QO‘QON DAVLAT PEDAGOGIKA INSTITUTI ILMIY XABARLARI
(2026-yil 8-son)

TABIIY FANLAR

NATURAL SCIENCES

https://doi.org/10.70728/a.series.tab.v08.i08.029

DIVERSITY AND BIOTECHNOLOGICAL POTENTIAL OF THE MICROBIOME OF SALSOLA PLANTS DISTRIBUTED IN THE DESERT REGIONS OF UZBEKISTAN

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Abstract. The deserts of Uzbekistan -Kyzylkum, Ustyurt, and Aralkum -represent extreme ecosystems characterized by high soil salinity, water deficit, and sharp temperature fluctuations. Plants of the genus Salsola (family Amaranthaceae/Chenopodiaceae) are among the key edificators of halophytic and psammophytic vegetation in these territories. Over the past decade, microbiology worldwide has increasingly recognized that halophyte resilience to stress conditions is largely mediated by associated microbial communities -rhizosphere, endophytic, and phyllosphere microbiomes. This article summarizes current knowledge on the taxonomic structure and functional diversity of the microbiome of Salsola species and related halophytes of arid zones, and examines their biotechnological potential -ranging from the development of biofertilizers and biopreparations to enhance salt and drought tolerance of crops, to the bioremediation of saline and technogenically contaminated soils, and the search for novel enzymes and bioactive compounds.

Keywords: Salsola, microbiome, rhizosphere, endophytic bacteria, halophytes, desert ecosystems, biotechnological potential, Kyzylkum, Aralkum, salt tolerance

Аннотация. Пустыни Узбекистана -Кызылкум, Устюрт, Аралкум -представляют собой экстремальные экосистемы с высокой засолённостью почв, дефицитом влаги и резкими температурными перепадами. Растения рода Salsola (солянка), относящиеся к семейству Amaranthaceae (Chenopodiaceae), являются одними из ключевых эдификаторов галофитной и псаммофитной растительности этих территорий. В последние годы в мировой микробиологии сформировалось понимание того, что устойчивость галофитов к стрессовым условиям во многом обеспечивается ассоциированными с ними микробными сообществами -ризосферными, эндофитными и филлосферными. В статье обобщены современные представления о структуре и функциональном разнообразии микробиома растений рода Salsola и родственных им галофитов аридных зон, а также рассмотрен их биотехнологический потенциал -от создания биоудобрений и биопрепаратов для повышения соле- и засухоустойчивости

сельскохозяйственных культур до биоремедиации засолённых и нефтезагрязнённых почв и поиска новых ферментов и биологически активных соединений.

Ключевые слова: Salsola, микробиом, ризосфера, эндофитные бактерии, галофиты, пустынные экосистемы, биотехнологический потенциал, Кызылкум, Аралкум, солеустойчивость

Annotatsiya. O‘zbekiston cho‘l hududlari - Qizilqum, Ustyurt, Orolqum -yuqori tuproq sho‘rlanishi, namlik tanqisligi va keskin harorat tebranishlari bilan ajralib turadigan ekstremal ekotizimlardir. Amaranthaceae (Chenopodiaceae) oilasiga mansub Salsola (sho‘ra) turkumi o‘simliklari ushbu hududlarning galofit va psammofit o‘simlik qoplamining asosiy edifikatorlaridan biri hisoblanadi. So‘nggi yillarda jahon mikrobiologiyasida galofit o‘simliklarning stress sharoitlariga chidamliligi ko‘p jihatdan ular bilan assotsiatsiyalangan mikroblar hamjamiyatlari -rizosfera, endofit va fillosfera mikrobiomlari -tomonidan ta’minlanishi haqida tushuncha shakllandi. Maqolada Salsola turkumiga mansub hamda unga yaqin galofit o‘simliklar mikrobiomining tuzilishi va funksional xilma-xilligi bo‘yicha zamonaviy ma’lumotlar umumlashtirilgan, shuningdek uning biotexnologik salohiyati - qishloq xo‘jaligi ekinlarining sho‘rlanish va qurg‘oqchilikka chidamliligini oshiruvchi bio-o‘g‘itlar va biopreparatlar yaratishdan tortib, sho‘rlangan va texnogen ifloslangan yerlarni bioremediatsiya qilish hamda yangi fermentlar va biofaol birikmalarni izlashgacha bo‘lgan yo‘nalishlarda - ko‘rib chiqilgan.

Kalit so‘zlar: Salsola, mikrobiom, rizosfera, endofit bakteriyalar, galofitlar, cho‘l ekotizimi, biotexnologik salohiyat, Qizilqum, Orolqum, sho‘rlanishga chidamlilik.

Introduction. Deserts cover more than 20% of the territory of Uzbekistan, and the degradation and secondary salinization of irrigated lands -aggravated by the shrinking of the Aral Sea -continue to expand the area of low-productivity saline soils. Under these conditions, natural halophytic vegetation, primarily species of the genus Salsola (Russian saltwort, cherkez, boyalych, biyurgun, and other saltwort species), plays an important environment-forming role: it stabilizes shifting sands, participates in soil formation, and serves as a forage base for pastoral livestock farming.

For a long time, research on Salsola was limited to botanical systematics, physiology of drought and salt tolerance, and chemotaxonomy (alkaloids, flavonoids). However, the body of knowledge accumulated over the past decade on the microbiomes of desert halophytes in Pakistan, China, Iran, and the Atacama shows that the adaptation of halophyte plants to extreme conditions results not only from their own physiological mechanisms but also from close metabolic interaction with associated microorganisms. Studies focused specifically on Salsola in Uzbekistan remain scarce; however, closely related work carried out on other desert halophytes of the region (teresken shrublands and saltwort communities of the Aral Sea region and the Ustyurt Plateau), together with the substantial body of data on Salsola stocksii and other saltwort species from neighboring arid zones of Central and South Asia, allows a reasonably complete picture to be drawn.

Botanical and ecological characteristics of salsola in Uzbekistan

The genus Salsola comprises several dozen species of annual and perennial shrubs and subshrubs adapted to saline substrates -takyrs, solonchaks, sandy and gravelly deserts. In Kyzylkum and on the Ustyurt Plateau, the most widespread species are cherkez (Salsola richteri, now frequently placed within the broadly defined genus Haloxylon/Salsola), boyalych (Salsola arbuscula), biyurgun (Salsola orientalis), and a number of annual species forming saltwort wastelands on solonchaks. These plants are true xerohalophytes: they tolerate soil-solution salinity of tens of parts per thousand, high summer surface soil temperatures (up to 45–50 °C), and prolonged rainless periods.

The rhizosphere of Salsola forms under conditions of sharp contrast with the surrounding saline soil: root exudates (sugars, organic acids, amino acids) create a local zone of elevated carbon availability and reduced salinity relative to the surrounding soil matrix. This effect -a decrease in salinity and enrichment with organic matter in the root zone -is a key factor shaping the specific composition of the microbial community of halophytes, a pattern also confirmed by data on other desert plants of the region.

Methodological approaches to studying the halophyte microbiome

Modern studies of the halophyte plant microbiome rely on a combination of culture-dependent and culture-independent (metagenomic) methods:

Culture-dependent methods allow isolation and identification of bacterial and fungal strains (including on selective media with elevated NaCl content), followed by 16S rRNA gene or ITS-region sequencing and testing of their biochemical and physiological properties.

High-throughput sequencing of variable regions of the 16S rRNA gene (usually V3–V4 or V4) on platforms such as Illumina MiSeq allows the taxonomic structure of a community to be characterized without prior cultivation, including uncultured groups of archaea and bacteria.

Metagenomic and metatranscriptomic analysis is applied less frequently but allows assessment of the functional potential of a community -genes for nitrogen fixation, phytohormone synthesis, and degradation of toxic compounds.

Comparable work has already been carried out for adjacent objects in the arid soils of Uzbekistan: a study of the rhizosphere of Ewersmann's teresken (Krascheninnikovia ewersmanniana), growing on the former bed of the Aral Sea, using 16S rRNA gene sequencing on an Illumina MiSeq platform, showed that the transition from saline ground to the plant rhizosphere is accompanied by a sharp increase in microbial diversity and a shift in dominant groups. This methodology is directly applicable to the study of Salsola species as well.

Structure and diversity of the salsola microbiome

Rhizosphere community

Studies of the saltwort rhizosphere (specifically Salsola stocksii), carried out in the saline soils of the Khewra Salt Mine in Pakistan, showed that bacteria of the genera Bacillus, Halobacillus, and Kocuria dominate in the near-root zone, whereas Halobacillus and Halomonas prevail in soil away from the roots and at the edges of saline water bodies. At the phylum level, the rhizosphere of desert halophytes, including saltwort communities, is

generally characterized by a high proportion of Actinobacteria (Actinomycetota) and Proteobacteria (Pseudomonadota), while the surrounding saline soils typically show an elevated representation of Actinobacteria compared with non-saline soils.

Data on related halophytes of the Aral Sea region complement this picture: in the rhizosphere of teresken growing on saline ground of the former Aral seabed, archaea accounted for only about 4% of the community (compared with near-monodominance of halophilic archaea in the saline ground and seawater itself), and one-third of all prokaryotes were uncultured representatives of the phylum Actinomycetota; Bacteroidota, Chloroflexota, and Planctomycetota also played a notable role. The microbial community of the rhizosphere turned out to be structurally closer to the soils of the Ustyurt Plateau than to the saline substrate from which the plant itself grew -that is, the root system and its exudates effectively "reassemble" a typical arid-zone soil community around themselves, despite the initially extreme salinity of the substrate.

Endophytic community

Endophytic bacteria colonizing the internal tissues of roots, stems, and leaves of halophytes are of particular interest owing to their protection from competition and direct contact with host plant tissues. In desert halophytes (Haloxylon ammodendron, Halostachys caspica, and other saltworts), representatives of the genera Bacillus/Priestia, Streptomyces, and Nocardiopsis have repeatedly been described as dominant endophytes, capable of growing at NaCl concentrations of around 1.4 mol/L and at alkaline pH values above 11. For Salsola species across various regions of the arid zone, the presence of endophytic actinobacteria and bacilli producing indole-3-acetic acid (auxin), solubilizing poorly available phosphates, and synthesizing siderophores is likewise characteristic.

Phyllosphere community

The phyllosphere -the surface of photosynthetic (in largely leafless saltworts, the stem) organs -has been studied considerably less than the rhizosphere and endosphere. Nevertheless, it is known that communities resistant to high insolation, temperature fluctuations, and osmotic stress form on the surface of the assimilating organs of halophytes, with a notable contribution from pigmented and spore-forming bacterial forms as well as yeasts.

Biotechnological potential of the salsola microbiome

Microorganisms associated with plants of the genus Salsola are of interest for several biotechnological directions.

Biofertilizers and microbial inoculants (PGPR/PGPB). Rhizosphere and endophytic bacteria of halophytes often possess a set of plant-growth-promoting properties: synthesis of indole-3-acetic acid, atmospheric nitrogen fixation, phosphate solubilization, siderophore production, and ACC-deaminase activity, which lowers the stress-induced ethylene level in plants. Inoculation with such strains (isolated, in particular, from halophytes of related genera) has already been shown to improve seed germination and productivity of wheat, soybean, and other crops under saline conditions. Strains isolated from the root zone of

Uzbekistani halophytes could potentially form the basis for salt-tolerant biofertilizers for irrigated agriculture in the Aral Sea region and the Hungry Steppe.

Salt and drought tolerance. Osmoprotectant microorganisms that accumulate compatible solutes (proline, glycine betaine, trehalose), as well as strains that regulate the host plant's ionic homeostasis (Na^+/K^+ ratio), are regarded as a promising resource for enhancing the salt and drought tolerance not only of wild halophytes but also of cultivated plants, through co-inoculation or the transfer of specific metabolic pathways.

Enzymes and bioactive compounds. Halotolerant and halophilic microorganisms from the rhizosphere of saltwort deserts are a source of thermo- and halo-stable hydrolytic enzymes (proteases, amylases, cellulases, lipases) in demand in the food, textile, and detergent industries, as they retain activity under high ionic strength conditions in which conventional enzymes denature. Actinobacteria, abundant in the rhizosphere and endosphere of saltworts, are traditionally regarded as a source of antimicrobial and other secondary metabolites.

Bioremediation. Microorganisms associated with Salsola are capable of degrading a number of toxic organic compounds and participating in the bioremediation of saline and technogenically disturbed lands, which is especially relevant for the exposed bed of the Aral Sea (Aralkum Desert) and for territories subject to secondary salinization after decades of irrigated agriculture.

Phytoremediation and stabilization of shifting sands. The combined use of saltworts themselves as phytomeliorants together with their specific microbial consortia may increase the effectiveness of programs for stabilizing shifting sands and rehabilitating degraded pastures in Kyzylkum and Ustyurt.

Prospects and limitations

Despite growing interest in the topic, dedicated metagenomic studies specifically on the genus Salsola in Uzbekistan remain few; much of the discussion above is extrapolated from work on related saltwort species (Pakistan, Iran, China) and on other halophytes of the region (Aral Sea teresken, saline soils of Ustyurt). Promising directions for Uzbekistani researchers include: (1) systematic metagenomic mapping of the rhizosphere, endosphere, and phyllosphere of various Salsola species across different ecotopes -Kyzylkum, Ustyurt, Aralkum; (2) isolation of pure cultures of halotolerant and halophilic strains with assessment of their growth-promoting and enzymatic properties; (3) establishment of a collection of candidate strains for biopreparations adapted to the country's soil and climatic conditions; (4) field trials of microbial inoculants on crops in saline and desertified areas.

Conclusion. The microbiome of Salsola plants represents a poorly studied but potentially valuable biological resource for agriculture and the ecological rehabilitation of arid territories in Uzbekistan. A synthesis of data on related halophytes shows that the rhizosphere, endosphere, and phyllosphere communities of saltworts are characterized by high taxonomic diversity, dominated by Actinomycetota, Pseudomonadota, Firmicutes/Bacillota, and Bacteroidota, and carry a rich set of physiological adaptations to salinity and drought. Further targeted study of these communities using high-throughput

sequencing and culturomics, combined with assessment of the biotechnological potential of the strains, could make a substantial contribution to the sustainable development of the agricultural sector and the ecological recovery of the country's desert regions, including the Aral Sea zone.

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