directly on field emergence and early survival. A technical assessment of reclamation on such land must therefore treat soil texture, moisture accumulation, surface condition and sowing date as design variables rather than as background. Observations in the 2023–2024 and 2024–2025 agricultural years were used to separate their effects. Three factors were found to determine emergence:

- a) the water–physical condition of the soil, which may produce a crust above the seed and a hard, dry monolith beneath it - in the first case the seedling of an arid species dies under the crust, in the second the cotyledon root cannot penetrate the hardened layer and the seedling dies as well;
- b) the temperature regime during emergence and the precipitation received in that period;
- c) the level of field weed infestation.

In the 2023–2024 agricultural year 268.3 mm of precipitation fell, 78.5 mm above the long-term mean of 189.8 mm, but its distribution over the emergence period was uneven — 46.1 mm in March and 1.6 mm in April 2024. The autumn–winter period gave 164.7 mm against a mean of 89 mm, so the profile entered spring close to saturation. Emergence was nevertheless determined by temperature and not by moisture: despite the March rainfall the seed did not germinate, and seedlings appeared only on 18 April, when mean air temperature rose from 1.8 °C in March to 16.4 °C in April and monthly precipitation had fallen from 46.1 to 1.6 mm (Table 2).

Table 2. Biometric parameters of growth and development of arid plant species in the first year of life (Atyrau Region, 2024).

Variants	Plant density, plants m ⁻²		Height, cm		Number of weeds, plants m ⁻²
	at the beginning of growing season	at the end of growing season	at the beginning of growing season	at the end of growing season	at the beginning of growing season
Kochia prostrata	104	57.2	5.8	7.3	61.2
Camphorosma monspeliaca	130.5	66.8	3.8	4.4	49.2
Grass mixtures (Kochia prostrata + Camphorosma monspeliaca)	112	71	7.6	8.8	38.5

Kochia prostrata, *Camphorosma monspeliaca* and the grass mixture responded to the high soil moisture of March–April 2024 with a stand density at emergence of 104–130.5 plants m⁻², two to five times the long-term average for the region (25–34 plants m⁻²). Heights were 5.8 and 3.8 cm at emergence and 7.3 and 4.4 cm at the end of the season for *K. prostrata* and *C. monspeliaca* respectively. *Salsola orientalis*, a species of the southern Kazakh deserts, did not germinate under northern desert conditions, and *Ceratocarpus arenarius* emerged over about three quarters of its plots with no seedlings on the remainder; the same pattern was repeated at the second sowing. In the first year these species complete their cycle at the stem-formation stage, with a single stem of 4.4 cm (*C. monspeliaca*) to 7.3 cm (*K. prostrata*), and cannot form a productive mass. The 2024–2025 agricultural year was dry, with 147.2 mm against the long-term 189.8 mm, but its distribution was sharply contrasting: the moisture accumulated in the profile during autumn, winter and early spring was close to the long-term norm and proved more favourable for first-year growth, which reached 8.2 cm (*C. monspeliaca*) and 9.8–11.6 cm (*K. prostrata* and the mixture), as shown in Table 3.

Table 3. Biometric parameters of growth and development of arid plant species in the first year of life (Atyrau Region, 2025).

Variants	Plant density, plants m ⁻²		Height, cm		Number of weeds, plants m ⁻²	Plant retention (%)
	at the beginning of growing season	at the end of growing season	at the beginning of growing season	at the end of growing season	at the beginning of growing season	
Kochia prostrata	98	82	9,8	21	49,6	83,7
Camphorosma monspeliaca	90	71	8,2	18	40,3	78,9
Grass mixtures	62	55	11,6	24	30,9	88,7

By the end of the growing season plant heights were 18 cm (*C. monspeliaca*), 21 cm (*K. prostrata*) and 24 cm (the mixture). Stand density was favourable both at emergence and at the end of the season — 62 to 98 plants m^{-2} in spring and 55 to 82 plants m^{-2} in autumn — which is sufficient to secure a productive aboveground mass in the second and subsequent years. *Kochia prostrata* combined the highest density (98 plants m^{-2} at the beginning and 82 at the end of the season) with growth from 9.8 to 21 cm and a weed count of 49.6 plants m^{-2} . *Camphorosma monspeliaca* held 90–71 plants m^{-2} , grew from 8.2 to 18 cm and carried 40.3 weeds m^{-2} . The mixture gave a lower but satisfactory density (62–55 plants m^{-2}), the greatest height increment (11.6 to 24 cm) and the lowest weed infestation of all variants (30.9 plants m^{-2}), indicating that the two species together occupy the growing space more completely than either alone. *Ceratocarpus arenarius* again emerged unevenly, and in some plots not at all, while *Salsola orientalis* did not emerge, confirming that neither is suitable for reclamation under these conditions.

Plant retention characterises the persistence of the restored cover. The highest value was recorded for the grass mixture (88.7%), followed by *K. prostrata* (83.7%) and *C. monspeliaca* (78.9%). Retention above three quarters in all three variants indicates that, once established, the stands persist through the season under arid and moderately saline conditions. The combination of the highest retention, the greatest final height and the lowest weed density places the mixture ahead of the single-species stands. In geoecological terms, holding a high proportion of the established plants prolongs the period over which the surface is covered, and this is the mechanism by which phytomelioration acts against deflation and further loss of the soil–vegetation cover. Weeds did not noticeably suppress growth in the first year of establishment.

In the 2024–2025 agricultural year an early spring - snowmelt on 8 March - brought emergence forward to 10 March for *K. prostrata* and 9 March for *C. monspeliaca*, a month earlier than in 2023–2024. Air temperature during the two days before and after emergence rose sharply to +6...+9 °C, close to the optimum for the germination of these species. Both entered the stem-formation phase of the first year on 2 May (*K. prostrata*) and 31 May (*C. monspeliaca*) and remained in it until the end of the growing season in November–December.

Second-year *K. prostrata* emerged on 6 April, reached stem formation on 11 May, budding on 28 May, flowering on 8 June and fruiting on 16 July; full fruit maturity was recorded on 18–21 October. *Camphorosma monspeliaca* developed 2–4 days ahead of *K. prostrata* and 5–7 days behind the grass mixture. Second-year stands responded to the high early-spring moisture supply with the heights and foliage shown in Table 4: the mixture reached 30 cm and *K. prostrata* and *C. monspeliaca* 27 cm each, with foliage of 33% in the mixture, 40% in *K. prostrata* and 38% in *C. monspeliaca*.

Table 4. Biometric parameters of growth and development of arid plant species in the second year of life (Atyrau Region, 2025).

Variants	Plant density, plants m ⁻²	Height, cm	Foliage, %
Kochia prostrata	15	27	40
Camphorosma monspeliaca	14,2	27	38
Grass mixtures	9,5	30	33

Weeds suppressed the growth of second-year *K. prostrata* and *C. monspeliaca* less than that of first-year plants, the established stands having by then occupied the growing space.

Table 5. Chemical composition and nutritional value of the forage of arid plant species (Atyrau Region, 2025).

Variant no.	Sample name	DM	In natural form, %										Feed units per 1 kg	DP, g	EE, MJ	EFU	EC
			Protein	Fat	Fiber	NFES	Sugar	Starch	Ash	Ca	P	Carotene, mg					
1	Second year's Kochia prostrata hay	92,63	22,90	5,49	20,06	41,91	2,80	49,11	2,27	1,37	0,45	35,58	0,75	174,04	10,70	1,07	1,15
2	Second year's Kochia prostrata fruit forage	93,07	23,56	6,27	18,33	39,98	-	43,88	4,94	0,90	0,48	34,57	0,76	179,02	10,77	1,08	1,15
3	Second year's Camphorosma monspeliaca hay	93,82	20,92	3,90	24,72	40,09	-	27,18	4,19	0,96	0,32	23,67	0,68	161,09	9,84	0,98	1,04

Note: DM – dry matter; NFES – nitrogen-free extractive substances; Ca – calcium; P – phosphorus; FU – feed units; DP – digestible protein; ME – metabolizable energy; EFU – energy feed units per kg of natural-moisture feed; EC – energy feed units per kg of dry matter.

Dry matter in *K. prostrata* hay of different ages ranges from 92.63 to 93.82% at natural moisture and varies little between samples (Table 5). The differences that matter for forage value lie in protein, fat and fibre. Fruit forage exceeds hay on every one of them: 23.56% protein, 6.27% fat and 18.33% fibre, against 22.90, 5.49 and 20.06% respectively in hay.

Camphorosma monspeliaca hay is the poorest of the three samples, with 20.92% protein, 3.90% fat and 24.72% fibre. Per kilogram, the fruit forage yields 179.02 g of digestible protein, 10.77 MJ of metabolizable energy and 1.08 energy feed units; *K. prostrata* hay 174.04 g, 10.70 MJ and 1.07; and *C. monspeliaca* hay 161.09 g, 9.84 MJ and 0.98. GOST R 55452–2021 sets its quality limits on a dry-matter basis; recalculated to dry matter, crude protein, crude fibre and metabolizable energy are 247 g kg⁻¹, 217 g kg⁻¹ and 11.6 MJ kg⁻¹ in *K. prostrata* hay, 253 g kg⁻¹, 197 g kg⁻¹ and 11.6 MJ kg⁻¹ in the fruit forage, and 223 g kg⁻¹, 263 g kg⁻¹ and 10.5 MJ kg⁻¹ in *C. monspeliaca* hay. All three feeds exceed the first-class limits the standard sets for hay from natural forage lands (at least 120 g kg⁻¹ crude protein, at most 290 g kg⁻¹ crude fibre and at least 8.9 MJ kg⁻¹ metabolizable energy). Against its strictest

first-class limits, those for seeded legume hay (150 g kg^{-1} , 260 g kg^{-1} and 9.2 MJ kg^{-1}), *K. prostrata* hay and the fruit forage still qualify, whereas *C. monspeliaca* hay exceeds the fibre limit marginally. The productivity of the second-year stands is given in Table 6.

Table 6. Productivity and energy–protein value of two-year-old arid plants promising for the reclamation of degraded lands in the semi-desert and desert zones of Kazakhstan (Atyrau Region, 2025).

Variants	Pasture mass, c/ha	Hay, c/ha	Feed units, c/ha	Digestible protein, c/ha	Metabolizable energy, GJ/ha
Kochia prostrata	20,0	6,0	4,5	1,04	6,10
Camphorosma monspeliaca	17,5	5,2	3,54	0,84	5,12
Grass mixtures(Kochia prostrata+ Camphorosma monspeliaca)	22,0	6,6	4,75	1,10	6,77
LSD _{0.05} , c/ha	-	0,42	-	-	-

Single-species *K. prostrata* and the grass mixture gave the highest yields of feed units, digestible protein and metabolizable energy - 4.5 c ha^{-1} , 1.04 c ha^{-1} and 6.10 GJ ha^{-1} , and 4.75 c ha^{-1} , 1.10 c ha^{-1} and 6.77 GJ ha^{-1} respectively. *Camphorosma monspeliaca* was lowest, at 3.54 c ha^{-1} , 0.84 c ha^{-1} and 5.12 GJ ha^{-1} . *Salsola orientalis* and *Ceratocarpus arenarius* formed too sparse a stand to yield a measurable mass and are of no practical value in pure sowing. Among the salt-, solonetz- and drought-tolerant species of the northern desert of Western Kazakhstan, therefore, adaptive capacity ranks in the order: grass mixture > *K. prostrata* > *C. monspeliaca*.

This ranking was obtained across two contrasting years - a wet first year and a dry second year, with 268.3 and 147.2 mm of annual precipitation - which indicates that productivity in the second year is set largely by the moisture conditions of the first: the better the establishment year, the higher the subsequent yield. The principal obstacle to wider use of these species is not their productivity but the unevenness of their field emergence, which becomes more pronounced as the sown area increases. Emergence counts on soils of differing texture show that the optimum stand is obtained on light-textured soils — sand, sandy loam and light loam - whereas on heavy loam and clay the stand alternates between dense patches and bare ground. The mechanism is the differential drying of the surface layer in which the seed lies. On uneven terrain and on convex slope elements the surface loses moisture faster, and a crust forms that the seedling of an arid semi-shrub cannot break through. Beneath the seed, the same layers are dried by wind into hard monoliths through which the root of the young plant cannot reach the moister soil below, so that the seedling dies. Where plants do establish on rapidly drying convex elements they grow slowly and remain stunted. The unevenness of the first year thus propagates into every subsequent year, and the design of a reclamation scheme on heavy-textured saline land must treat surface texture and microrelief as criteria for selecting the site, not as noise.

Water availability is the principal ecological constraint on vegetation development in drylands. Wang et al. (2022) found that vegetation restoration dominated the increase in water-use efficiency of Chinese drylands, so that recovering cover modifies the relation between water supply and productivity. The comparison of the two agricultural years here shows that the amount of precipitation alone does not characterise reclamation conditions: its timing relative to germination and early root growth does.

Climatic thresholds matter when judging whether restoration is feasible at all. Zhang et al. (2024) showed that the relation between ecological restoration and atmospheric drought depends on the degree of aridity and on land–atmosphere coupling, restoration mitigating atmospheric drought under suitable conditions but being constrained where water limitation is severe. For the Atyrau Region this places precipitation, air temperature, seasonal moisture supply and soil water status together in any assessment of reclamation potential.

A restored cover must also be monitored at the scale at which land degradation occurs. Retallack et al. (2024) demonstrated the use of remote sensing to track rangeland condition over fifteen years following the removal of livestock. Field measurements of density, retention, biomass and cover can therefore be combined with spatial monitoring to follow reclamation over large areas and long periods.

Sowing decisions are themselves a technical lever. Copeland et al. (2025) showed that restoration outcomes depend strongly on seeding decisions and on the weather encountered immediately after germination - which is precisely what the earlier emergence of *K. prostrata* and *C. monspeliaca* under the warm early spring of 2025 illustrates. Surface management acts on the same stage: Leger et al. (2022) found mulch more effective than compost in restoring soil health and supporting re-establishment on semiarid rangeland, and Kimmell et al. (2023) showed across drylands that soil restoration improves soil health by a margin set by context. Although the present work tested species rather than amendments, its results point the same way: the establishment of *K. prostrata* and *C. monspeliaca* should be evaluated by its contribution to maintaining cover, adding organic matter and reducing the exposed soil surface, and not by biomass alone.

Finally, the hydrological consequences of reclamation constrain its scale. Fu et al. (2025) argued that cost-effective dryland restoration requires the water balance to be considered explicitly, because measures that raise productivity also raise water demand. The higher productivity and retention of the grass mixture must therefore be read together with its water requirement under limited supply. Assessing *K. prostrata*, *C. monspeliaca* and their mixture as components of a reclamation strategy for degraded arid land thus requires soil properties, soil moisture, the precipitation and temperature regimes, field emergence, density, retention, growth, weed competition, biomass, forage quality and cover stability to be treated as one system.

Conclusion. The species tested differ sharply in their suitability for the reclamation of degraded arid land in the semi-desert and desert zones of the Atyrau

Region. *Kochia prostrata* and *Camphorosma monspeliaca* established reliably and held high stand densities under low weed pressure. Retention at the end of the growing season was 83.7% for *K. prostrata*, 78.9% for *C. monspeliaca* and 88.7% for their mixture, indicating a cover that persists through the season on arid, moderately saline soil.

The grass mixture gave the highest biomass, 22.0 c ha⁻¹ against 20.0 for *K. prostrata* and 17.5 for *C. monspeliaca*, together with the highest yields of feed units (4.75 c ha⁻¹), digestible protein (1.10 c ha⁻¹) and metabolizable energy (6.77 GJ ha⁻¹). *Kochia prostrata* followed with 4.50 c ha⁻¹, 1.04 c ha⁻¹ and 6.10 GJ ha⁻¹, and *C. monspeliaca* with 3.54 c ha⁻¹, 0.84 c ha⁻¹ and 5.12 GJ ha⁻¹; the lower productivity of the latter is offset by its tolerance of salinity, which makes it valuable as a component of the mixture rather than in pure stand.

Salsola orientalis did not germinate in the field under the conditions of the northern desert of Western Kazakhstan, and *Ceratocarpus arenarius* established very unevenly; neither can be recommended for reclamation here.

The decisive constraint, however, is not the choice of species but the physical state of the seedbed. On light-textured soils the stand is even; on heavy loam and clay, and on convex slope elements that dry rapidly, a surface crust together with a hardened layer beneath the seed produces alternating dense and bare patches that persist into later years. Soil texture and microrelief should therefore be used as site-selection criteria in the design of phytomeliorative schemes on degraded arid land.

Taken together, the retention, establishment and productivity of *K. prostrata* and *C. monspeliaca*, and particularly of their mixture, demonstrate a high geoecological potential for restoring the productive function of degraded arid land, maintaining vegetation cover, reducing exposed soil surfaces and slowing desertification in the northern desert and semi-desert of Western Kazakhstan.

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<http://www.geolog-technical.kz/index.php/en/>
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)**

Managing Editor: *T. Apendiyev*
Editors: *D.S. Alenov, A.Shormakova*
Computer layout: *G.D. Zhadyranova*

Signed for print: Oktober 14, 2026
Format: 70×90 1/16. 26.5 printed sheets. Order No. 5.

*«Central Asian Academic Research Center» LLP
Almaty, Shevchenko Street, 28*