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# Agronomic and reclamation strategies to enhance soil fertility, productivity and water accessibility

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**Introduction:** Over the last decade, yields and profitability of crops on agricultural lands in the Kyzylkum irrigation massif in the south of Kazakhstan, as well as soil fertility, have been decreasing. The Kyzylkum irrigation basin, located in the Syrdarya River basin, is affected by various factors such as agronomic practices, reclamation factors, and human activities including tourism. This study aims to monitor the yields of cotton and alfalfa in alfalfa-cotton crop rotations in the Kyzylkum irrigation massif, assess soil fertility after alfalfa and cotton cultivation under production conditions, and evaluate the profitability of water consumption.

**Methods:** The research methodology involved experimental and observational studies conducted on a nine-pole alfalfa-cotton crop rotation area in the Kyzylkum basin within the Syrdarya river basin. The study was conducted on three farms: Didar, Toishy, and Ali-Myrza. Productivity, soil fertility after crop cultivation, and profitability of water consumption were determined through these studies.

**Results:** The study found that the Ali-Myrza farm experienced a 21% increase in cotton yield, a 24% increase in alfalfa yield, a 36% increase in profit from crop rotation, a 34% increase in profitability, and a 5-6% increase in water consumption. After alfalfa rotation, the Ali-Myrza farm recorded the highest cotton yield at 3.5 t/ha and a profit of 1,316 euros/ha. However, in the following year, cotton yields decreased to 2.52 t/ha, and profits dropped to 576 euro/ha. The first year of alfalfa cultivation resulted in a yield of 10 t/ha and a profit of 462 euro/ha, which increased to 14 t/ha and 967 euro/ha in the subsequent year. Soil analysis revealed that after two years of growing alfalfa in a six-pole rotation, the root mass in the top 20 cm of soil reached 8.89 t/ha. In contrast, rotations with seven (Toishy) and nine (Didar) crops resulted in lower root masses of 4.68 t/ha and 3.47 t/ha, respectively. The corresponding humus content was 1.65%, 1.40%, and 1.1%, respectively.

**Discussion:** Comparing the seven and nine-pole rotations of alfalfa and cotton, the six-pole rotation demonstrated significant improvements in soil fertility (30-40% increase), cotton yield (18-23% increase), alfalfa yield (20-28% increase), and water consumption (5-6% increase). These findings confirm the effectiveness of the alfalfa-cotton rotation method in enhancing soil fertility, productivity, water efficiency, and grey soil productivity in Kyzylkum irrigated fields. The results obtained from this study can be applied in cotton farms in South Kazakhstan that use nine-layer cotton and alfalfa rotations. Furthermore, the findings have implications for cotton cultivation in any country worldwide.

KEYWORDS

**south Kazakhstan, agronomic factors, ameliorative factors, soil fertility, al-falfacotton rotation, crop rotation schemes**

## 1 Introduction

In the 5 years after the proclamation of independence of the Republic of Kazakhstan from the Soviet regime in 1991, due to economic recession and lack of stability, the area of irrigation systems decreased by 38.5%, and crop yields decreased by 1.5 times (Saparov, 2014). In South Kazakhstan, the main agricultural region, due to the lack of demand for cotton and alfalfa and low yields, many farms were unable to purchase machinery, fuel, fertilisers and pesticides. As a result, arable land was abandoned, and the area of irrigated land decreased from 500.5 thousand ha to 395.0 thousand ha, including in cotton rotation - from 220 thousand ha to 174.4 thousand ha (Tokbergenova et al., 2023). Currently, farmers of Arys, Maktaaral, Otyrar, Saryagash and Shardara administrative districts of Turkestan region throughout Kazakhstan are engaged in cotton cultivation (Poshanov et al., 2022). To solve the problems of sustainable and improved agricultural production in these areas, as well as the reuse of land excluded from crop rotation, scientifically sound solutions are needed, including the development of agrotechnical and reclamation technologies aimed at improving soil fertility (Ashirbekov, 2000).

It is also very important to revise the outdated system of water use in irrigated areas, such as the Kyzylkum irrigation basin in the south of the country (Yusupov et al., 2010; Penjiyev, 2013). This is due to the fact that reclamation systems of cotton crop rotation were introduced in 1984 when "state farms" were established, then in 1993 after the dissolution of "state farms" the water use system was transferred to the local population, and then farms were established (Tanirbergenov et al., 2020). In some farms, weeds have grown, irrigation canals and drains have been deformed, irrigated lands have become saline and degraded due to non-use of land due to low productivity (Nurzhanovna, 2011). In order to include these lands into cotton and alfalfa crop rotation, weeding of irrigated plots, repair of water outlets, and complex soil leaching are necessary. Thus, when implementing reclamation systems on this territory, it is necessary to take into account the cost of the complex of works, and the resources spent on growing crops should be compensated by productivity and improvement of soil fertility. In addition, it is very important to reduce the impact of soil degradation and its consequences (Issanova et al., 2014).

Literature review (Bishimbayeva et al., 2008; Petrick et al., 2017; Laiskhanov et al., 2018; Savelyev, 2018; Mukhamedova and Pomfret, 2019; Kalybekova et al., 2023; Laiskhanov et al., 2023) has shown that to obtain commercially acceptable yields of cotton and alfalfa on grey soils of the Kyzylkum irrigation massif in South Kazakhstan, an integrated approach is required, including crops with high biopotential, agrotechnical practices, reclamation methods and technologies that increase soil productivity and water consumption. In addition, irrigation parameters for cotton and alfalfa on grey soil can increase soil fertility in irrigated areas, which allows consistent application of techniques that ensure optimal water consumption and environmental protection (Khassanov et al., 2011; Bekhzod et al., 2016). Therefore, the choice of techniques should take into account irrigated agrolandscapes, including soil-hydrogeological, climatic and organisational-economic conditions, which require a differentiated approach to agrotechnical and reclamation techniques (Berezovsky, 1976; Gulov, 1978).

In the southern region of Kazakhstan, availability of land and rational use of water resources allow to conduct highly efficient irrigated farming and obtain high and stable yields of agricultural crops, including alfalfa and cotton in crop rotation. Alfalfa enriches the soil with organic matter, improves its chemical properties, increases fertility and increases cotton yield (Samaddar et al., 2021). Improving the efficiency of ameliorative systems of alfalfa-cotton crop rotation is a priority task that requires solving a set of economic, social and environmental problems (Yudakhin, 1975).

In the arid zone of the Kyzylkum irrigation massif, the amount of precipitation during the growing season varies within 20–30 mm, and the total water consumption during the growing season is 100–120 mm. The aridity of the climate and increased demand for agricultural products have led to a sharp increase in water consumption for agricultural needs (Dedova and Dedov, 2021). To increase the accumulation of winter precipitation in the 140–160 mm thick soil layer, autumn deep ploughing to a depth of 20–25 cm is carried out (Rau et al., 2023).

In the Kyzylkum irrigation basin, the average annual air temperature is +12.5°C, the sum of temperatures above 10°C ranges from 4,600–4,800°C, and the radiation level is 58–62 kcal/cm$^2$ per year. In hot and dry years, radiation balance (R), amount of photosynthetically active PAR radiation and dryness index increase. The dryness index is calculated as $J = R/(LOC)$, where LOC is the heat loss to evaporation of precipitation (Budyko, 1977). Data from the weather station Shardara in 2021 compared to long-term data show an increase in the sum of active temperatures by 9.15%, air humidity by 5–11%, dryness index by 6.15% and water consumption of cotton crops in rotation by 6–9%. During the growing season, surface irrigation is carried out to maintain soil moisture at a level of at least 75% MC (minimum moisture content), which helps to increase soil moisture and, ultimately, yield and economic indicators (Golovanov, 2011).

Hypothesis of the study is that alfalfa-cotton crop rotation is an optimal technique to increase fertility, productivity and water availability of soils to increase productivity of grey soils of Kyzylkum irrigated massif of South Kazakhstan. The purpose of the study is to monitor the yield of cotton and alfalfa crops in the alfalfa-cotton crop rotation of the Kyzylkum irrigation array, soil fertility after alfalfa and cotton cultivation in industrial conditions and the profitability of water consumption. The methodological basis of the study is the alfalfa-cotton crop rotation method, which provides a comprehensive study of measures to improve and preserve soil fertility and utilisation of arable land. The study was conducted in 2021–2022 on crop rotations of peasant farms Didar, Toishy and Ali Myrza on one hectare of alfalfa and one hectare of cotton. This is due to the fact that it was very important to determine fertility, productivity, water availability and productivity of soils of irrigated areas of Kyzylkum. This study will help the development of cotton and alfalfa production in Kazakhstan and other countries of the world.

## 2 Materials and methods

The study was conducted on one hectare of alfalfa and one hectare of cotton fields in cotton-alfalfa rotation of farms "Didar," "Toishy" and "Ali Myrza" in the Syrdarya river basin of Kyzylkum irrigation massif in Kazakhstan (Figure 1). The study was conducted in 2021–2022 on the plots of the following farms: Didar – nine – field crop rotation (control): irrigated area-28.7 ha, including alfalfa – 10.7 ha (37%), cotton – 18 ha (63%); Toishy – seven – field crop rotation: irrigated area – 20. 0 ha, including alfalfa – 6.3 ha (46%), cotton – 13.7 ha (54%); Ali Myrza – six-field crop rotation: irrigated area – 30.7 ha, including alfalfa – 15.3 ha (49.7%), cotton – 15.4 ha (50.3%).

Every year before sowing and in autumn after harvesting, soil samples were taken for chemical analysis by envelope method in five parts per hectare of cotton and alfalfa experimental plots: 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm deep. The chemical composition of salts and soil moisture were determined to a depth of 120 cm. The total number of cuttings in the three peasant farms was 30, and the number of samples was 180. All soil analyses are carried out at the certified laboratory of the U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry in Almaty using various methods and instruments, including Specord 210 PLUS ionometer, I-160 MI, FLAPHO-4 flame photometer, electronic scales ScoutProSPS202 F and special techniques for determining humus, nitrogen, phosphorus and potassium content were used. The distance between the certified laboratory of the U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry in Almaty and the Kyzylkum irrigation area is 850 km.

Before sowing cotton, discing and levelling works were carried out, irrigation holes were cut. Furrows were made every 90 cm. Tashkent cotton variety was sown on 20–25 April. After germination of cotton growth up to 3–4 leaves, cultivation and sowing of mineral fertiliser ammophos in the amount of 120 kg/ha were carried out. At the height of cotton more than 100 cm in the upper part of the cotton stalk, shortening works were carried out. The variety "Tashkent" was dropped in 130 days, defoliated before harvesting. Cotton was harvested first by combine harvester-75%, then manually-25%.

Alfalfa seeds (m.sativa) were sown continuously, row spacing 15 cm, planting depth 2–3 cm. Alfalfa was harvested in the period of budding - at the beginning of flowering. During the sowing period alfalfa was fertilised with ammophos, up to 90 kg/ha. Before sowing alfalfa, the soil was washed, ploughed, disced and levelled.

Mineral fertilisers, particularly superphosphate, were sown at the rate of 120 kg/ha for both alfalfa and cotton. Piezometers were installed in alfalfa and cotton fields to monitor groundwater levels, and hydrometric crosspieces were installed in irrigation canals to

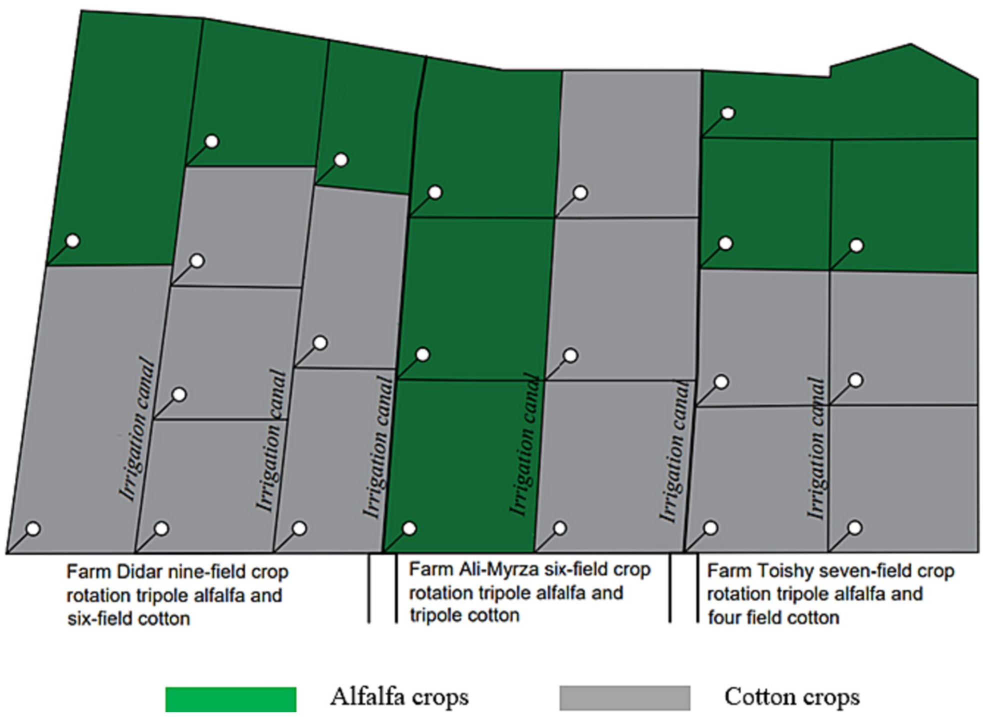


FIGURE 1
Scheme of experimental cotton and alfalfa crop rotations.

measure water flow using a GRM-21 water meter. Phenological zones were established to determine soil moisture, growth and development phases of alfalfa and cotton, and to monitor yields. Root biomass of 100 alfalfa plants was sampled according to the described methodology (Budyko, 1977). Figure 1 shows excerpts from field studies of farms Didar, Toishy and Ali Myrza.

Judging by the mechanical composition, the arable soil layer consists of light loam and clay, the depth of which is 18–20 cm. The thickness of fine silt fraction in all profiles is 2–3 m. Light clay prevails in the granulometric composition, the content of "physical clay" (the sum of fractions from 0.01 to 0.001 mm) is from 65 to 80% by mass of all fractions. The light clay is dominated by fractions of fine dust (0.005–0.001 mm) and silt (0.001 mm), which are also dominant in medium and heavy clays. The study of soils showed that the upper part of the profile of the experimental field (0–150 cm) contains a minimum amount of coarse and medium sand fractions, the content of which varies from 0.24 to 14.0%. At the same time, in light loams and sandy loam soils the share of medium sand (0.25–0.05 mm) is quite high and in some cases exceeds 50% (horizon 100–150 and 150–200 cm; Table 1).

Ongoing oxidation–reduction processes in the soil lead to changes in its water-physical properties. During cotton irrigation, the plow and subsoil layers become compacted, resulting in an increase in bulk density to 1.40–1.50 g/cm$^3$ and a decrease in porosity by 1–2%. This compaction is due to the movement of clay particles with down-ward water flow and the processes of peat formation. As a result, the compacted layer experiences restricted aeration. However, during alfalfa cultivation, the soil becomes loose, and the bulk density decreases to 1.36 g/cm$^3$, while the porosity increases by 2%. Field soil moisture increases by 4–7% during cotton cultivation as compared to completely dry soil (Makhmadjanov et al., 2023).

Irrigated agriculture relies heavily on the field moisture content of the soil. At depths exceeding one meter, the field moisture content is high, reaching 26–28%, which corresponds to the soil's field capacity. This high moisture content is due to the saturation of the lower soil horizons, which is caused by the groundwater level's proximity (2.0 meters). The soil's salinity regime can significantly impact water requirements, crop yield, and cost-effectiveness (Danierhan et al., 2013). In this regard, after autumn cotton harvesting, ploughing with rakes is carried out as an important agrotechnical operation preventing capillary movement of groundwater and accumulation of salts in the upper soil layer. Positive temperatures during the autumn months of October–November result in favourable soil warming, making this an ideal time to stop water runoff at 0–20 cm in the surface soil layer. This action prevents the movement of salts into the aeration zone and salts remain in the lower soil layers at a depth of 1.5–2.0 metres. Wetting the soil in spring and flushing 3,500 m$^3$ /ha in March removes salts from the aeration zone and creates fresh groundwater with salinity of 1.5–2.5 g/L, which is maintained by water withdrawal during the irrigation period (Busscher et al., 2007).

The experimental fields have a groundwater level of 2.0–2.5 meters, and the groundwater mineralisation ranges from 1.2–2.5 g/L. The hydro-morphic and au-to-morphic meliorative regimes ensure soil fertility reproduction in alfalfa cultivation and high cotton yields of up to 3.5 tons/ha and alfalfa yields of up to 15 tons/ha.

Thus, the object of this study was to determine cotton and alfalfa yields on a nine-field crop rotation plot in the Kyzylkum lowland (farms Didar, Toishy, Ali-Myrza), soil fertility after harvesting and economic efficiency of water use.

## 3 Results and discussion

The results of research showed that after 2 years of alfalfa cultivation the yield of root mass in the 0–60 cm soil layer depending on the crop rotation structure was from 5.7 to 12.5 t/ha. The yield of dry grass for the same period was 18.27–24.14 t/ha. The results showed that the main mass of the root system (60–70%) is concentrated in the 0–20 cm soil layer. At greater depth the mass of the root system did not exceed 1.0 t/ha at a depth of 60 cm (Table 2).

After 2 years of alfalfa cultivation, humus accumulation in soil layer 0–20 cm in six-field crop rotation of agricultural enterprise Ali-Myrza was 16% higher than in seven-field crop rotation of agricultural enterprise Toishy and higher than in nine-field crop

TABLE 1 PQs registered on UNESCO World Heritage list, source: (Penjiyev, 2013).

| No section | Depth | Particle size fractions in mm | | | | | | Granulometric composition | Type of soil |
|---|---|---|---|---|---|---|---|---|---|
| | | 1–0.25 | 0.25–0.05 | 0.05–0.01 | 0.01–0.005 | 0.005–0.001 | 0.001 | | |
| | | sand | | silt | | clay | | | |
| P – 1 18/04–2021 | 0–20 | 0.46 | 1.54 | 33.44 | 8.36 | 32.32 | 23.88 | 64.56 | Light clay |
| | 20–40 | 0.58 | 0.42 | 30.0 | 11.92 | 31.16 | 25.92 | 69.0 | – |
| | 40–60 | 0.56 | 1.12 | 31.32 | 11.36 | 29.24 | 26.4 | 67.0 | – |
| | 60–80 | 0.75 | 7.13 | 33.92 | 9.0 | 20.84 | 28.36 | 58.2 | Heavy loam |
| | 80–100 | 0.88 | 2.64 | 31.72 | 14.32 | 22.6 | 27.84 | 64.76 | Light clay |
| | 100–120 | 1.32 | 57.56 | 13.0 | 5.48 | 5.32 | 17.32 | 28.12 | Light loam |
| | 120–150 | 1.98 | 72.86 | 9.2 | 0.96 | 3.72 | 11.28 | 15.96 | Loamy sand |
| | 150–200 | 1.56 | 73.84 | 9.32 | 1.48 | 1.32 | 12.48 | 15.28 | – |

Mechanical composition of experimental soil samples.

TABLE 2 Content of humus and mobile objects in soil on lands of farms Didar, Toishy and Ali-Myrza.

| Farms, area, crop rotations | Soil layer, cm | After two years of alfalfa cultivation | | | | | After two years of cotton cultivation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Root mass, t/ha | Humus, % | Mobile forms, mg/kg | | | Humus, % | Mobile forms, mg/kg | | |
| | | | | Nitrogen | Phosphorus | Nitrogen | | Nitrogen | Phosphorus | Nitrogen |
| Farm didar | 0–20 | 3.47 | 1.1 | 53.6 | 60.0 | 260.0 | 0.64 | 47.6 | 37.0 | 130.0 |
| Total area: 39.7 hectares | 20–40 | 1.16 | 0.42 | 43.6 | 31.0 | 190.0 | 0.30 | 36.4 | 25.0 | 100.0 |
| Cotton: 63% (29 hectares) | 40–60 | 1.06 | 0.34 | 45.2 | 31.0 | 80.0 | 0.11 | 19.6 | 20.0 | 60.0 |
| Alfalfa: 37% (10.7 hectares) | 0–60 | 5.69 | 0.62 | 47.46 | 40.66 | 176.6 | 0.3 | 32.67 | 25.67 | 95.0 |
| Farm Toishy | 0–20 | 4.68 | 1.40 | 49.0 | 39.0 | 420.0 | 0.635 | 36.4 | 20.5 | 225.0 |
| Total area: 20.0 hectares | 20–40 | 1.34 | 1.03 | 33.6 | 23.0 | 250.0 | 0.52 | 28.0 | 8.0 | 130.0 |
| Cotton: 54% (13.7 hectares) | 40–60 | 0.62 | 0.79 | 30.8 | 10.0 | 130.0 | 0.34 | 30.8 | 8.0 | 120.0 |
| Alfalfa: 46% (6.3 hectares) | 0–60 | 6.64 | 1.07 | 35.93 | 23.3 | 158.33 | 0.49 | 33.6 | 12.83 | 140.6 |
| Farm Ali-Myrza | 0–20 | 8.89 | 1.65 | 86.2 | 28.0 | 555.0 | 0.74 | 30.8 | 11.0 | 160.0 |
| Total area: 30.7 hectares | 20–40 | 1.92 | 1.14 | 33.6 | 29.0 | 180.0 | 0.58 | 33.6 | 12.0 | 90.0 |
| Cotton: 50.3% (15.5 hectares) | 40–60 | 0.92 | 1.0 | 47.6 | 29.0 | 210.0 | 0.41 | 33.6 | 20.0 | 160.0 |
| Alfalfa: 49.7% (15.2 hectares) | 0–60 | 11.73 | 1.26 | 55.8 | 33.0 | 315.0 | 0.60 | 32.67 | 20.0 | 136.67 |


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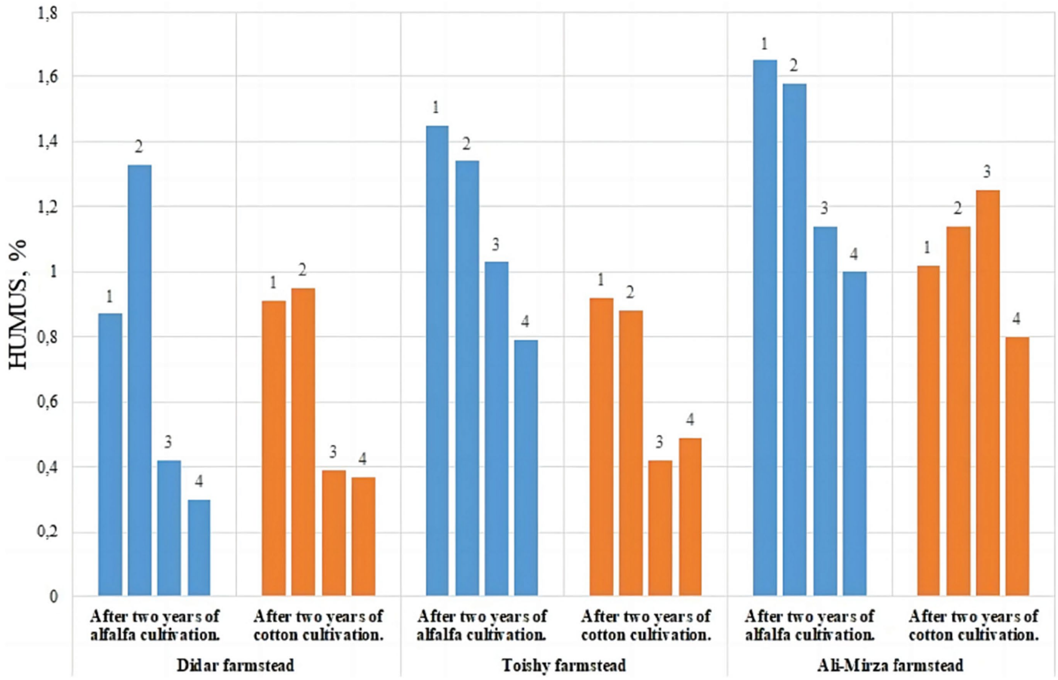


FIGURE 2
Organic matter content in soil on irrigated lands with alfalfa-cotton crop rotation, alfalfa cultivated after cotton as the predecessor. Soil layer: (1) 0–10 cm, (2) 10–20 cm, (3) 20–40 cm, (4).

TABLE 3 Humus content in alfalfa and cotton cultivation, t/ha.

| Farms | Crop rotation | Soil layer, cm | Humus content after two years of alfalfa cultivation | Humus content after two years of cotton cultivation | Humus content after alfalfa and cotton cultivation |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| Farm Didar alfalfa & cotton | nine-field crop rotation (three fields of alfalfa and six fields of cotton) | 0–40 | 44.08 | 22.91 | 21.17 |
| | | 0–60 | 52.78 | 26.1 | 26.68 |
| Farm Toishy alfalfa & cotton | seven-field crop rotation (three fields of alfalfa and four fields of cotton) | 0–40 | 70.325 | 32.48 | 37.85 |
| | | 0–60 | 93.235 | 41.47 | 51.77 |
| Farm Ali-Myrza alfalfa & cotton | six-field crop rotation (three fields of alfalfa and three fields of cotton) | 0–40 | 79.895 | 33.495 | 46.40 |
| | | 0–60 | 108.895 | 43.355 | 65.54 |

rotation of agricultural enterprise Toishy. In the agricultural enterprise Didar the crop rotation increased humus accumulation by 34%. In the 0–60 cm soil layer, the difference was 18 and 50%, respectively.

On the other hand, after 2 years of cotton cultivation, the humus content in the 0–20 cm soil layer in the nine-field rotation decreased by 53%, in the seven-field rotation by 22%, and in the six-field rotation by 19%. Similarly, in the 0–60 cm soil layer, humus content decreased by 15 and 51%, respectively. The decrease in soil organic matter content is due to the replacement of alfalfa in the cotton rotation scheme. The decrease occurs throughout the soil profile and depends on the structure of alfalfa-cotton rotation (Figure 2; Karasev, 1958; Jaynes et al., 2001; Chen et al., 2022). It is noteworthy that in six-field crop rotation humus accumulation in the 0–60 cm soil layer is 19% higher than in nine-field crop rotation.

After 2 years of alfalfa cultivation, humus accumulation in the 0–40 cm soil layer in the six-field rotation was 35.8 t/ha higher than in the nine-field rotation. In the 0–60 cm layer, humus accumulation in the six-field rotation was 56.11 t/ha higher than in the nine-field rotation, and in the seven-field rotation it was 26.24 t/ha and 40.45 t/ha higher. Similarly, in the six-field crop rotation after 2 years of cotton cultivation, the organic matter content in the soil at the depth of 0–60 cm was 17.2 t/ha higher than that in the nine-field crop rotation. This increase in soil organic matter content led to a rise in cotton yield by 0.8 t/ha and alfalfa yield by 2–4 t/ha (Table 3).

Alfalfa was harvested three times during the growing season. In the first and second years, the average yield in Didar farm was 8.0 tonnes/ha, in Toishy farm - 9.0 tonnes/ha, and in Ali-Myrza farm - 10.0 tonnes/ha.

TABLE 4 Growth and development of cotton depending on the structure of alfalfa-cotton crop rotations.

| No | Cotton plant density per 1 m$^2$ | | Cotton plant density (thousand plants/ha) | Cotton plant height (cm) | Number of bolls (thousand/ha) | Yield (c/ha) |
|---|---|---|---|---|---|---|
| | farm | Total area | | | | |
| 1 | Didar | cotton 29 ha | 84 | 95 | 130.0 | 27.0 |
| 2 | Toishy | cotton 13.7 ha | 88 | 103 | 109.0 | 31.0 |
| 3 | Ali-Myrza | cotton 15.5 ha | 96 | 110 | 180.0 | 35.0 |

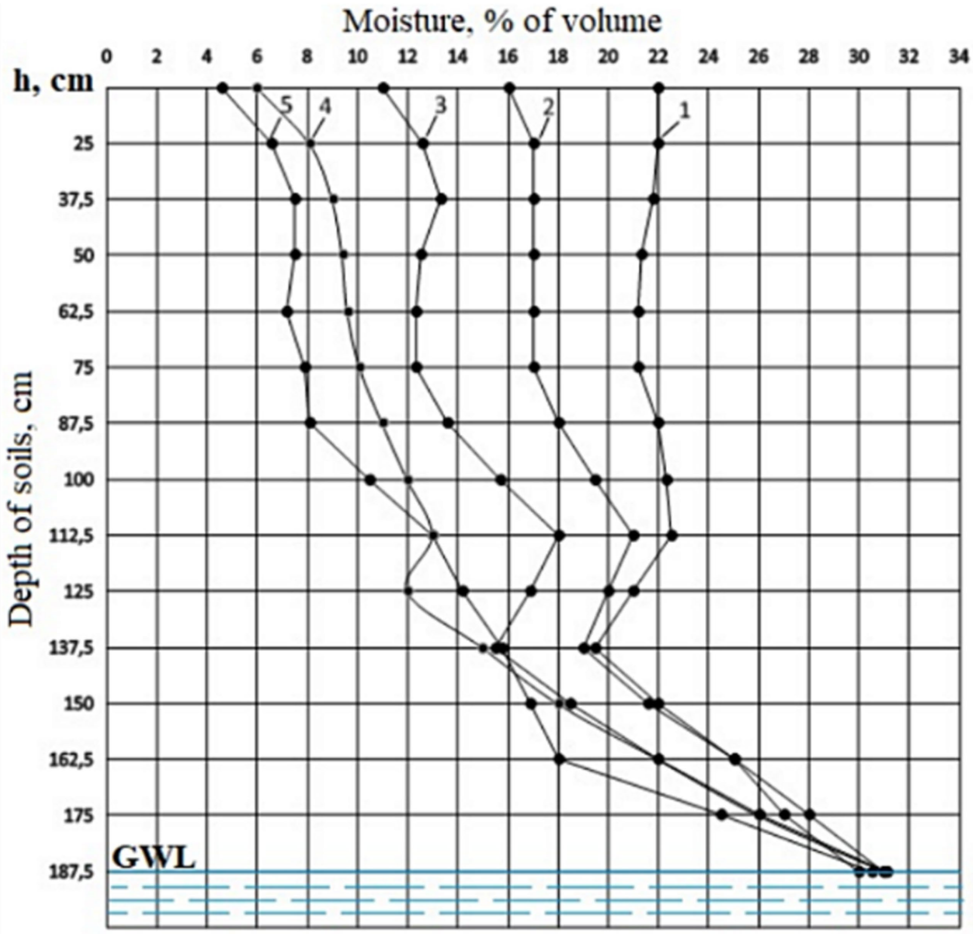


FIGURE 3
Dynamics of soil moisture in different seasons: 1 – in spring before planting, 2 – during the vegetation period, 3 – in autumn before harvesting, 4 – during the winter period, 5 – in spring be-fore leaching, h – soil depth, cm, GWL – groundwater level.

The structure of the alfalfa-cotton cycle plays a crucial role in the growth, development and accumulation of cotton biomass. Increasing the share of alfalfa in the crop rotation up to 50% in six-field crop rotation led to an increase in soil fertility and the number of cotton plants by 13%, spikelets by 18%, height by 14%, and productivity by 23% compared to nine-field crop rotation. In the six-field rotation of Ali-Myrza farm, the energy intensity of cotton biomass is 13% higher than in the nine-field rotation of Didar farm, and 9% higher than in the seven-field rotation of Toishy farm. In addition, the yield in the six-field rotation is 11% higher than in the nine-field rotation (Table 4).

Cotton and alfalfa are irrigated three times during the irrigation period. The irrigation rate for cotton is from 8,116 to 8,568 m$^3$/ha, and for alfalfa - 7348 m$^3$/ha. The recommended irrigation norm is 2,100–3,000 m3/ha, which allows to maintain fresh top layer of groundwater and create a moisture reserve in the soil above 75% of the field capacity within 20–25 days. This, in turn, ensures normal growth and development of cotton-alfalfa crop rotation.

The soil moisture content corresponding to the field capacity is maximum during the leaching and soil water recharge period in March, and the minimum soil moisture content is observed before the leaching process (Figure 3).

The cotton yield is heavily reliant on the soil moisture content. For the Tashkent variety, the biological yield is 4.5 t/ha when the soil moisture is between 75 and 85% of the field capacity, with water use efficiency (WUE) equal to 1 and (Q)/Q_max = 1. However, a de-crease in soil moisture below 75% of the field capacity results in reduced water availability and a decline in cotton yield (Figure 4).

After irrigation, the topsoil was loosened to conserve soil moisture and prevent the movement of salts from groundwater through the soil profile to the aeration zone (Figure 5). Water consumption per 1 tonne of annual cotton crop in a six-field crop rotation is 3,220 $m^3$/t, and 520 m3/t for alfalfa. For seven-field crop rotation these values are 10% higher, and for nine-field crop rotation - by 22% (Table 5).

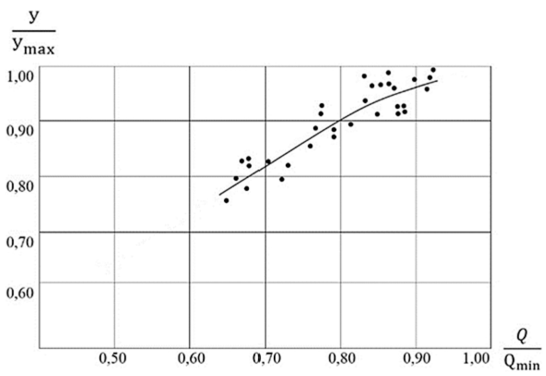


FIGURE 4
Dependence of cotton yield on water availability. Y/Y_max – relative cotton yield; Q/Q_max – water availability; Y_max – cotton yield at the optimal irrigation rate; Q_max – optimal irrigation rate.

In farms Didar, Toishy and Ali-Myrza groundwater in the irrigation period lies at a depth of 2.0 m and more, which do not participate in subirrigation of alfalfa and cotton crop rotations. However, in the most depressed areas of irrigated lands of the Kyzylkum massif, groundwater in the irrigation period lies at a depth of 1.5 m and participates in subirrigation of alfalfa and cotton crop rotations. Therefore, it is extremely important to assess the influence of groundwater level on irrigation and irrigation rates of alfalfa and cotton crop rotations.

The conducted studies allowed to establish the dependence of groundwater participation in sub-irrigation on total water consumption and water table depth for different types of soils. The share of groundwater participation in sub-irrigation can be determined using the following equations:

For heavy soils, the equation is as follows:

$$Kg = \left(0.161 - 0.037h\right) Ev0.749 + 0.35h + 0.0025h2 \tag{1}$$

For light soils, the equation is as follows:

$$Kg = \left(0.86 - 0.019h\right) Ev1.323 + 0.189h + 0.034h2 \tag{2}$$

where Ev represents total water consumption of the crop, thousand $m^3$/ha; h represents average depth of groundwater level, m.


FIGURE 5
**(A)** – Soil sampling on a cotton field; **(B)** – Soil sampling on the alfalfa field; **(C)** – Measuring of cotton seedlings; **(D)** – Determination of plants, cotton bolls before harvesting; **(E)** – Irrigation furrow after irrigation; **(F)** – Irrigation furrow after chiselling.

TABLE 5 Technology of water reclamation in chestnut soils of Kyzylkum irrigation basin of farms Didar, Toishy and Ali-Myrza.

| Farms, crop rotations, total area, ha | Spring soil water recharge and leaching – March ($m^3$/ha) | Irrigation norm ($m^3$/ha) | | Crop yield (t/ha) | | Water consumption per 1 t of yield ($m^3$/t) | |
|---|---|---|---|---|---|---|---|
| | | By crop | By crop rotation area | 2021 | 2022 | 2021 | 2022 |
| Farm Didar, nine-field crop rotation −39,7 ha, Cotton-29 ha, Alfalfa-10.7 ha | 3,500<br>3,500 | 8,453<br>7,348 | 8,155 | 2.7<br>8.0 | 2.06<br>10.27 | 3130.7<br>918.5 | 4103.3<br>715.5 |
| Farm Toishy, seven-field crop rotation −20.0 ha, Cotton-13.7 ha, Alfalfa-6.3 ha | 3,500<br>3,500 | 8,568<br>7,348 | 8,184 | 3.1<br>9.0 | 2.16<br>12.83 | 2763.8<br>816.4 | 3966.6<br>572.7 |
| Farm Ali-Myrza, six-field crop rotation – 30.7 ha, Cotton-15.5 ha, Alfalfa-15.2 ha | 3,500<br>3,500 | 8,116<br>7,348 | 7,738 | 3.5<br>10.0 | 2.52<br>14.14 | 2318.8<br>734.8 | 3220.6<br>519.6 |

TABLE 6 Potential groundwater use coefficients based on total water consumption in case of groundwater depth of 1.5 m.

| Soils | Mineralisation, g/l | Total Water Consumption, $m^3$/ha | | |
|---|---|---|---|---|
| | | 7,000–8,000 | 8,000–9,000 | 9,000 |
| Heavy clay and clay loam | 2.0–0.3.0 | 0.31 | 0.35 | 0.39 |
| Light clay loam, dry | 2.0–0.3.0 | 0.29 | 0.34 | 0.39 |

Correction coefficients (Kg) are applied for slightly mineralised groundwater, which do not have a significant impact on soil salt regime and changes in ameliorative condition. Values of these coefficients are presented in Table 6.

Practical data show that the share of groundwater participation in crop water consumption depends not only on the above-mentioned indicators, but also on the degree of salinity. Under conditions of Kyzylkum irrigation massif, groundwater participation in subirrigation is estimated at 1400–1600 m3/ha for cotton and 2000–2,100 m3/ha for alfalfa. However, it is crucial that this contribution does not exceed 35% of the irrigation norm or total water consumption.

The use of groundwater for subirrigation in low-lying areas of irrigated lands may lead to salt accumulation in the active layer of soil, which will negatively affect the development of crops. Consequently, it is inappropriate to allow inclusion of mineralised groundwater in the total water consumption for irrigated agriculture. Strict control over water exchange processes between the active layer of soil and groundwater is necessary. Involvement of groundwater in formation of evapotranspiration is presented in Figure 6.

Field studies have shown that as the share of groundwater participation in total water consumption decreases, the permissible level of its mineralisation increases. Besides, significant depth of groundwater occurrence under soil surface can also lead to increase of permissible mineralisation under subirrigation. Introduction of soil-permissible irrigation norms taking into account groundwater depth and salinity in agro-industrial production can lead to increase of water and land resources use efficiency, reduction of capital investments in drainage construction and mitigation of negative processes in irrigation systems.

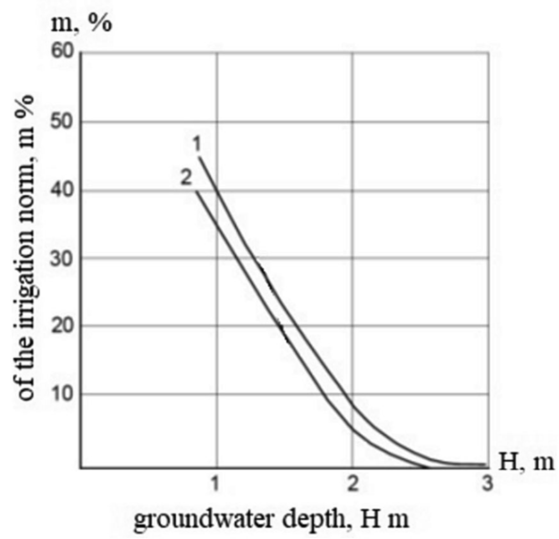


FIGURE 6
Dependence of groundwater participation in formation of total evaporation on depth of their occurrence, %. 1 – heavy loam, clay; 2 – light loam, sandy loam.

In conditions of alfalfa-cotton crop rotation on reclaimed lands with the use of subirrigation it is extremely important to prevent deterioration of soil fertility as a result of secondary salinisation, water erosion and other anthropogenic factors. This requires special attention to irrigation technologies and regimes, especially to the reduction of irrigation rates.

To ensure effective functioning of irrigation systems, it is necessary to improve the economic mechanism of interaction between land users and reclamation authorities, attracting public, private and personal investments for the implementation of reclamation projects. Active participation in development and defence of laws related to land reclamation, water and land resources is also extremely important.

Efficiency of alfalfa-cotton crop rotation on irrigated lands of Kyzylkum massif is shown in increase of cotton yield and profitability. Gross income from cotton exceeds the costs of its cultivation in 2.03–2.63 times, and from alfalfa - in 1.5–1.9 times. In a six-field rotation, the profit from cotton reaches 37% in 2021 and 34% in 2022, and in nine-field and seven-field rotations - 31 and 33%, respectively. However, already in the second year after alfalfa cultivation, cotton yield decreases by 0.5–1.0 tonnes/ha, and the profit per rotation area decreases by 13–38% (Table 7).

Thus, the natural-climatic conditions of grey soil of the Syrdarya river basin in the South of Kazakhstan are favourable for cotton cultivation, as hot and dry summers and the availability of irrigation water allow cotton yields of more than 3.0 t/ha. In particularly hot years, when the air temperature during capsule formation in July exceeds 45°C, cotton yields exceed those of cooler summers with air temperatures of 40°C (Dudchik, 1978).

Alfalfa application in cotton crop rotation has a positive effect on fertility and nitrogen balance of grey soil, especially in short cotton rotations (Wang et al., 2006). At the same time, the consumption of mineral fertilisers and chemical plant protection products is reduced. The decomposition of alfalfa root residues as a cotton predecessor leads to the formation of organic matter with an increased content of nutrients in a more accessible form for cotton, including nitrogen, phosphorus and potassium (Shpakov, 2021).

Analysis of soil samples from irrigated lands in alfalfa-cotton rotation shows that humus and nutrient content in soil depends on cotton rotation. The most complete productive potential of alfalfa, including its nitrogen-fixing capacity, is realised in the rotation with three-year alfalfa cultivation, the yield of which is 15.0 t/ha, which serves as a basis for the production of field fodder in specialised sheep and dairy-meat farms (Svechnikov, 2020).

Alfalfa plays an important role in providing high quality fodder. Expansion of alfalfa crops in the desert zone of South Kazakhstan contributes to the successful development of livestock breeding, given the limited pasture conditions in this region. The vegetation appears in March after winter precipitation, the vegetation period is short and dries up by May (Temirbekov, 2020). In alfalfa-cotton crop rotation, the yield of alfalfa hay reaches 10–12 t/ha, which is characterised by high biomass productivity and resistance to adverse environmental factors, and also has a positive effect on soil fertility and nitrogen balance. Moreover, the ecological-nomic indicators of the six-field crop rotation are 30–40% higher than those of the nine-field rotation. Abundant green mass of alfalfa covers the surface of the field, preventing overheating and reducing evaporation of soil moisture, which reduces the need for irrigation by 10%.

In addition, alfalfa serves as an excellent ameliorant for saline soils, reducing salt content in alfalfa fields by 8 times (Wang et al., 2009). It also helps to reduce the incidence of cotton wilt: the severity of wilt decreases 3–4 times and almost completely disappears when crops are alternated in cotton rotation.

TABLE 7 Efficiency of alfalfa-cotton crop rotation on Kyzylkum irrigated massif.

| Farms, crop rotations, total area, ha | Yield, t/ha | | Purchase Price (Cost), Euro /t | Gross Income, Euro/ha | | Costs for Agrotechnical and Irrigation Melioration, Euro/ha | | Profit, Euro/ha | | Profit from Crop Rotation, Euro/ha | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2021 | 2022 | | 2021 | 2022 | 2021 | 2022 | 2021 | 2022 | 2021 | 2022 |
| farm Didar, nine-field crop rotation −39,7 ha, Cotton-29 ha, Alfalfa-10.7 ha | 2.7<br>8.0 | 2.06<br>10.27 | 606.1<br>152.8 | 1636.5<br>1222.4 | 1248.5<br>1569.3 | 805.1<br>941.4 | 869.5<br>1016.7 | 831.3<br>281.0 | 379.0<br>552.5 | 83.0 | 424.8 |
| farm Toishy, seven-field crop rotation −20.0 ha, Cotton-13.7 ha, Alfalfa-6.3 ha | 3.1<br>9.0 | 2.16<br>12.83 | 606.1<br>145.85 | 1878.9<br>1312.6 | 1309.1<br>1871.2 | 805.1<br>941.4 | 869.5<br>1016.7 | 1195.0<br>371.2 | 562.7<br>854.5 | 935.5 | 654.6 |
| farm Ali-Myrza, six-field crop rotation – 30.7 ha, Cotton-15.5 ha, Alfalfa-15.2 ha | 3.5<br>10.0 | 2.52<br>14.14 | 606.1<br>140.32 | 2121.3<br>1403.2 | 1527.3<br>1984.1 | 805.1<br>941.4 | 869.5<br>1016.7 | 1316.2<br>461.8 | 576.0<br>967.4 | 893.2 | 774.2 |

## 4 Conclusion

The main conclusions of this work are as follows:

Increase of soil fertility and agrotechnical methods in the irrigated territory of Kyzylkum provide for the inclusion of alfalfa in crop rotation. After growing alfalfa in a six-field crop rotation, the accumulation of root mass in the 0–20 cm soil layer is 8.89 t/ha, and in the 0–60 cm layer - 11.73 t/ha. In the nine-field crop rotation these indicators are 3.47 t/ha and 5.69 t/ha, respectively. It is noteworthy that the maximum accumulation of humus occurs in the six-field rotation alfalfa - cotton in the farm Ali-Myrza. After 2 years of alfalfa cultivation, the humus content in the 0–20 cm soil layer reaches 1.615%, and in the 0–60 cm layer - 1.26%. These indicators are 30% higher than in seven-field alfalfa-cotton crop rotation in agrocomplex Toishy, and 40% higher than in nine-field crop rotation in agrocomplex Didar. Moreover, the content of mobile forms of nitrogen, phosphorus and potassium in the soil increases by 10–15% in six-field crop rotation compared to nine-field crop rotation. In the six-field crop rotation after cotton cultivation, the humus content in the 0–60 cm soil layer is 17.2 tonnes/ha higher than in the nine-field crop rotation.

Irrigation norms, groundwater level and salinity influence reclamation technologies and agrophysical properties of soil. To maintain soil moisture in farms at a level not lower than 75% MC, the irrigation norm for cotton is 8,116 $m^3$/ha, for alfalfa - 7,345 $m^3$/ha, and for spring water recharge in the fields of alfalfa and cotton crops the norm is set at 3,500 $m^3$/ha. This provides leaching of salts from aeration zone and creation of fresh groundwater, which is maintained during the whole irrigation period under observance of irrigation norms. Groundwater level in the study area is 2.0 m and more, mineralisation is 1.3–2.0 G/L, soil is slightly saline. In the areas where groundwater is used for supplementary irrigation, irrigation norms are adjusted taking into account the volume of supplementary irrigation in the range of 1,500–2,500 $m^3$/ha.

High yields in the alfalfa-cotton rotation were achieved in the six-field rotation at Ali-Myrza farm, with cotton and alfalfa yields 20–30% higher and profits 35% higher than in the nine-field alfalfa-cotton rotation at Didar farm. Profits from cotton with alfalfa were 1316.2 euro/ha in the first year and 576 euro/ha in the second year, while profits from alfalfa were 461.8 euro/ha in the first year and 967.4 euro/ha in the second year. The results of the study of irrigation array in Kyzylkum confirm the feasibility of replacing the currently used nine-field crop rotation, which occupies 80% of the irrigated area, with a six-field alfalfa-cotton rotation.

According to the results of the conducted pilot studies in peasant farms on Kyzylkum irrigation array six-field cotton-alfalfalfa crop rotation is recommended, which allows to increase the profitability of cotton production by - 36% alfalfa by – 42%, cotton-alfalfa crop rotation by – 34%, productivity of water consumption by 5–6%.

Peasant farms cultivating cotton in nine-field rotations with alfalfa are recommended to switch to six-field cotton-alfalfa rotations with cotton – 50% and alfalfa – 50%, which will increase profit and profitability by 34–36%, respectively, compared to nine-field rotations, where alfalfa occupies – 37% of the cultivated area and cotton – 63%.

The results of this research will be useful for peasant farms engaged in cotton growing, specialists of water management industry and workers of hydromeliorative direction, as well as bachelors, masters and doctoral students studying in the fields of training "Water management," "Land melioration, reclamation and protection," "Water resources and water use" and "Agronomy."

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

AR: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. KZ: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. BN: Conceptualization, Data curation, Formal analysis, Writing – original draft. MM: Data curation, Investigation, Methodology, Writing – original draft. KY: Data curation, Formal analysis, Methodology, Writing – original draft. MB: Data curation, Formal analysis, Methodology, Writing – original draft. MN: Data curation, Formal analysis, Methodology, Writing – original draft. ZK: Data curation, Formal analysis, Methodology, Writing – original draft. YI: Data curation, Formal analysis, Methodology, Project administration, Resources, Writing – original draft. SA: Data curation, Formal analysis, Methodology, Writing – original draft. AU: Data curation, Formal analysis, Methodology, Writing – original draft. LD: Funding acquisition, Project administration, Resources, Writing – review & editing.

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## Conflict of interest

BN is employed by Kazakh Scientific Research Institute of Water Economy LLP.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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