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Assessing sustainable irrigation and soil restoration approaches for controlling soil salinisation in arid regions: Evidence from Karakalpakstan, Uzbekistan.

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ABSTRACT

Soil salinisation is one of the major problems that pose a threat to crop production in arid and semi-arid areas where agriculture highly depends on irrigation systems. In Uzbekistan, one of the most affected areas is Karakalpakstan due to high evaporation levels, water shortages and the consequences left by the Aral Sea crisis. This study focuses on exploring sustainable methods of irrigation and soil management for preventing salinity problems in Karakalpakstan. This study is based on literature review of current methods for mitigating soil salinization through such measures as drainage, leaching, irrigation, gypsum treatments, drip irrigation, adding organic matter to soils, and using salt-tolerant crops. Moreover, a social survey involving 200 respondents was carried out to test public awareness, observed signs, and solutions concerning soil salinity. From the survey findings, it is evident that 74.5% of respondents knew about soil salinization, while only 37% were aware about solutions. Results also show that more respondents from oasis areas reported signs of soil salinity compared to those from valley areas, but such a comparison is restricted due to the unequal regional representation of the respondents until cross-tabulation was carried out. In general, none of the methods discussed can solve the problem of soil salinization alone. However, an integrated approach that involves drainage enhancement, proper leaching, improved irrigation management, soil management, use of organic materials and salt-tolerant crops is the most appropriate method in addressing the situation in Karakalpakstan.

Keywords: soil salinization; irrigation management; Karakalpakstan; Aral Sea; drainage; leaching; salt-tolerant crops

INTRODUCTION

Soil salinisation is a major soil threat that primarily affects agricultural land, posing a significant risk to food security. It is a process where water-soluble salts accumulate on the soil surface, constraining soil fertility and crop production. Soil salinity is mainly driven by the combination of arid climate and irrigation without proper drainage, which leads to salt accumulation in root zones of the plants. Soil salinization can be summarized in two subcategories: primary soil salinization and secondary soil salinization (Tsanis et al., 2015). Primary soil salinity is linked to natural processes such as physical or chemical weathering and transport from parent material, geological deposits or groundwater. In arid and semi-arid regions, saline soils are formed because of high evaporation levels and due to a lack of rainfall to flush the soil. Secondary soil salinization is caused by human activities such as irrigation with poor-quality water, weak drainage and rising water tables. Soil salinization is one of the major problems in agriculture as salinity reduces plants' ability to absorb water, damages soil structure, lowers microbial activity and crop yields (Ayers and Westcot, 1985; Litalien and Zeeb, 2020). Over time, soil salinization may lead to land degradation, desertification, decreased agricultural productivity, and consequently threaten food security.

Globally, soil salinization is one of the most common land degradation types experienced by different communities. The area of salt-affected soils is estimated at 1,381 million ha (Mha), which accounts for 10.7% of the total global land area (FAO, 2024b). With the current rise in temperatures, the affected area could grow to 24–32%. Most of the aridification is predicted to happen in developing nations. Currently, 10 nations (Afghanistan, Australia, Argentina, China, Kazakhstan, Russia, the United States, Iran, Sudan, and Uzbekistan) represent 70% of the global salt-affected soils (FAO, 2024b). If continued in similar trends, soil salinisation can become a constraint in meeting growing global food demands.

In Uzbekistan, soil salinization is one of the biggest problems, as irrigated agriculture accounts for around one quarter of the country's GDP and employment (World Bank, 2025). Soil salinization impacts almost half of the nation's irrigated areas, reducing agricultural yield and endangering the economy and people's livelihoods (Jumaniyazov et al., 2024). An area of 1.9 million hectares (approximately 46% of irrigated land) is saline with 87,600 hectares being highly saline. This problem is especially severe in Karakalpakstan which is located in the western part of Uzbekistan, in the lower basin of Amudarya River and this region is heavily affected by the environmental consequences of the Aral Sea crisis. Recent data show that 95% of Karakalpakstan's agricultural land faces soil salinization, which affects crop yield, farmer's income and food security in the area (FAO, 1997).

Therefore, it is important to take appropriate adaptation and mitigation measures to address this issue. Multiple practices are used to manage soil salinity, particularly in arid regions. One of the most common ways of coping with soil salinity is the improved drainage systems, which helps to flush accumulated salt from the root-zone and reduce groundwater tables. Another common practice is applying leaching techniques, which means using a large amount of water to wash salts from the soil down below the root level. Other common ways used in tackling soil salinization are adding organic matter and manure to keep moisture and reduce irrigation, using salt-tolerant plants as it enables plants to grow well even under the presence of salts, and applying crop rotation. Nevertheless, all these strategies depend on environmental conditions as well as financial possibilities and should be applied to certain regions.

According to current existing practices used in managing soil salinization, it is evident that one single solution cannot be effective in reducing soil salinity in arid regions like Karakalpakstan. Therefore, this research paper aims to analyze the current solutions such as improved drainage systems, leaching, adding organic manure, planting salt-tolerant plants, crop rotation and improved irrigation methods, and seeks to determine which practices work best in Karakalpakstan under local environmental, economic, and social conditions. Finally, the research intends to propose specific strategies that can enhance soil quality and improve the resilience of communities affected by salinity in the region.

LITERATURE REVIEW

1. What is Soil salinization?

According to the UNCCD, land degradation is defined as the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices (UNCCD, 1993). Land degradation is caused by natural processes or human activities and is divided into six classes: water erosion, wind erosion, soil fertility decline, salinization, waterlogging, and lowering of the water table (FAO, 1994). Among those, soil salinization, the second major cause of land degradation after soil erosion, is recognized as one of the most significant types of land degradation, especially in arid and semi-arid regions where agriculture highly depends on irrigation (Shahid et al., 2018). Soil salinization is the process of accumulation of water-soluble salts in excessive amounts in the soil surface, reducing soil fertility and crop production, while soil salinity is referred to as the measure of concentration of all the soluble salts in soil, and is typically measured through electrical conductivity (EC), which indicates the soil's ability to conduct electricity due to the presence of dissolved ions. Usually, salinized soil contains the cations: sodium (Na^{+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and the anions: chloride (Cl^{-}), sulfate (SO_4^{2-}), bicarbonate (HCO_3^{-}), carbonate (CO_3^{2-}), and nitrate (NO_3^{-}). Hyper-saline soil water may also contain boron (B), selenium (Se), strontium (Sr), lithium (Li), silica (Si), rubidium (Rb), fluorine (F), molybdenum (Mo), manganese (Mn), barium (Ba), and aluminum (Al), some of which can be toxic to plants and animals. When the electrical conductivity of soil equals to or exceeds 4 deci Siemens per meter (dS m^{-1}) at 25 °C, soil is considered to be saline (USSL Staff, 1954).

1.2. Units and Measurement Techniques of Soil Salinity.

There are a number of ways in which soil salinity can be measured, with Electrical conductivity being the most common technique (Hardie and Doyle, 2012). Before, electrical conductivity was measured in milli mhos per cm (mmho cm^{-1}), which is now replaced by Siemens. Currently Electrical conductivity has an SI unit represented by:

- milli Siemens per centimetre (mS cm^{-1}) or
- deci Siemens per metre (dS m^{-1})

These are represented as: 1 mmho cm^{-1} = 1 dS m^{-1} = 1 mS cm^{-1} = 1000 micro Siemens per cm (1000 µS cm^{-1}). EC values can change as the temperature alters, therefore 25 °C is chosen as a standard condition (Hardie and Doyle, 2012). Soil Salinity can also be expressed in the form of total dissolved solutes (TDS) in milligram per liter (mg l^{-1}) or total soluble salts (TSS) in milli equivalents per liter (meq l^{-1}). Even though no specific relationship between EC and TDS exists, TDS is multiplied by a factor of 600 or 800 in highly saline soils (Hardie and Doyle, 2012).

The table below summarizes key indicators of soil salinization, the purpose of the indicator and the methods used to measure or assess soil salinization.

TABLE I.

Indicators	**Purpose**	**Method**
Electrical Conductivity (EC)	Measure overall salt content	Salinity sensors, laboratory sampling, electromagnetic induction
Exchangeable Sodium Percentage (ESP)	Measure the concentration of sodium relative to the other cations	ESP = Exchangeable {(Na)/(Ca + Mg + K + Na)} x 100
Sodium Adsorption Ratio (SAR)	Measure of the sodicity of soil, as determined from analysis of water extracted from the soil.	SAR = Exchangeable {(Na)/(Ca + Mg) 0.5}
Salt profile	Show how salt is distributed in soil layers	Soil sampling at different depths
Remote sensing indices	Map salinity over large areas	Satellite data (NIR, SWIR bands)
Field symptoms	Visual detection of salinity	White crust, poor plant growth, presence salt-tolerant weeds

Soil salinity can also be detected by visual observations. Common visual indicators include the formation of a white salt crust or salt stains on the soil surface, with the loose or fluffy soil. Soil salinization also affects plant growth, therefore leading to slow or no germination, leaf burn, and marked changes in the shape and colour of leaves. Also, in saline lands, trees are either dead or dying and the number of salt-tolerant plants increases (Litalien and Zeeb, 2020).

FIGURE I: WHITE CRUST FORMATION ON THE SOIL SURFACE

1.3. Types of Soil Salinization

Soil salinization can be broadly categorized into two main broad types according to their origin of cause: (natural) primary soil salinization and (human-induced) secondary soil salinization (Tsanis et al., 2015). Primary salinization is caused by natural processes including geological and environmental processes. In arid and semi-arid regions, high evaporation rates and low rainfalls prevent the soil from leaching from the soil. Also, weathering from rock material, salty groundwater and sea water influence in coastal areas lead to primary soil salinization. In areas like Karakalpakstan, which is experiencing disappearance of the Aral sea, wind may carry salt into agricultural lands.

Secondary soil salinization is driven by human activities, mainly by agriculture. Mostly in dry regions, poor irrigation systems without adequate drainage systems lead to accumulation of salts in the root zone. Irrigation water, even if it is fresh, contains some amount of salt and when agricultural lands are overly irrigated, those salts gradually accumulate and build up in the root zones of plants as water evaporates. Secondary salinization is dominant in many cultivated areas worldwide and poses a serious threat to sustainable farming.

In addition to these categories, soil salinity can also be classified based on their soil chemical properties into saline, sodic (alkaline), and saline-sodic soils (Shahid et al., 2018). Saline soils contain high levels of dissolved salts but relatively low sodium concentrations. Sodic (alkaline) soils, on the other hand, show high concentrations of sodium and elevated pH as a result of high carbonate concentrations. Saline-sodic soils pose the most threat as they combine the properties of both saline and sodic soils, influencing plant development by altering osmotic concentrations. The table below summarizes these three classifications according to their pH, EC, and ESP.

Table II. *Classification of saline, sodic, and saline-sodic soils by pH, EC, and ESP (adapted from Shahid et al., 2018; USSL Staff, 1954).*

Classifications	EC(ds/m)	ESP	pH
Saline soils	>4	<15	<8.5
Alkaline soils	<4	>15	>8.5
Saline-alkaline soils	>4	>15	>8.5

2. Soil salinization on a Global scale.

2.1. Global Distribution of Soil Salinity

Soil salinity is not evenly distributed around the world, being concentrated mainly in arid and semi-arid regions. The total area affected by soil salinity is around 1,381 million ha, or 10.7 percent of the total land area, of which 60 percent are saline, 26 percent sodic and the remaining 14 percent saline-sodic (FAO, 2024b). Statistical data on distribution of soil salinity around the world can be obtained through the Global Map of Salt affected Soils, GSAS (FAO and ITPS, 2021). The GSAS map was produced from the contributions of over 118 countries in 257,419 locations containing measured soil data. More than 350 experts were involved in analysing the data and standardising mapping methods of salt-affected soils after being educated on state-of-the-art methods for digital soil mapping (FAO and ITPS, 2021). Following the agreed technical specifications, every country produced their own report. The GSAS map measures soil salinity in two depth intervals: topsoil and subsoil (0–30 cm and 30–100 cm respectively) based on soil's EC, ESP and pH.

Topsoils have 85% of the salt-affected soil as saline, 10% sodic and 5% as saline-sodic. Meanwhile, 62% of salt-affected subsoils are saline, 24% are sodic and 14% are saline-sodic (FAO and ITPS, 2021).

From all, 10 countries around the world account for 70% of global salt-affected soils: Australia (357 million ha), Argentina (153 million ha), Kazakhstan (94 million ha), the Russian Federation (77 million ha), the United States (73.4 million ha), the Islamic Republic of Iran (55.6 million ha), the Sudan (43.6 million ha), Uzbekistan (40.9 million ha), Afghanistan (38.2 million ha), and China (36 million ha) (FAO, 2024b).

Figure II presents this ranking visually. None of the top four countries like Oman, Uzbekistan, Jordan, and Kuwait appear on the earlier list of countries with the largest total affected area. This is because these countries are small, so even though most of their land is affected, the total amount of land is not large enough to rank among the biggest in the world. These countries have high percentages mainly because they are desert countries, where naturally salty soil is common. Uzbekistan's case is different: much of its affected land was once used for farming, and became salty over time due to decades of irrigation-heavy cotton farming and the shrinking of the Aral Sea.

Figure II: *Top Ten Nations Most Affected by Soil Salinization(FAO, 2024b)*

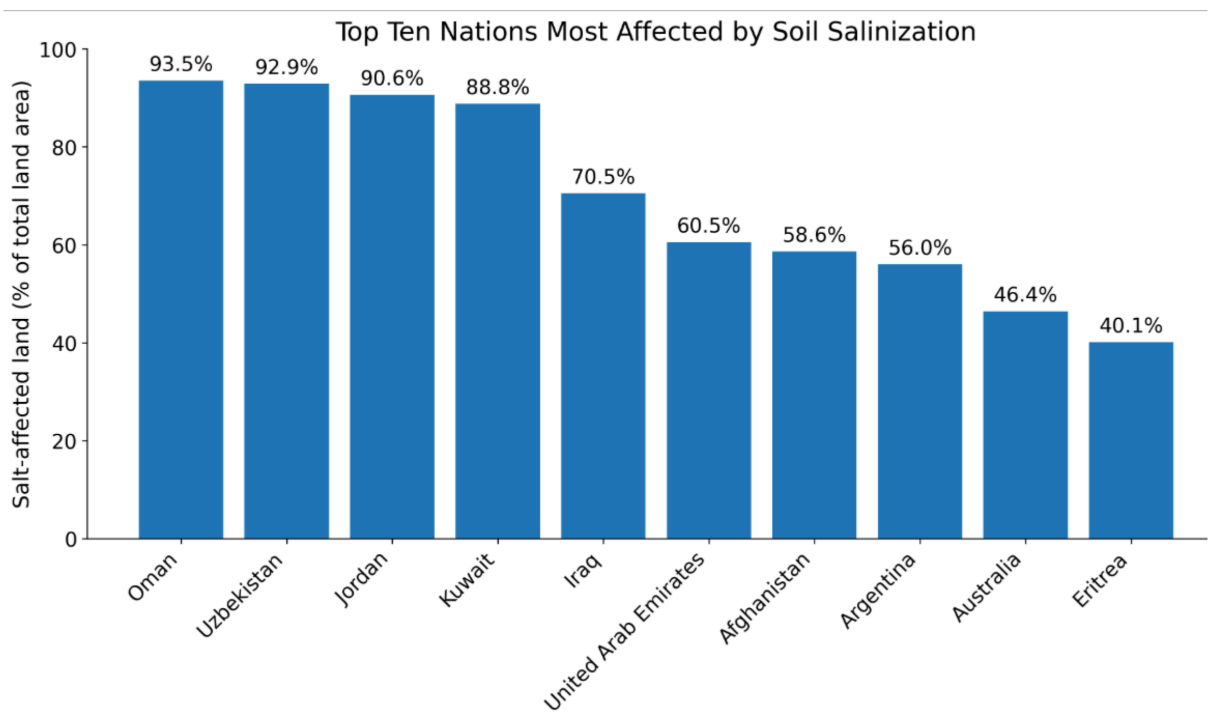


Table IV shows how this total is broken down by region. The Pacific stands out with 42.1% of its land area being affected, which is more than double any other region, while North America (4.3%) and Africa (4.0%) show the lowest exposure to soil salinity.

Table IV. *Areas of salt-affected soils at the regional level(FAO, 2024b)*

Region	**Area of salt-affected soils (km2)**	**Land area (km2)**	**%**
Europe and Eurasia	2 378 209	27 049 956	8.8

Pacific	3 570 000	8 472 605	42.1
Latin America and the Caribbean	2 352 857	20 026 933	11.7
Near East and North Africa	2 303 461	13 033 953	17.7
Asia	1 543 269	20 722 790	7.4
Africa	883 795	22 046 043	4
North America	779 912	17 936 120	4.3
Total	13 811 503	129 288 400	10.7

Figure III shows the total area affected by salinity in each country. It shows a similar dry-belt pattern to the regional data, from the southwestern United States through North Africa, the Middle East, and Central Asia to western China. Australia has the largest affected area of any country, suggesting that dry climates are the main factor causing large-scale salinization, rather than any single human activity or regional practice.

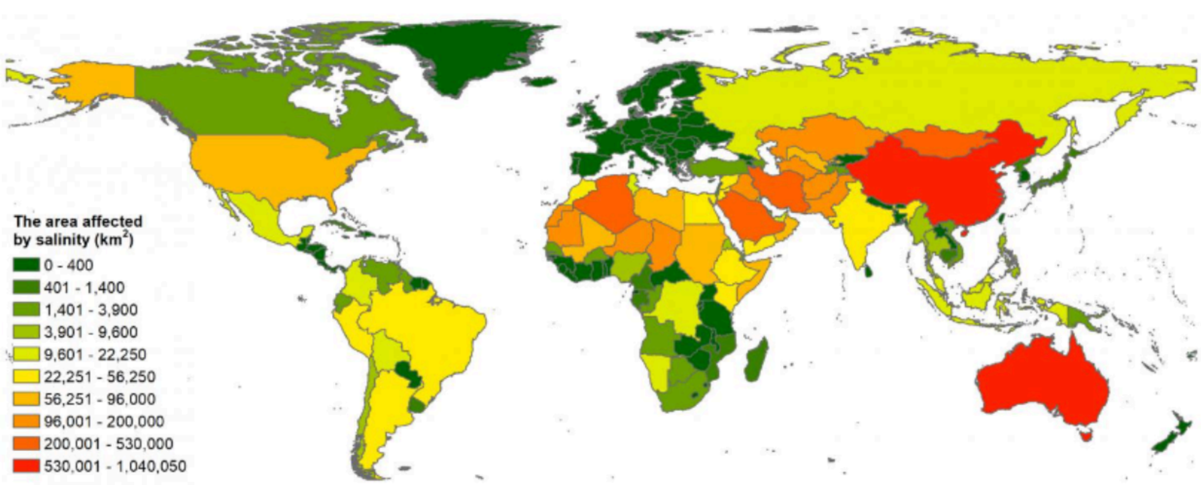


Figure III. *The illustration shows the total area affected by soil salinity in each country, averaged between 1980–2018 and predicted by their model. Source: Hassani et al. (2020).*

Figure IV shows the type and severity of soil salinity. Saline soils, represented in pink/red, are common around the Mediterranean, the Middle East, and coastal Australia. Sodic soils (blue) are mainly found in Kazakhstan, southern Russia, northern China, and inland Australia. The most severe areas are concentrated in Central Asia and parts of Australia. This suggests that these regions have more seriously degraded soils, which may be harder to restore than areas with slight or moderate salinity.

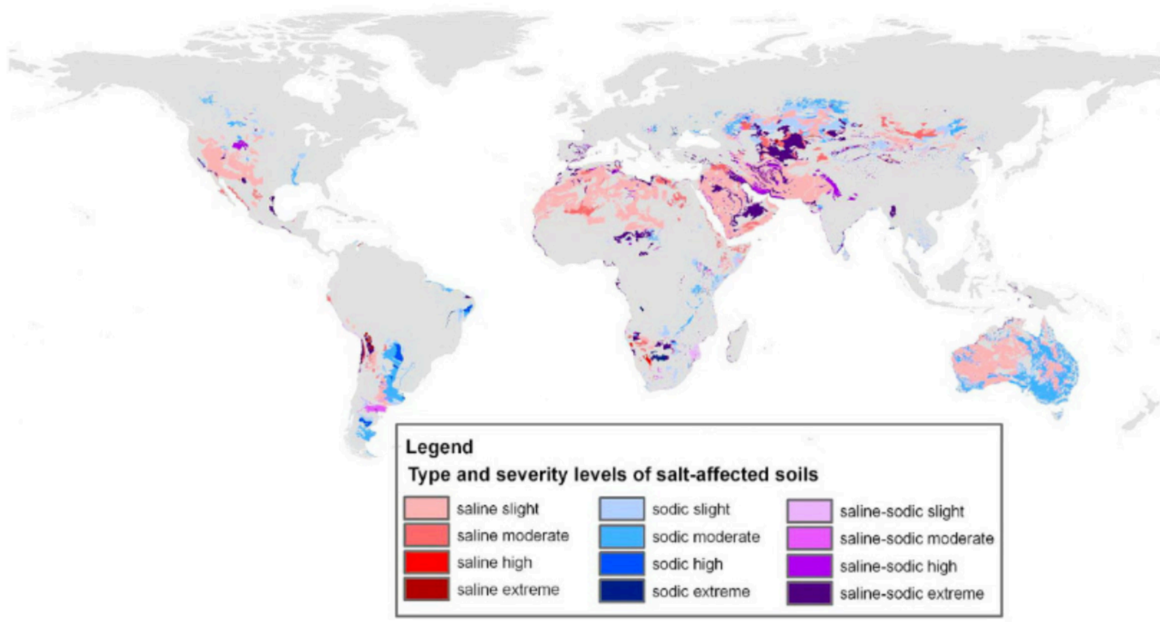


Figure IV. *Global map of saline, sodic and saline-sodic soils by severity level. The distribution of saline, sodic and saline-sodic soils in the world. Source: Wicke et al. (2011).*

2.2. Global Threats

Soil salinization creates serious threats to agriculture, global food security and human livelihoods. Globally, a tenth of irrigated and similarly a tenth of rain-fed croplands experience excessive salt accumulation (FAO, 2024b). Soil conditions are directly linked with global food production as high concentrations of salt reduce plant's ability to absorb water even when the moisture exists in the soil. This causes osmotic stress, poor seed germination, reduced plant growth, leaf burn and lower yields. Therefore, soil salinization can lead to crop losses, putting a stress on providing food to a fast growing global population. In most affected countries, potential crop losses due to salinity stress are up to 72% for rice, 68% for bean, 45% for sugarcane, and 40% for potato (FAO, 2024b).

Soil salinization also has economic impacts. The annual loss in agricultural productivity caused by salinization is estimated to be 31 million dollars, meaning soil salinization not only destroys the soil, but also reduces farmer's income and increases the amount of money spent on better irrigation, drainage systems or salt-tolerant plants (FAO, n.d.). For small income farmers, these costs may be difficult to afford leading to higher levels of poverty or even land abandonment. For example, soil salinization removes up to 1.5 million hectares of agricultural land from production annually (FAO, n.d.).

Soil salinity also increases land degradation around the world and has a direct impact on the environment. When vegetation cannot grow properly, ecosystems fail leaving salt open to be transported by the wind, leading to water erosion. This may lead to increased desertification, and a decline in biodiversity. In dry areas, wind can carry eroded soil and salt dust, impacting local farms, communities, and water bodies, worsening the situation of already water-stressed communities — around 2.6 billion people (FAO, 2024b).

3. Soil Salinization in Uzbekistan and Karakalpakstan

3.1 National Scale of Soil Salinization in Uzbekistan

Uzbekistan is one of the double land locked countries in the world, which does not have direct access to oceans. It is a dryland located in Central Asia in the Aral Sea basin, surrounded by the Amudarya and Syrdarya rivers. Central Asia has 91.5 million ha and accounts for 20% of all areas affected by soil salinization (Khasanov et al., 2023). In the 1960s and 1970s, agricultural lands were expanded and large scale irrigation systems mainly in arid places were established for the purpose of cotton production. However, old technologies led to a rise in groundwater levels and contributed to secondary soil salinization.

Uzbekistan occupies 447,400 km² and less than 43,000 km² is used for agriculture. Soil salinization is one of the biggest agricultural problems faced in Uzbekistan, placing the country second among the most salt-affected countries in the world (see Figure II). Saline soils make about 50% of irrigated land in Uzbekistan with 30% weakly saline, 16% moderately saline, and 4% extremely salty (Jumaniyazov et al., 2024).

Uzbekistan has 12 provinces and one autonomous republic — the Republic of Karakalpakstan. The landscape of Uzbekistan changes from west to east, from arid deserts, to foothills, mountains and large valleys. Uzbekistan's landscape can be divided into two categories: oasis (voha) in the west and valley (vodiy) in the east. Salinity levels are higher in oasis compared to valley regions as agriculture in oasis depends on high levels of irrigation due to aridity. High temperatures and high rates of evaporation worsen the secondary salinization in the area in addition to already suffering communities from the disappearance of the Aral Sea. Nowadays, 77% of irrigated areas in the Republic of Karakalpakstan, 100% in Khorezm province, 87% in Bukhara province, 79% in Jizzakh province, and 87% in Navoi province are saline to varying degrees (Jumaniyazov et al., 2024).

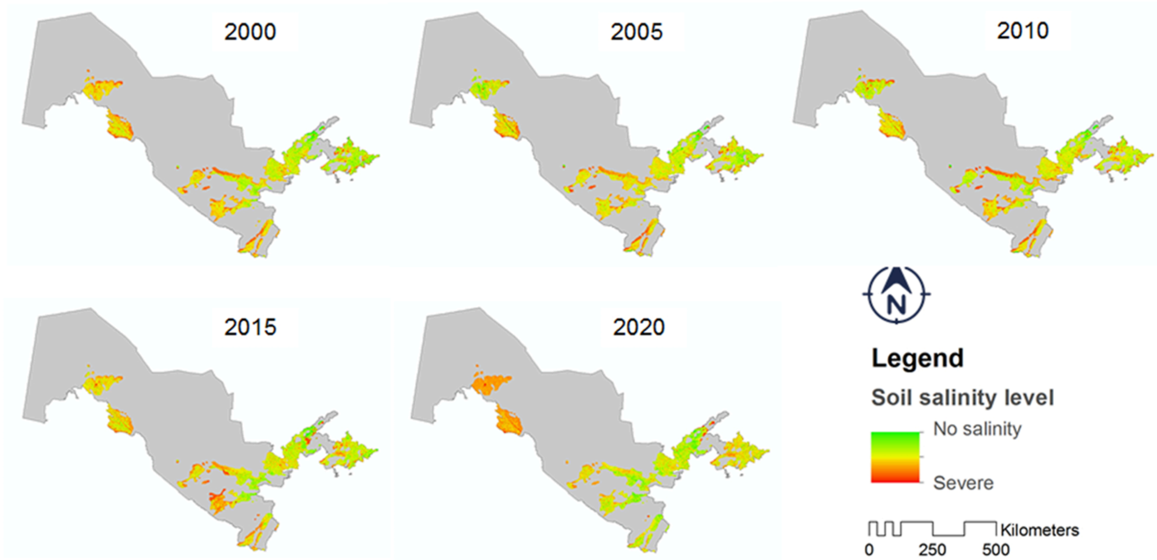


Figure V. *Soil salinity map of croplands of Uzbekistan (Hasanov et. al.,2019)*

The table below illustrates the salinity levels across the different regions of Uzbekistan. It is evident from the chart that salinity levels are highest in oasis provinces such as Karakalpakstan, Bukhara, Navoi, Jizzakh and Sirdarya, containing a larger share of weakly, moderately and highly saline soils, while valley regions such as Fergana, Andijan and Namangan have a higher proportion of non-saline or less saline land.

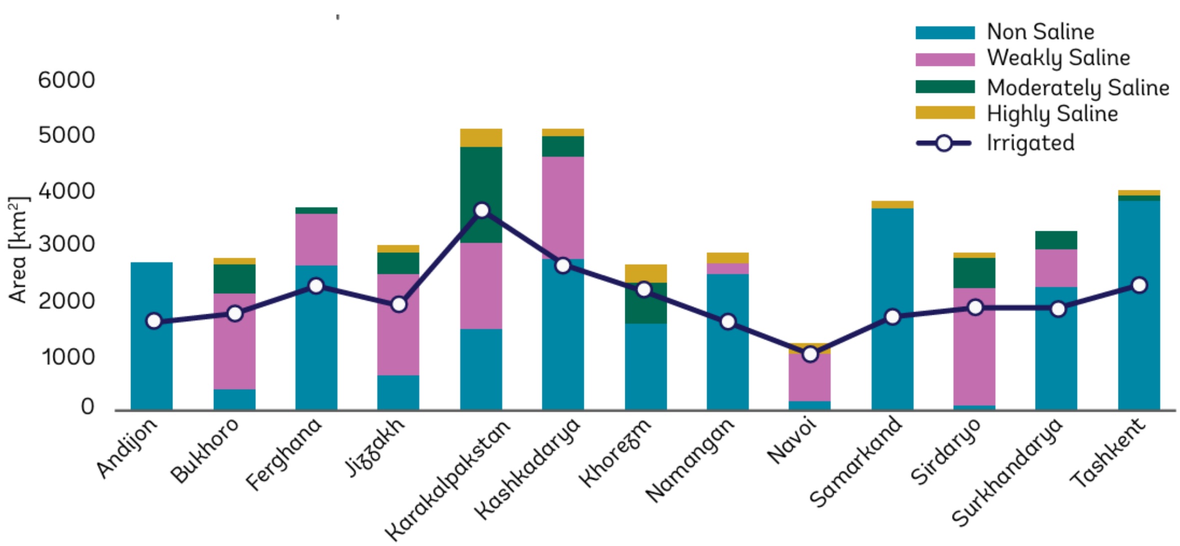


FIGURE VI. *Sources: FAO AQUASTAT; State Committee of the Republic of Uzbekistan on Statistics.*

3.2. Karakalpakstan as a Salinity Hotspot

Karakalpakstan is an autonomous Republic within the Republic of Uzbekistan, located in the northwest part of the country in the flatlands of Amu Darya and southern beaches of former Aral Sea. Karakalpakstan has an area of 166.6 thousand square kilometers, accounting for 31.7% of Uzbekistan's total area. More than 80% of Karakalpakstan is covered with dunes and has Aral Sea seabeds in the north, with the Karakum and Kyzylkum deserts. Karakalpakstan has a sharp continental climate, having average temperatures of -8 to -6°C during January and 28 to 32°C in June. In summer, especially around July and August, the temperature can rise above 45°C.

Environmental degradation in the Karakalpakstan area was intensified by the Aral Sea crisis. The Aral Sea crisis refers to the human-induced shrinkage of the Aral Sea, which was once the world's fourth largest lake, starting around 1960 (Britannica, 2026). With the economic plans of the Soviet Union, the two rivers that fed the Aral Sea, the Amu Darya from the south and the Syr Darya from the north, were increasingly diverted into irrigation canals to grow more cotton across Central Asia (Britannica, 2026). Much of this diverted water never reached the fields it was meant to irrigate. Due to poorly built canals, large amounts of water were lost to evaporation and seepage into the desert soil before reaching the crops (EBSCO Research Starters, 2025). Without its river inflow, the Aral Sea began to shrink quickly. By 2018 the Aral Sea had lost 88 percent of its original surface area and about 1,000 cubic kilometres of water compared with its 1960 volume (ScienceInsights, 2026). As the water receded, the Aral Sea split into saltier remnants and its salinity roughly tripled (Fipps, n.d.). This process created a new desert, Aralkum, covering about 5.5 million hectares in the Aral Sea basin (EBSCO Research Starters, 2025). Beyond the loss of the Aral Sea itself, the disaster changed the climate: winters became colder, summers became hotter and drier (The Diplomat, 2023; Facts and Details, n.d.). Dust storms are now spreading year-round, and winds send over 100 million tons of dust and dangerous salts from the soil into the atmosphere (Fipps, n.d.).

Agricultural lands in Karakalpakstan are highly vulnerable to salinity. 77% of irrigated areas in Karakalpakstan have different salinity levels, although there are other sources that argue that the percentage might even be higher in some agricultural regions (Jumaniyazov et al., 2024). The case of Shimbay District demonstrates the impact of salinity on district-level agriculture. In Shimbay district, located in the northeast part of the Republic of Karakalpakstan and the western part of Uzbekistan, 30% of the total area was made up of slightly salty lands, making 127,735.4 ha. Salty lands accounted for 28.1%, covering 119,612.9 ha of the district area. Non-saline lands were present only at 20.55%, while the area covered by strongly salty and extremely salty lands reached 21.34% (Jumaniyazov et al., 2024).

4. Mitigation and Adaptation Strategies for Soil Salinization

4.1. Improved Drainage Systems

Drainage is one of the most important and effective ways of mitigating soil salinization, controlling groundwater tables (Ali, 2013). When the groundwater table is shallow and close to the surface, water may move up through small soil pores by capillary action and evaporate, eventually leaving salts in the root zones. Drainage removes excess water from the soil so that the groundwater table does not rise too close to the surface and maintains groundwater at a safe depth.

In practice, improving drainage systems should begin with cleaning existing pipes, replacing them, and preventing sediment and vegetation blockages (Ali, 2013). Such measures are important to Karakalpakstan as most of its lands used for irrigation are located at the basin of Amu Darya river and therefore experience poor drainage. Another reason for improving drainage is the need for proper leaching. If salts are washed away but drainage is not functioning, saline water may remain in the soil and be returned back.

Drainage can be an effective measure for managing soil salinity because it addresses one of the major causes of salinity — high water table levels. However, drainage is expensive and requires maintenance. It also poses the problem of disposal, because saline drainage water can pollute canals and rivers if returned without proper control. Therefore, drainage systems are important in solving soil salinity, but should not be seen as the only solution.

4.2. Leaching

Leaching is one of the oldest and most common ways to reclaim saline lands (Ali, 2013). Leaching means applying additional water to dissolve salts in the soil and to move them below the root zone. However, leaching only works if enough quality water and working drainage systems are available. Otherwise, saline water may temporarily move below the root zone before returning to the surface with rising groundwater.

To achieve leaching, an adequate amount of good-quality water should be applied appropriately. It is normally done before planting or during winter, when there is no active plant growth and evaporation rates are low (Ali, 2013). This requires proper levelling of the field to ensure the water is distributed evenly across the land. If the field is uneven, some parts will get excessive water, while other sections will have residual salts in poorly washed areas. Leaching should be accompanied by drainage to allow salty water to drain from the rooting zone.

Studies on soil reclamation indicate that intermittent leaching may offer greater benefits than continuous leaching (Ali, 2013). Intermittent leaching was found to eliminate 75% of the salt content in the top 60 cm of the soil, compared to continuous leaching, where 64% salt removal was observed.

Leaching, however, has certain disadvantages. It consumes large quantities of water that are very difficult to obtain in drought areas such as Karakalpakstan, where water shortage is one of the pressing issues. Leaching can also wash away nutrients like nitrates from the soil, leading to reduced fertility. In addition, if used water with salts and agrochemicals is returned to canals, water quality may worsen, continuing the salinization cycle. Therefore, leaching has to be used in combination with drainage and other methods.

4.3. Improved Irrigation Scheduling

Irrigation scheduling involves providing crops with adequate water when needed. Irrigation problems are responsible for salination because over-irrigation raises groundwater levels, while under-irrigation may cause salts to accumulate in plant root zones. Although low salt content water is used in irrigation, it still contributes to the salt buildup in the soil.

In implementing irrigation scheduling, farmers must base irrigation on crop water requirements, soil moisture, climate, and salinity levels. Irrigation is not done by routine, but irrigation planning must consider the crop growth stage. In fact, crops need water during the growing and flowering stages, but over-irrigation at other times will only contribute to waterlogging.

Irrigation water quality, irrigation practice, and drainage are crucial in preventing salinization (Paz et al., 2020). When ECw is less than 0.7 dS/m, there are no restrictions, but in cases where ECw is in the range of 0.7–3.0 dS/m, drainage must be sufficient to provide enough leaching (Paz et al., 2020).

In the case of Karakalpakstan, scheduling irrigation must avoid over-watering of soils while providing enough moisture for plant growth and salt leaching. This will help conserve water while reducing the risks of groundwater rising in the region.

4.4. Gypsum Application for Sodic and Saline-Sodic Soils

Gypsum is a solution for treating sodic and saline-sodic soils but not all saline soils. When there is an excess of sodium in the soil, it results in poor soil structure that leads to soil compaction. The gypsum provides calcium, which then replaces the sodium in the soil. Following this, the sodium can be leached away using the leaching water.

The process will start by conducting soil tests. It is essential for farmers to check whether the SAR or ESP levels are high. In case there is sodicity, the gypsum must be applied according to the gypsum requirement of the soil. The gypsum will have to be incorporated into the upper soil layer followed by leaching and drainage, as those are necessary in the replacement of sodium from the root zone.

Gypsum proved more efficient than other chemicals in reclaiming calcareous saline-sodic soils (Ali, 2013). Applying manure with a 50% gypsum requirement resulted in improved infiltration rates of up to 11.2 cm/day after 4 years of use, compared to 0.5 cm/day without amendments (Ali, 2013). Thus, it becomes clear that gypsum proves to be more efficient if applied alongside organic matter due to its ability to improve soil structure and replace sodium.

Thus, gypsum can be recommended for use in saline-sodic or sodic soils in Karakalpakstan. If the soil is only saline, gypsum may not solve the problem. It also costs money and requires proper application. Therefore, gypsum should be used only after soil testing with leaching and drainage.

4.5. Drip Irrigation

Drip irrigation seems to be a good solution, as it uses less water and delivers water directly to the root zone. This becomes very helpful in arid environments due to water shortage. Nevertheless, it is worth noting that drip irrigation does not ensure solving the problem of soil salinization. Due to frequent water application in small amounts, salts tend to accumulate in the edges of the wetting zone or accumulate near the soil surface. Consequently, if no leaching occurs, salts will have an adverse effect on plant root germination and development.

The advantage of using drip irrigation technology is that water consumption will be minimized and the overall effectiveness of the plant in utilizing the water will increase. Drip irrigation may be useful for vegetable crops and orchards. However, there is one problem associated with it. For its implementation, financial resources, filtering equipment, technical knowledge and maintenance will be required. Drip irrigation may not be used at all in poor farmer communities unless some financial assistance is provided, which is the case for many farmers in Karakalpakstan.

4.6. Organic Matter, Manure and Green Manure

The significance of organic matter lies in the fact that saline soils generally have poor soil structure and low biological activity. Farmyard manure, composting, addition of green manure will increase soil structure formation, infiltration and water retention. The improved soil structure formation will make the movement of water easy within the soil and leaching salts away from the root zone. The fertility of the soil will also improve along with increased soil microbial activities.

Implementation methods may include applying farmyard manure before planting, recycling crop residues, growing green manure crops like Sesbania, or applying compost. A Sesbania crop of 45 days old having 1.5–1.8 m height is considered fit to use as green manure (Ali, 2013).

Organic materials are highly beneficial when mixed with gypsum on soils of saline-sodic nature. Organic materials help to increase infiltration, whereas gypsum will help to improve the chemical constituents of the soils. The single use of organic material will not help to remove salts if there is still shallow groundwater in the region. Poor quality manure might have salt content, so manure must be chosen carefully. This technique can prove to be quite effective in Karakalpakstan due to its relative affordability compared to engineering solutions.

4.7. Salt-Tolerant Crops

Salt-tolerant crops are one example of coping in soils where it is not possible to remove the salinity. Salt-tolerant crops have the ability to survive and produce crops better than sensitive crops. This will help the farmer maintain his income while using other reclamation techniques.

Some examples of salt-tolerant crops are barley, cotton, some kinds of wheat and rice, oilseed crops and certain forage crops. Salt-tolerant varieties of wheat, rice, cotton and oilseed could help to increase farm incomes from saline soils (Ali, 2013). It was also observed that the growth of Kallar grass decreased pH, EC and SAR in highly saline-sodic soils (Ali, 2013).

In Karakalpakstan, salt-tolerant crops are useful for highly affected fields where full reclamation is difficult. However, salt-tolerant crops are best used as an adaptation, not as the only solution.

Method	**Purpose**	**How it works**	**Limitation**
Improved drainage	Mitigation	Lowers groundwater and prevents salts from rising to the root zone	Expensive and needs maintenance
Leaching	Reclamation	Uses extra water to wash salts below the root zone	Needs good water and drainage
Gypsum application	Soil restoration	Replaces sodium with calcium and improves soil structure	Useful only for sodic/saline-sodic soils
Drip irrigation	Water-saving adaptation	Delivers water directly to roots and reduces water waste	Salts may build up without leaching
Organic matter/manure	Soil improvement	Improves infiltration, water retention and soil fertility	Poor-quality manure may add salts
Salt-tolerant crops	Adaptation	Allows production to continue under saline conditions and reduces pressure on affected land	Does not solve the cause of salinity;
Irrigation scheduling	Prevention	Gives crops the right amount of water at the	Requires monitoring and farmer training

		right time	

TABLE V. *Summary of mitigation and adaptation methods for soil salinization*

4.8. Best Practices for Karakalpakstan

The best approach for Karakalpakstan will involve a number of measures rather than a single method, as soil salinization in the region results from multiple interacting causes, including shallow groundwater, water scarcity, and Soviet-era irrigation practices, meaning no single strategy discussed above is sufficient on its own (Fipps, n.d.; Khaitov et al., 2025). Firstly, the focus must be on drainage and groundwater management because shallow groundwater is responsible for secondary salinization. Drainage is the first thing that must be fixed. If drainage does not work, leaching and irrigation management will only lower surface salinity temporarily before salts climb up through capillary action again. The second priority should be planned leaching, but only where drainage works and water quality is acceptable. Since Karakalpakstan already deals with water scarcity, leaching should be used selectively and, where possible, timed for winter months when evaporation rates are lower and demand from active crops is minimal, reducing unnecessary water loss. Thirdly, better irrigation management should be a next priority to avoid wasting water and waterlogging. It will involve scheduling irrigation based on the growth stage of the crops and soil salinity levels rather than routine, because over- and under-irrigation alone leads to salt buildup in the soil root zone (Paz et al., 2020). If soils are sodic or saline-sodic, gypsum should be added, preferably with organic matter. Gypsum has been shown to lower sodicity by up to 62 percent in some studies, making it more effective in terms of chemical properties than plant-based methods; however, because of its high costs and maintenance issues, it may not be affordable for small-scale farmers (Nainwal et al., 2024). Finally, salt-tolerant crops should be used to reduce yield loss and support long-term adaptation. In this classification, there should be an addition of halophytes as well, because research on halophyte legumes in Uzbekistan has shown that the planting of productive and edible halophytes would enable the restoration of abandoned irrigated lands and production of fodder for livestock at the same time, providing an economic advantage for farmers to participate in the restoration process rather than looking at it as a cost (Khaitov et al., 2025). Since many farmers in the area have financial limitations, interventions such as halophyte planting along with externally-funded drainage investments might be the most realistic way forward.

4.9. Current Practices in Karakalpakstan

In addition to the theoretical solutions mentioned above, there are already some programs being implemented in Karakalpakstan, providing examples of what is becoming popular in practice.

The drainage and irrigation facilities continue to be the most commonly adopted measures. The Drainage, Irrigation, and Wetlands Improvement Project (DIWIP) has sought to maintain the water tables below one meter in Karakalpakstan through improved drainage infrastructure, and thus has helped reduce secondary salinity due to high groundwater levels (Ministry of Agriculture and Water Resources, n.d.). However, deterioration of old irrigation and drainage systems, as well as inadequate funds for their maintenance, have kept promoting soil salinization in some regions (Ministry of Agriculture and Water Resources, n.d.).

International development agencies have also started playing an active role in this region. The International Center for Biosaline Agriculture (ICBA) has recently launched a project aimed at reducing the vulnerability of small-scale farmers in Karakalpakstan through the use of climate-smart, biosaline, and integrated modular agriculture systems, along with assessment of the irrigation and drainage facilities available at different project sites (ICBA, 2023).

Agroforestry is also being explored as an approach to restoring the landscape on a longer-term basis in this region. Scientists from the National University of Uzbekistan, the Karakalpak Botanic Garden, and international partners such as Tottori University and Mie University from Japan have suggested implementing technology for creating a landscape restoration system that would include forestry, agriculture, and gardening combined into a single system, recreating sustainable communities of trees, bushes, and herbs serving as an analogue of natural ecosystems rather than traditional mono-culture farming (Akinshina et al., n.d.). At present, two experimental model gardens have been created to test this approach: one in the delta of the Amu Darya river, and another in the area of Nukus close to the Kyzylkum desert. Both cover an area of approximately six hectares (Akinshina et al., n.d.).

It should be noted that the approach chosen by scientists specifically includes honey-producing and medicinal plants in order to earn additional money for local communities and make them interested in participating in landscape restoration (Akinshina et al., n.d.). This approach is similar to other examples described in this paper, and the findings suggest that restoration is much more likely to succeed if it provides economic benefit for farmers rather than making them pay for the cost of reclamation without any profit.

At the national policy level, the government of Uzbekistan has indicated growing commitment to land degradation issues. Through the presidential decree declaring 2025 as the "Year of Environmental Protection and Green Economy," water savings were identified as the core problem leading to the salinization process, alongside incorporating climate change adaptation into national policies (WorldSciencePub, n.d.). In addition, the national commitment to addressing the problem of salinization has been supported through international partnerships such as the Country Planning Framework of the Global Green Growth Institute (GGGI) (2024–2028), worth $1 billion in green investment, including $50 million in climate-resilient agriculture (WorldSciencePub, n.d.).

On the other hand, the Aral Sea Green Rehabilitation Investment Project (GRIP), an initiative of GGGI in collaboration with Human Asia, has focused specifically on the most disaster-affected districts, including Chimbay, Karauzyak, Bozataw, and Kegeyli, to assist people in establishing disaster-resilient livelihoods despite desertification, water shortages, and depletion of the Aral Sea (GGGI & Human Asia, 2022).

5. SURVEY RESULTS AND ANALYSIS

To understand the problem of soil salinization from a local perspective, a social survey was conducted to collect primary data, assessing people on their awareness of soil salinization, causes, observed signs, and possible solutions. The survey was collected from 200 people of various backgrounds and 5 age groups (18 years old or younger; 18-25; 25-40; 40-60; 60+). The results reflect their awareness and are useful in interpreting how different communities understand soil salinity.

5.1 . Background:

The age distribution of 200 respondents shows that survey was mainly answered by younger people under 18 years old, representing almost half of the total respondents with 48%. 20% of all respondents were aged 26-40, followed by the 41-60 age group with 14.5% and 18-25 with 13.5%, while 4% of all respondents were above 60 years old. This means that survey reflects youth awareness strongly, which is useful as young people are future researchers, farmers and decision-makers. However, this also creates a limitation simultaneously, as survey results may not directly represent older farmers or agricultural specialists who may have more direct experience with soil salinity.

In terms of regional distribution, most of the respondents were from Andijan region, which is located in Fergana valley, accounting for 85.5% of all respondents. This creates a major limitation as valley regions are overrepresented compared to regions like Karakalpakstan, Bukhara, Navoi, Jizzakh and Syrdarya located in oasis, where soil salinity is a major threat. This means that the survey is useful for understanding general awareness, but it cannot fully prove regional differences. However, after analyzing individual responses, it can be concluded that oasis regions face severe forms of soil salinization compared to valley regions, leading more portion of people from oasis to be aware of the problem, its causes and solutions.

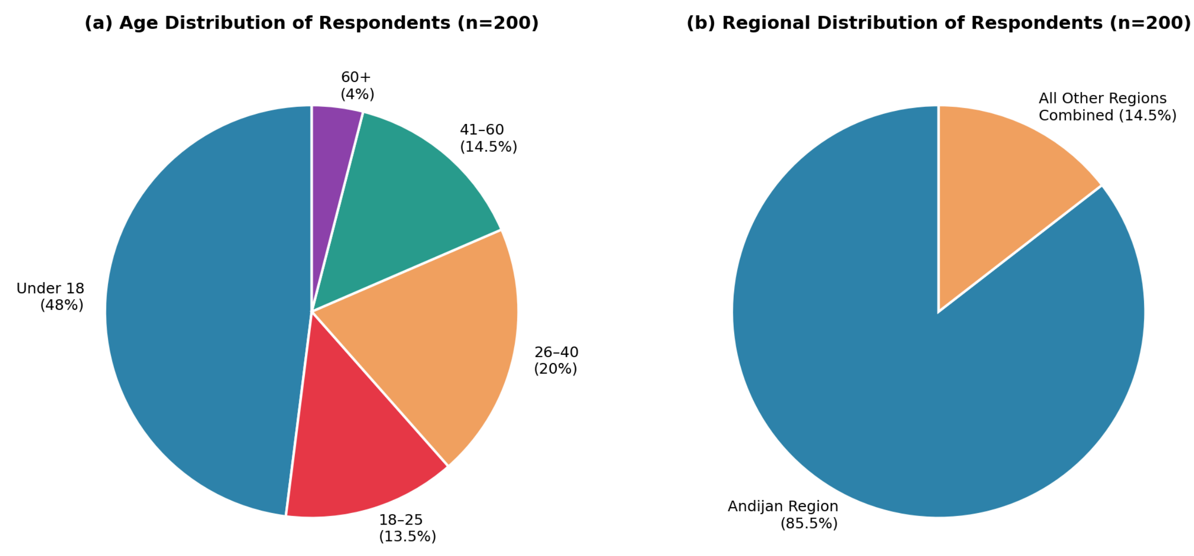


Figure VII. *Respondent Background: Age and Regional Distribution (n=200)*

5.2 . Awareness

The survey results demonstrate high awareness levels about soil salinization. When respondents were asked whether they heard about soil salinization or not, 74.5% of respondents answered “yes,” while 25.5% answered “no.”

However, awareness does not necessarily mean deep understanding. When respondents were asked to rate their level of knowledge about soil salinization, only 11% rated their knowledge as “very good,” and 19% as “good.” The largest portion of respondents with 37.5% described their level of knowledge as “average”, while 18% and 14.5% chose “very little” and “no knowledge at all” respectively. This indicates that although many people heard about soil salinization, their understanding is mostly basic or moderate. Therefore, public education and accessible information about causes, signs and solutions should remain necessary.

When people were asked about the causes of soil salinization, most people, with 32.5%, linked the problem with climate change, thinking it is caused by a broader issue of rising temperatures, droughts and water scarcity. 23.5% of all respondents selected “Improper irrigation” as the main cause, followed by “natural factors” with 15% and “Excessive water use” with 12%. However, a significant percentage of all respondents , with 17%, chose “I don’t know”, indicating people may recognize the problem but may not fully understand the mechanisms behind it.

The perceived seriousness of the problem was also high. 30% of all respondents consider soil salinization as a “Very serious” problem, while 48.5% think about it as a “Serious” problem, This means 78.5% of all respondents see soil salinization as a serious or very serious problem. 17.5% of the respondents view the problem as “Moderate”, while a very little percentage chose “Not serious”. Results indicate that although people may not be familiar with technical mechanisms or have not experienced soil salinization directly, many of them recognize the urgency of the problem as an environmental and agricultural issue

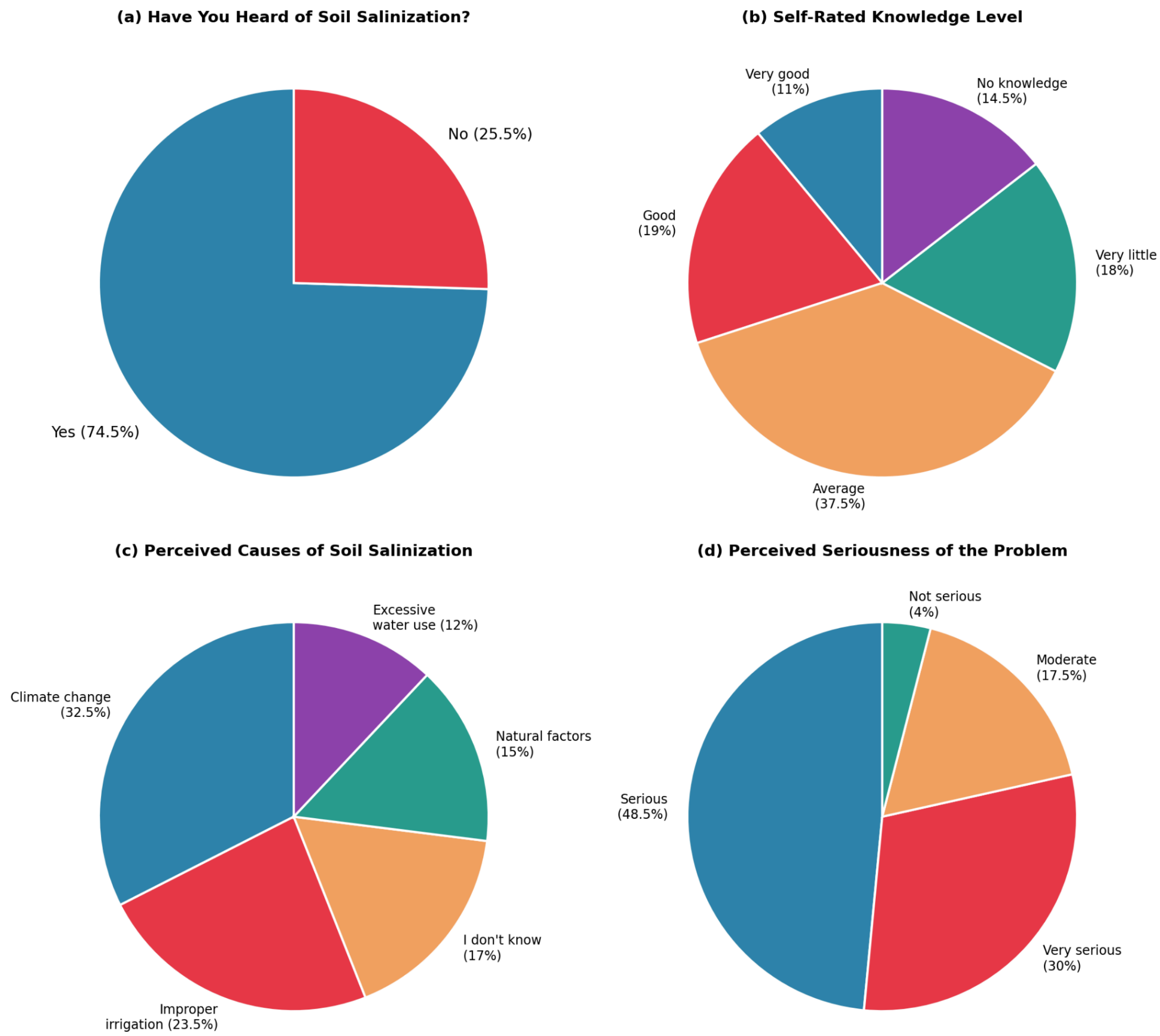


Figure VIII. *Public Awareness of Soil Salinization (n=200)*

5.3 . Local experience and solutions.

The survey also asked whether respondents had observed signs of soil salinity in their area. 38.5% of respondents answered “yes,” 31% answered “no,” and 30.5% were unsure.

After reviewing individual responses and cross-tabulating according to valley (Fergana, Namangan, Andijan), oasis regions(Republic of Karakalpakstan, Khorezm, Bukhara, Navoi, Jizzakh, Syrdarya, Kashkadarya, Surkhandarya, Samarkand) and other (Tashkent city and Tashkent region), it was found that people in valley observed less signs of soil salinity compared to people in oasis regions, indicating to severity of the problem in oasis regions.

***TABLE VII.** Respondents' Observation of Soil Salinity Signs in Valley and Oasis Regions*

Response	Valley	Oasis	Other	Total
Yes	33.5%	93.8%	50.0%	38.5%
No	33.0%	6.2%	50.0%	31.0%
Not sure	33.5%	0.0%	0.0%	30.5%

44.5% of those who have observed the signs of sail salinity stated that they had seen "White salt layers on the soil". 22% of respondents said "Reduced crop yields", followed by 22% who chose "Drying of plants". Also, 8.5% described other signs they have witnessed. From open responses, most people stated they observed white or grey crust on the surface of the soil. A respondent from Nukus said that they observe white salt layer on the surface everyday and they link it with the salt from the Aral Sea.

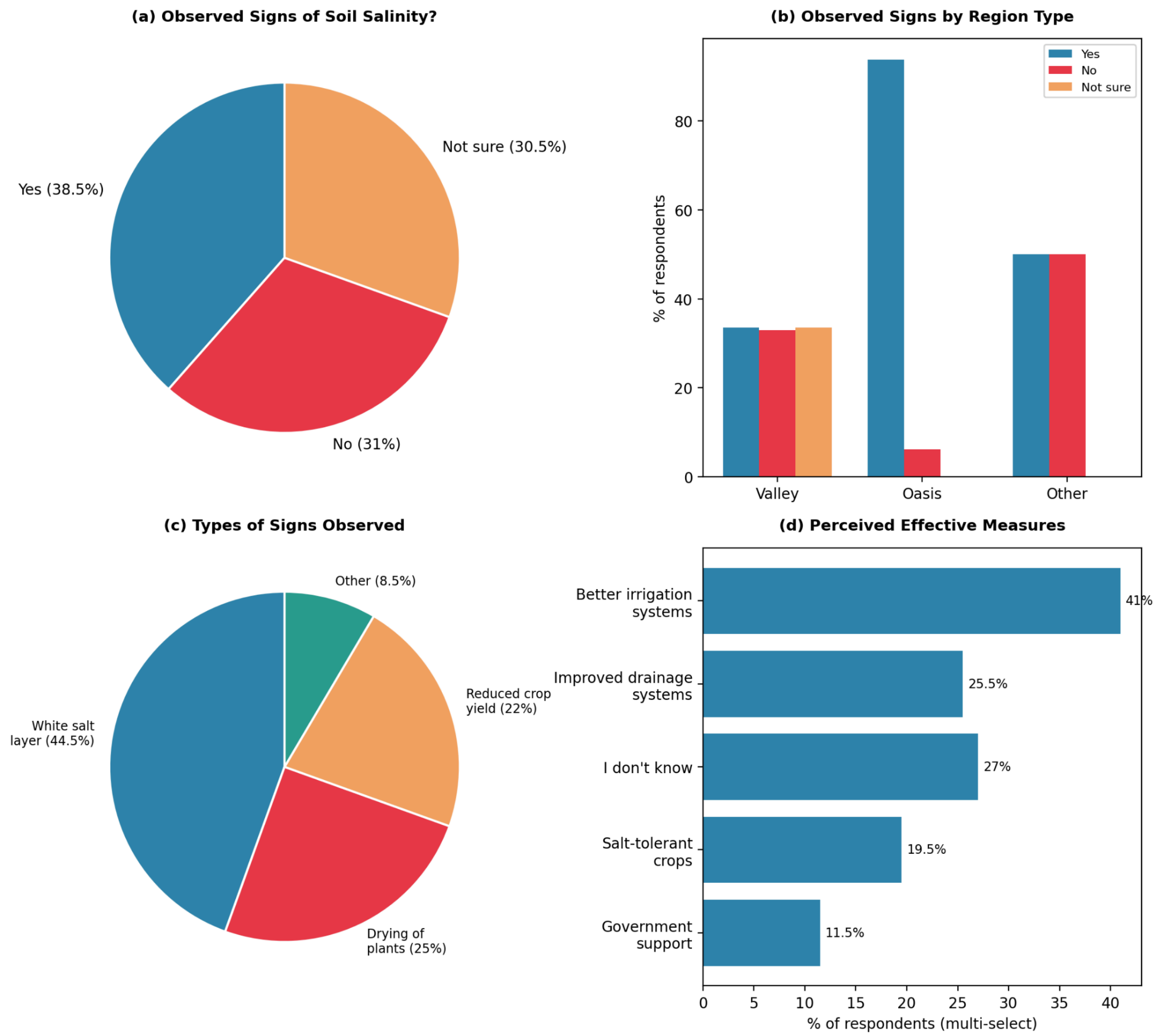
A respondent from Gulistan, Syrdarya, described her experience as follows: *"In Gulistan, the soil contains too much water. This causes soil salinization. Over time, many types of plants die. The groundwater level is located only about one meter below the surface, which is very shallow. Because of this, people in my area mostly grow small-rooted plants instead of trees"*.

These qualitative answers indicate that people can identify the signs of soil salinization without having a direct experience in agriculture if the problem is severe enough.

However, there is a gap between awareness of the problem and the awareness of the solutions. When people were asked whether they know any methods to tackle soil salinisation, the majority of them chose "No", accounting for 63% and only 37% chose "Yes". These results can be explained by the fact that most of the respondents were 18 years old or below without prior experience in the field of agriculture.

When respondents were asked which measures they considered effective, the most selected solution was "Better irrigation systems", chosen by 82 respondents, or 41%. The second most selected answer was "I don't know," chosen by 54 respondents, or 27%, again confirming the lack of solution awareness. "Improved drainage systems" were selected by 51 respondents, or 25.5%, while "Salt-tolerant crops" were selected by 39 respondents, or 19.5%. Government support was selected by 23 respondents, or 11.5% .

Figure IX. *Local Experience, Awareness of Solutions, and Perceived Effectiveness (n=200)*



CONCLUSION

It can be concluded that soil salinization is a major challenge for agricultural production and environment in Karakalpakstan. This area is extremely vulnerable due to its arid climate, intensive evaporation processes, low level of underground water, weak drainage systems, heavy reliance on irrigation, and the negative influence of the Aral Sea tragedy. As a result of salts accumulation in the soil layer, the fertility decreases, making crop growing less effective and decreasing yield, and consequently, causing economic hardship. Thus, soil salinization is not only an issue related to soils, but also a matter of water, drainage, agricultural production, and livelihood.

Based on the results of this research, it may be concluded that no single method leads to the full soil salinization reduction. Effective drainage is needed to control the level of groundwater, and leaching helps to remove the excessive salts from the roots zone. Irrigation improvement prevents over-irrigation and waterlogging, and gypsum application is effective against sodic and saline-sodic soils. The addition of organic matter and manure facilitates soil structure improvement, and salt-tolerant plants allow farmers to continue their work despite unfavorable conditions. Drip irrigation may be useful in water conservation; however, it needs to be done in combination with leaching since salts tend to build up in the wetting zone. Thus, the best option for Karakalpakstan is the use of an integrated approach.

REFERENCES

Akinshina, N., Toderich, K., Matsuo, N., Azizov, A., Babajanov, R., Berdiev, E., Myachina, O., Ilyasov, T., Zeybert, E., Muminova, M., & Kutibaeva, E. (n.d.). *Managing salt-affected soils for a sustainable future.* Food and Agriculture Organization. https://openknowledge.fao.org/server/api/core/bitstreams/c471f26a-4578-4f1c-811a-8968dec7b667/content

Ali, A. (2013) 'Best practices and procedures of saline soil reclamation systems in Pakistan', in T.R. Gurung and A.K. Azad (eds.) *Best Practices and Procedures of Saline Soil Reclamation Systems in SAARC Countries.* Dhaka: SAARC Agriculture Centre.

Ayers, R.S. and Westcot, D.W. (1985) *Water Quality for Agriculture.* FAO Irrigation and Drainage Paper 29 Rev. 1. Rome: Food and Agriculture Organization of the United Nations.

Britannica. (2026, July 25). *Aral Sea: Description, history, map, shrinking, & facts.* Encyclopædia Britannica. https://www.britannica.com/place/Aral-Sea

EBSCO Research Starters. (2025). *Aral Sea.* EBSCO. https://www.ebsco.com/research-starters/environmental-sciences/aral-sea

Facts and Details. (n.d.). *Aral Sea: History, irrigation, towns, tourism.* https://factsanddetails.com/central-asia/Uzbekistan/sub8_3g/entry-9409.html

FAO (1994) *A land degradation assessment and mapping method.* Food and Agriculture Organization of the United Nations. https://www.fao.org/4/v4360e/v4360e03.htm

FAO (1997) *Irrigation in the countries of the former Soviet Union in figures* (Water Report 15). Food and Agriculture Organization of the United Nations. https://www.fao.org/4/w6240e/w6240e20.htm

FAO (n.d.) *Soil salinity.* Global Soil Partnership. Food and Agriculture Organization of the United Nations. https://www.fao.org/global-soil-partnership/areas-of-work/soil-salinity/en/

FAO (2024a) *FAO launches first major global assessment of salt-affected soils in 50 years.* Food and Agriculture Organization of the United Nations. https://www.fao.org/newsroom/detail/fao-launches-first-major-global-assessment-of-salt-affected-soils-in-50-years/en

FAO (2024b) *Global Status of Salt-Affected Soils: Main Report.* Rome: Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/handle/20.500.14283/cd3044en

FAO (2024c) *Global Status of Salt-Affected Soils: Technical Report.* Rome: Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/server/api/core/bitstreams/31be1fac-a057-4b6b-80ea-a4554910368c/content

FAO and ITPS (2021) *Global Map of Salt-Affected Soils: GSASmap v1.0.* Rome: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils. https://www.fao.org/global-soil-partnership/gsasmap/en/

Fipps, G. (n.d.). *The Aral Sea disaster.* Texas A&M University. https://gfipps.tamu.edu/files/2019/12/Aral-sea.pdf

GGGI and Human Asia (2022) *Karakalpakstan Agriculture Risk Profile for Climate Resilience Capacity Development.* Tashkent: Global Green Growth Institute.

Hardie, M. and Doyle, R. (2012) 'Measuring soil salinity', *Methods in Molecular Biology*, 913, pp. 415–425.

Hassani, A., Azapagic, A., & Shokri, N. (2020). Predicting long-term dynamics of soil salinity and sodicity on a global scale. *Proceedings of the National Academy of Sciences, 117*(52), 33017–33027.

International Center for Biosaline Agriculture (ICBA). (2023, July 12). *Development of sustainable agricultural production systems in degraded areas of Karakalpakstan.* https://www.biosaline.org/projects/development-sustainable-agricultural-production-systems-degraded-areas-karakalpakstan

Jumaniyazov, I., Juliev, M., Khudaybergenov, Y., Jaksibaev, R., Orazbaev, A. and Amangeldieva, U. (2024) 'Analysis of soil salinity monitoring in irrigated areas: In case of Shimbay district, Republic of Karakalpakstan', *E3S Web of Conferences*, 590, 01007.

Khaitov, B., et al. (2025). *Halophyte legumes in saline soil restoration and reclamation of abandoned irrigated lands.* Eurasian Journal of Soil Science, 14(3), 198–207.

Khasanov, S., Kulmatov, R., Li, F., van Amstel, A., Bartholomeus, H., Aslanov, I., Sultonov, K., Kholov, N., Liu, H., & Chen, G. (2023). Impact assessment of soil salinity on crop production in Uzbekistan and its global significance. *Agriculture, Ecosystems & Environment, 342*, 108262.

Litalien, A. and Zeeb, B. (2020) 'Curing the earth: A review of anthropogenic soil salinization and plant-based strategies for sustainable mitigation', *Science of the Total Environment*, 698, 134235.

Ministry of Agriculture and Water Resources, Republic of Uzbekistan. (n.d.). *[Report on drainage improvement in Karakalpakstan].* World Bank. https://documents1.worldbank.org/curated/en/317111468173048196/pdf/E41550V20REVIS00Box385217B00PUBLIC0.pdf

Nainwal, R. C., Chaurasiya, P., Kumar, A., Singh, M., Singh, D., & Tewari, S. K. (2024). Phytoremediation: A sustainable approach to combat soil salinity. *Advances in Environmental and Engineering Research.*

Paz, A., Hristov, B., Amezketa, E., Falsone, G., Zambujo, J., Canfora, L., Mastrorilli, M., Gonçalves, M., Prins, P. and Ramos, T. (2020) *Prevention, mitigation and adaptation strategies for soil salinisation at farm level.* EIP-AGRI Focus Group Soil Salinisation.

Shahid, S.A., Zaman, M. and Heng, L. (2018) 'Introduction to soil salinity, sodicity and diagnostics techniques', in *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques.* Cham: Springer.

ScienceInsights. (2026, March 9). *Why the Aral Sea is shrinking: A man-made crisis.* https://scienceinsights.org/why-the-aral-sea-is-shrinking-a-man-made-crisis/

The Diplomat. (2023, November 17). *How the Soviet Union created Central Asia's worst environmental disaster.* https://thediplomat.com/2014/10/how-the-soviet-union-created-central-asias-worst-environmental-disaster/

Tsanis, I.K., Daliakopoulos, I.N., Koutroulis, A.G., Karatzas, G.P., Varouchakis, E.A., Kourgialas, N. and Mills, J. (2015) *Fact sheet: Soil salinization.* RECARE Project.

UNCCD (1993) *United Nations Convention to Combat Desertification.*

USSL Staff (1954) *Diagnosis and Improvement of Saline and Alkali Soils.* USDA Agriculture Handbook No. 60. Washington, DC: United States Department of Agriculture.

Wicke, B., Smeets, E., Dornburg, V., Vashev, B., Gaiser, T., Turkenburg, W., & Faaij, A. (2011). The global technical and economic potential of bioenergy from salt-affected soils. *Energy & Environmental Science, 4*(8), 2669–2681.

World Bank. (2025, May 21). *Uzbekistan to modernize its irrigation infrastructure with World Bank support.* https://www.worldbank.org/en/news/press-release/2025/05/21/uzbekistan-to-modernize-its-irrigation-infrastructure-with-world-bank-support

WorldSciencePub. (n.d.). *Soil degradation in Uzbekistan: A quantitative analysis.* https://worldsiencepub.com/index.php/lmc/article/download/563/528