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Evaluating the Long-Term Effects of Recycled Wastewater Irrigation on Soil Health, Crop Yield, and Ecological Sustainability in Arid Regions

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ABSTRACT

Water scarcity poses a significant global challenge, particularly acute in arid and semi-arid regions with limited freshwater resources and high agricultural water demands. This study investigated the impacts of recycled wastewater irrigation using hybrid poplar trees as a model crop in the Kyzylorda region, characterized by extreme climatic conditions and water scarcity. A randomized complete block design (RCBD) was employed to ensure robust comparisons between two irrigation treatments: the control using water from the Syrdarya River, and the experimental treatment involving biologically treated wastewater from the Kyzylorda Wastewater Treatment Plant. Chemical analysis revealed that the soil irrigated with wastewater exhibited higher pH levels (7.5 ± 0.3) compared to the control (7.0 ± 0.2), indicating increased alkalinity. Electrical conductivity, a measure of soil salinity, was significantly elevated in wastewater-irrigated soil (2.3 ± 0.2 dS/m) relative to the control (1.2 ± 0.1 dS/m), reflecting higher salinity levels. Moreover, organic matter content was substantially greater in wastewater-irrigated soil (3.5 ± 0.4%) compared to the control (2.1 ± 0.3%), suggesting enhanced organic enrichment. Nutrient levels, such as nitrogen (45 ± 5 mg/kg), phosphorus (30 ± 4 mg/kg), and potassium (189 ± 16 mg/kg) were markedly higher in the wastewater-irrigated soil compared to the control (27 ± 3 mg/kg, 15 ± 2 mg/kg, and 121 ± 10 mg/kg, respectively), highlighting the nutrient-rich nature of recycled wastewater. Seasonal dynamics in flora and fauna were also assessed. From January to March, both control and wastewater-irrigated plots exhibited a decline in species richness, reflective of winter dormancy. In January, for instance, control plots averaged 23 ± 4 species per square meter, whereas wastewater-irrigated plots had 18 ± 3 species per square meter. Fauna abundance followed a similar pattern, with both groups showing gradual increases from January to March, peaking in summer. The control plots consistently maintained higher fauna abundance levels compared to the wastewater-irrigated plots throughout the study period. Overall, this study provides insights into the complex interactions between recycled wastewater irrigation and soil health, crop performance, and ecological dynamics in arid environments.

Keywords: poplar, water scarcity, agricultural sustainability, flora and fauna, irrigation water quality.

INTRODUCTION

Water scarcity is a critical global challenge, particularly pronounced in arid and semi-arid regions where the access to freshwater resources is limited and demands for agricultural water use are high. In response to this pressing issue, the utilization of recycled wastewater for irrigation has emerged as a promising strategy to conserve freshwater resources, while potentially enhancing soil fertility [1]. This practice involves treating wastewater to remove contaminants and pathogens, making it suitable for agricultural use. However, the adoption of recycled wastewater irrigation raises concerns about its long-term effects on soil health, crop productivity, and ecological balance, necessitating comprehensive evaluation [2].

Arid and semi-arid regions cover significant portions of the Earth's surface, encompassing the regions where water availability is chronically low and precipitation is sporadic [3]. These regions are particularly vulnerable to water scarcity due to natural climatic conditions that limit freshwater replenishment and high rates of evaporation [4]. With global climate change exacerbating water stress in many areas, the demand for water for agriculture, industry, and domestic use continues to strain already limited water resources. This situation underscores the urgency of exploring sustainable water management practices that can alleviate the pressure on freshwater sources while supporting agricultural production [5].

As previously highlighted, recycled wastewater irrigation involves treating wastewater from urban, industrial, or agricultural sources to remove contaminants and pathogens, rendering it suitable for irrigation purposes. This approach not only reduces the demand for freshwater but also addresses the challenge of wastewater disposal, thereby contributing to environmental sustainability. The nutrient-rich nature of recycled wastewater can potentially enhance soil fertility and improve crop yields, offering a dual benefit for agricultural productivity in water-scarce regions [6]. However, the adoption of this practice necessitates careful consideration of its potential impacts on soil health, ecosystem dynamics, and human health. While recycled wastewater can enrich soil with essential nutrients, such as nitrogen, phosphorus, and potassium, continuous application may lead to soil salinity and accumulation of heavy metals or persistent organic pollutants [7]. These factors can alter soil structure, nutrient availability, and microbial communities, potentially affecting long-term soil fertility and productivity. Understanding these dynamics is essential for sustainable soil management and ensuring that agricultural practices do not compromise soil health over time. The ecological implications of recycled wastewater irrigation extend beyond soil and crop health to encompass broader ecosystem dynamics. Changes in soil nutrient levels and microbial communities can influence plant diversity as well as habitat suitability for native flora and fauna [8]. Moreover, the potential for contaminants from recycled wastewater to leach into groundwater or surface water systems raises concerns about water quality and ecosystem integrity. Evaluating these ecological impacts is essential for developing the strategies that minimize environmental risks and promote sustainable agricultural practices.

Studies have shown mixed results, with some indicating improved crop yields due to enhanced nutrient availability, while others report potential risks such as increased heavy metal uptake in crops. The choice of crop species and their tolerance to specific contaminants in recycled wastewater are critical factors influencing crop performance. Investigating these aspects helps in identifying suitable crops for wastewater irrigation and optimizing agricultural practices to maximize productivity without compromising food safety and quality. Mishra et al. [9], suggest that a critical determinant of water suitability for irrigation is salinization, where soil accumulates water-soluble salts, primarily anions (chloride) and cations (calcium, magnesium, iron, and sodium). According to Trotta et al. [10], polluted wastewater can adversely influence insect pest population dynamics within agroecosystems by impacting plant growth and physiology. This occurs through bottom-up effects involving the uptake and translocation of contaminants or increased stress from salinity. According to Wang et al. [11], who studied the impact of treated wastewater irrigation on soil, crops, and the environment in the loess area of China, the researchers found that in most instances, the quality of crops irrigated with treated sewage was not significantly different from those irrigated with conventional water sources. However, the yields of crops irrigated with treated sewage were consistently higher compared to those irrigated with conventional water sources. Despite the efforts in the field, comprehensive understanding of the potential effects of recycled wastewater irrigation on soil microbial communities and their ecological roles in arid environments remains significantly limited. This gap in knowledge hinders the ability to predict and manage the long-term impacts of using recycled wastewater for irrigation, particularly in the regions already vulnerable to water scarcity and environmental stressors. Achieving a deeper understanding of these dynamics is crucial for developing sustainable agricultural practices that balance water conservation with soil health and ecosystem integrity in arid environments.

This study aimed to comprehensively evaluate the effects of recycled wastewater irrigation using hybrid poplar trees as a model crop in the Kyzylorda region. Situated in Central Asia, the Kyzylorda region experiences extreme climatic conditions characterized by high temperatures, low precipitation, and limited freshwater resources. By focusing on hybrid poplars, known for their fast growth and ability to thrive in marginal soils, the study sought to assess how recycled wastewater irrigation influences soil properties, crop growth, and ecological sustainability indicators, such as groundwater quality and biodiversity.

MATERIALS AND METHODS

Study location

The study was conducted in the Kyzylorda region, Kazakhstan (44.8488° N, 65.4823° E), an area characterized by an arid climate with minimal annual precipitation of approximately 130 mm and extreme temperatures ranging from -15 °C in winter to 35 °C in summer. This region, with its challenging climatic conditions and sparse vegetation, provides an ideal setting for testing the viability and effects of using recycled wastewater for irrigation. The soil in this area is predominantly sandy-loam, with low organic matter content, posing additional challenges for agricultural productivity. The experimental site was a 1-hectare plot previously used for agricultural purposes, located 10 km north of the city of Kyzylorda. This location was selected due to its representative arid environment and the accessibility it offered for regular monitoring and maintenance activities. The proximity to the Syrdarya River allowed for easy access to the control water source, while the nearby Kyzylorda Wastewater Treatment Plant facilitated the provision of treated wastewater for the experimental plots. The selection of this site also considered the local agricultural practices and the potential for scalability of successful irrigation strategies to other similar regions.

Experimental design

The experimental design employed in this study was a randomized complete block design (RCBD) to ensure reliable comparisons between two irrigation treatments and minimize variability. The control treatment used the water sourced from the Syrdarya River, which is the standard irrigation source in the region. The experimental treatment involved irrigation with biologically treated wastewater from the Kyzylorda Wastewater Treatment Plant. This setup allowed for a direct comparison between traditional and alternative irrigation methods under identical environmental conditions.

To ensure robustness and replicability, each treatment was replicated three times within the study area. The entire 1-hectare experimental site was divided into six plots, each measuring 20m x 20m. The plots were systematically arranged in a grid pattern and separated by 5m buffer zones to prevent cross-contamination between the control and experimental treatments. This separation was essential to maintain the integrity of the study and ensure that any differences observed in soil health, crop growth, or ecological impact could be accurately attributed to the specific irrigation treatment used. Within each block, the layout of the plots was randomized to mitigate the effects of potential environmental gradients or other confounding factors that could influence the results.

Hybrid poplar cuttings, specifically the “Kazakhstanskiy” and “Kairat” varieties, were planted in each plot at a uniform density of 1m x 1m, resulting in 400 trees per plot. This consistent planting density ensured uniform growth conditions across all plots, facilitating accurate measurement of growth parameters such as tree height, trunk diameter, leaf area, and biomass yield. Soil health assessments were conducted by collecting samples from each plot at depths of 0–20 cm and 20–40 cm, both at the start of the study and after each growing season. These samples were analyzed for chemical properties (pH, EC, organic matter, nitrogen, phosphorus, potassium), physical (bulk density, soil texture), and biological properties (microbial activity).

This systematic and detailed experimental design provided a robust framework for evaluating the long-term impacts of using recycled wastewater for irrigation on soil health, crop productivity, and ecological sustainability in the arid Kyzylorda region.

Crop selection and planting

Hybrid poplars (Populus spp.), specifically the "Kazakhstanskiy" and "Kairat" varieties, were chosen for this study due to their adaptability to the arid climate of the Kyzylorda region and their fast growth rate. These varieties are well-suited to the local environmental conditions, including the extreme temperatures and limited precipitation, making them ideal candidates for assessing the viability of using recycled wastewater for irrigation.

Poplar cuttings, each 25 cm in length, were planted in the designated experimental plots. The planting was done at a uniform spacing of 1 m x 1 m to ensure optimal growth conditions and facilitate accurate measurements of growth parameters. This spacing resulted in each 20 × 20 m plot containing 400 trees. The consistent planting density across all plots allowed for a controlled comparison between the trees irrigated with water from the Syrdarya River (control) and those irrigated with biologically treated wastewater (experimental).

Prior to planting, the soil in each plot was prepared by removing any residual vegetation and debris, followed by tilling to a depth of 30 cm to improve soil aeration and root penetration. The cuttings were planted vertically, with approximately half of their length buried in the soil to ensure stability and promote root development. Each cutting was carefully positioned to ensure it was upright and evenly spaced from its neighbors. After planting, the plots were irrigated to field capacity to help establish the cuttings and initiate root growth. Regular monitoring and maintenance, including weeding and pest control, were carried out throughout the growing season to ensure the health and vigor of the hybrid poplars.

Irrigation treatments

Control treatment

The control treatment in this study utilized the irrigation water sourced from the Syrdarya River, applied specifically to hybrid poplar plots via a drip irrigation system. This system was chosen for its efficiency in water use and its precise delivery of water directly to the root zone, minimizing the losses due to evaporation. The drip irrigation setup consisted of a network of polyethylene tubing with emitters spaced at 1-meter intervals. This spacing ensured that each individual tree received a sufficient and uniform supply of water. The irrigation schedule was developed based on local agronomic recommendations, which were adjusted to accommodate the specific water requirements of hybrid poplars and the arid climate conditions prevalent in the Kyzylorda region. To maintain optimal irrigation practices, regular monitoring of soil moisture levels was implemented. This monitoring strategy was crucial in ensuring that irrigation remained consistent and appropriate, thereby avoiding both over-watering and under-watering.

Experimental treatment

The experimental treatment specifically involved the application of biologically treated wastewater, obtained from the Kyzylorda Wastewater Treatment Plant, to irrigate hybrid poplar trees. The wastewater underwent rigorous treatment processes to meet the national irrigation standards, ensuring it was safe for use in agricultural settings. The treated wastewater was then utilized in the experimental plots, delivered through a drip irrigation system designed to precisely target the root zones of the trees. This experimental setup was meticulously planned to evaluate the feasibility of using treated wastewater as an alternative irrigation source. The study aimed to compare its impacts on tree growth, soil quality, and other ecological parameters against those observed with conventional freshwater irrigation sourced from the Syrdarya River. To maintain consistency and accuracy in the experiment, irrigation scheduling was carefully managed based on real-time soil moisture measurements. Sensors installed at a depth of 20 cm in each plot monitored moisture levels continuously. Irrigation was triggered only when the soil moisture content dropped below 50% of the field capacity, ensuring that the trees received adequate but not excessive water. Monitoring protocols were in place to systematically assess the effects of this treatment on both the trees and the surrounding environment (Figure 1).

Soil health assessment

Soil samples were collected at depths of 0–20 cm and 20–40 cm at the start of the study

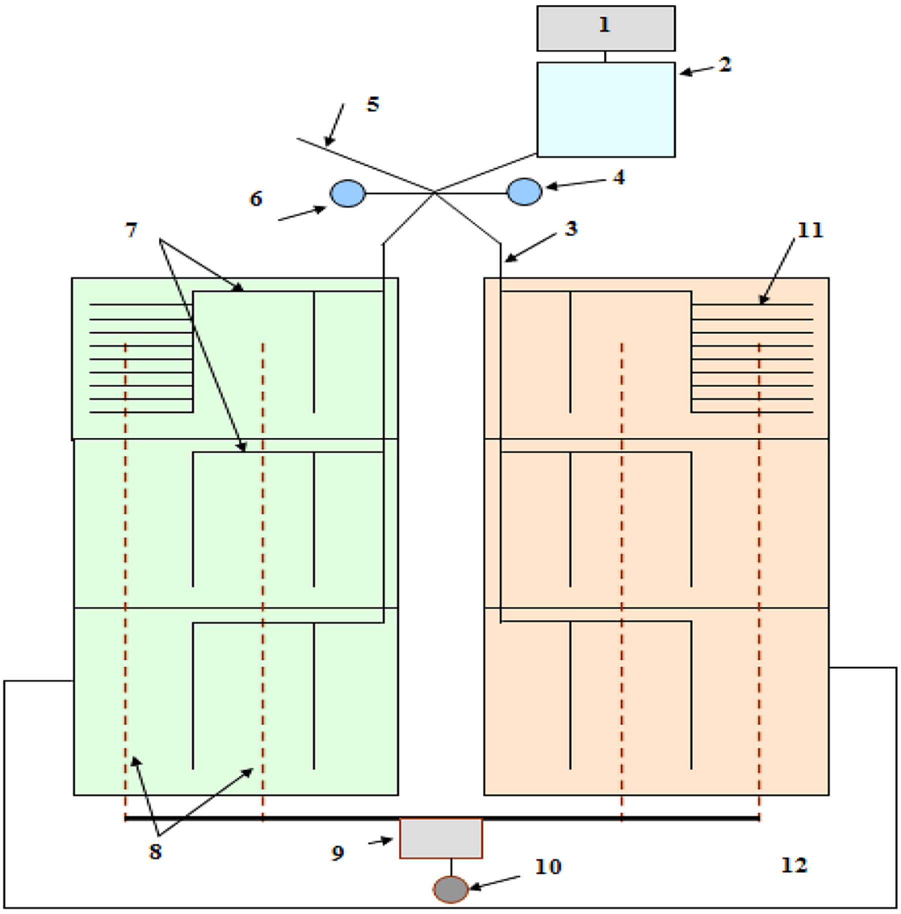

Figure 1. Schematic diagram of the irrigation system: 1 – wastewater treatment plants, 2 – storage pond, 3 – pumping station, 4 – distribution network for wastewater supply, 5 – distribution network for clean water supply, 6 – distribution hydraulic structure, 7 – precinct distribution channels, 8 – drainage network, 9 – the collector well, 10 – collector, 11 – temporary sprinklers, 12 – irrigation furrows

(baseline) and after each growing season (October) for three years. Analyses included:

Chemical properties

Soil properties were meticulously assessed using the following methods: pH was measured with a digital pH meter in a 1:2.5 soil-water suspension, providing precise acidity or alkalinity levels. Electrical Conductivity (EC) was determined using an EC meter in a 1:2.5 soil-water extract, reflecting the salinity of soil. Organic Matter content was quantified through the Walkley-Black method, involving oxidation with potassium dichromate and sulfuric acid. Nitrogen (N) levels were measured using the Kjeldahl method, which includes digestion with sulfuric acid, distillation, and titration. Phosphorus (P) was extracted using the Bray I method, which employs ammonium fluoride as well as hydrochloric acid, and then measured spectrophotometrically. Potassium (K) was extracted with ammonium acetate and quantified using flame photometry, ensuring accurate assessment of essential soil nutrients.

Physical properties

Bulk density was determined using the core method, involving the collection of undisturbed soil cores which were then oven-dried at 105 °C for 24 hours. The dry soil mass was measured and divided by the volume of the core to obtain the bulk density, expressed in grams per cubic centimeter (g/cm^3). Soil texture was analyzed using the hydrometer method, which involves dispersing soil particles in a solution and allowing them to settle over time. The hydrometer measures the density of the suspension at specific time intervals, providing data on the relative proportions of sand, silt, and clay particles in the soil. This method provides a detailed characterization of soil texture, essential for understanding soil behavior and its suitability for various applications.

Biological properties

Microbial activity in soil is gauged through soil respiration rates, utilizing the CO_2 evolution method via alkaline absorption. This process involves capturing the carbon dioxide released by soil microorganisms during organic matter decomposition. By measuring the amount of CO_2 absorbed by an alkaline solution over a specified period, the microbial activity level can be quantified, providing insights into soil health, microbial biomass, and overall ecosystem functionality. This method is widely used in soil science due to its accuracy and ability to reflect microbial metabolic processes.

Crop growth and yield measurements

Crop growth and yield measurements encompass a range of parameters essential for evaluating plant development and productivity. Growth parameters include tree height, measured from the base to the top using a measuring pole, and trunk diameter, assessed at 1 meter height using a digital caliper to ensure precision. Yield parameters are critical for understanding the output of the crop. Leaf area was determined with a leaf area meter (LI-3000C, LI-COR Inc.), providing accurate measurements of leaf surface area, which is crucial for photosynthetic analysis. Chlorophyll content, indicative of plant health and photosynthetic capacity, was measured with a SPAD chlorophyll meter (SPAD-502, Konica Minolta), offering a quick and non-destructive method to gauge chlorophyll levels. Biomass yield is determined by harvesting the above-ground biomass at the end of the growing season, followed by air-drying and weighing to assess the total biomass produced. Measurements were taken bi-monthly during the growing season (May-September), allowing for a detailed and dynamic understanding of crop growth as well as yield fluctuations throughout this critical period.

Ecological impact monitoring

Ecological impact monitoring includes assessments of groundwater quality and biodiversity. For groundwater quality, monitoring wells were installed at distances of 10 meters and 30 meters from the edge of each plot, with samples collected monthly. Key parameters measured included pH, electrical conductivity (EC), nitrate (NO_3^-), and phosphate (PO_4^{3-}), utilizing standard APHA methods to ensure consistency and reliability. Biodiversity assessment was conducted through flora and fauna monitoring. For flora, quadrat sampling in 1 m² plots was performed quarterly to document species presence and abundance, providing a snapshot of plant diversity and changes over time. Fauna monitoring involved transect surveys and the use of camera traps to observe wildlife presence and activity within as well as around the plots, offering insights into animal diversity and ecosystem health. These comprehensive ecological monitoring activities help to evaluate the environmental impacts of agricultural practices and develop informed strategies for sustainable land management.

RESULTS

Soil health assessment

The results of the study reveal significant differences between the soils irrigated with recycled wastewater and those irrigated with water from the Syrdarya River in terms of chemical, physical, and biological properties. Chemically, the soil irrigated with wastewater has a higher pH (7.5 ± 0.3) compared to the control (7.0 ± 0.2), indicating increased alkalinity. Electrical conductivity, a measure of soil salinity, is significantly elevated in the wastewater-irrigated soil (2.3 ± 0.2 dS/m) compared to the control (1.2 ± 0.1 dS/m), reflecting higher salinity levels. Organic matter content is substantially greater in the wastewater-irrigated soil (3.5 ± 0.4%) than in the control (2.1 ± 0.3%), suggesting enhanced organic enrichment. Additionally, nutrient levels, such as nitrogen (45 ± 5 mg/kg), phosphorus (30 ± 4 mg/kg), and potassium (189 ± 16 mg/kg) are considerably higher in the wastewater-irrigated soil compared to the control (27 ± 3 mg/kg, 15 ± 2 mg/kg, and 121 ± 10 mg/kg, respectively), highlighting the nutrient-rich nature of recycled wastewater.

Physically, the bulk density of the soil irrigated with wastewater is slightly lower (1.3 ± 0.1 g/cm³) than that of the control soil (1.4 ± 0.1 g/cm³), indicating a potentially more porous and less compact soil structure, which can be beneficial for root growth and water infiltration. Biologically, microbial activity is significantly higher in the wastewater-irrigated soil, with a rate of 252 ± 31 mg CO_2/kg soil/day compared to 153 ± 24 mg CO_2/kg soil/day in the control soil. This increased microbial activity suggests a more active soil microbial community, likely driven by the higher organic matter and nutrient availability in the wastewater-irrigated soil. These findings demonstrate that while recycled wastewater can enhance soil fertility and biological activity, careful management is necessary to address potential challenges, such as increased salinity and ensure sustainable agricultural practices (Table 1). The results from three years of wastewater irrigation reveal a gradual increase in soil electrical conductivity (EC), indicating rising salinity levels over time (Figure 2). In Year 1,

Table 1. Soil health assessment

Parameter	Control (Syrdarya River)	Wastewater	International standards
Chemical properties			
pH	7.0 ± 0.2	7.5 ± 0.3	6.5–8.5 (FAO)*
Electrical conductivity (dS/m)	1.2 ± 0.1	2.3 ± 0.2	< 3 dS/m (FAO)**
Organic Matter (%)	2.1 ± 0.3	3.5 ± 0.4	> 2% (FAO)***
Nitrogen (mg/kg)	27 ± 3	45 ± 5	-
Phosphorus (mg/kg)	15 ± 2	30 ± 4	-
Potassium (mg/kg)	121 ± 10	189 ± 16	-
Physical properties			
Bulk density (g/cm³)	1.4 ± 0.1	1.3 ± 0.1	< 1.6 g/cm³ (FAO)****
Biological properties			
Microbial activity (mg CO_2/kg soil/day)	153 ± 24	252 ± 31	-

Note: * FAO = Food and Agriculture Organization of the United Nations; * pH (FAO) – acceptable range for irrigation water in most agricultural systems, **electrical conductivity (FAO) – values below 3 dS/m are generally safe for most crops, *** organic matter (FAO) – a higher percentage of organic matter is beneficial for soil health, **** bulk density (FAO) – ideal for well-structured soils.

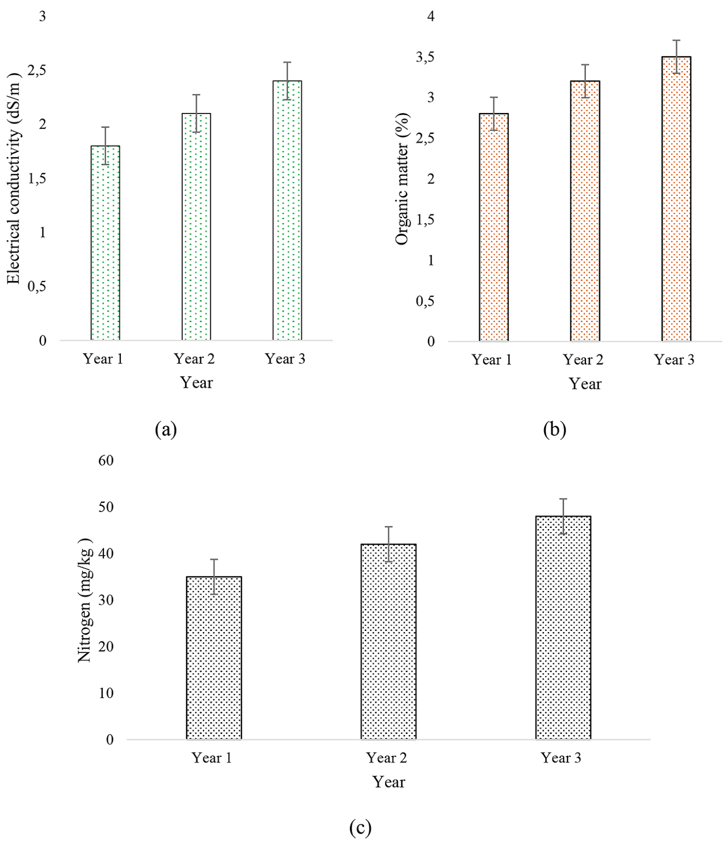

Figure 2. Yearly soil health assessment (a) electrical conductivity (b) organic matter (c) nitrogen

EC was measured at 1.8 ± 0.3 dS/m, increasing to 2.1 ± 0.4 in Year 2 and reaching 2.4 ± 0.5 dS/m by Year 3. This trend suggests that wastewater irrigation contributes to salinity buildup in the soil, which could pose long-term risks to plant health and soil structure if not managed carefully. Elevated salinity can affect plant water uptake and hinder crop productivity, making it crucial to monitor EC levels continuously and potentially implement the measures to mitigate salinity accumulation. The organic matter content in the soil has shown a positive trend, with percentages rising from 2.8 ± 0.5% in Year 1 to 3.5 ± 0.7% in Year 3. This increase indicates that wastewater irrigation is enhancing the organic content of the soil over time, which is beneficial for soil fertility and overall health. Higher organic matter improves soil structure, water retention, and nutrient availability, contributing to the sustainability of agricultural systems. This trend suggests that wastewater irrigation can improve soil quality by increasing organic matter levels, which may have long-term benefits for crop production and soil resilience. Nitrogen levels in the soil have also steadily increased with wastewater irrigation, from 35 ± 4 mg/kg in Year 1 to 48 ± 6 mg/kg in Year 3. Nitrogen is an essential nutrient for plant growth, and higher levels generally support better crop yields. However, the data shows that the rate of nitrogen accumulation is beginning to stabilize, which may indicate that the soil is nearing its nitrogen saturation point. While increased nitrogen is beneficial, excessive levels could lead to nutrient imbalances or environmental risks, such as nitrate leaching into groundwater. Ongoing monitoring will be needed to ensure that nitrogen levels remain optimal without exceeding safe thresholds for soil and environmental health.

Crop yield and growth

The results of the study indicate significant improvements in growth and yield parameters for the trees irrigated with recycled wastewater compared to those irrigated with the water from the Syrdarya River. In terms of growth parameters, the average tree height in the wastewater-irrigated plots is notably higher at 3.2 ± 0.3 meters, compared to 2.5 ± 0.2 meters in the control plots. Additionally, the trunk diameter of the trees irrigated with wastewater is larger, measuring 10 ± 0.6 cm compared to 8 ± 0.5 cm in the control. Leaf area is also significantly greater in the wastewater-irrigated trees, with an average of 182 ± 23 cm² versus 159 ± 14 cm² in the control group. These enhancements in growth metrics suggest that recycled wastewater provides better support for tree development, likely due to its higher nutrient content.

Regarding yield parameters, trees irrigated with wastewater produce a higher biomass yield, averaging 7 ± 0.7 kg per tree, compared to 5 ± 0.5 kg per tree in the control group. This increase in biomass yield indicates improved overall productivity and health of the trees. Furthermore, chlorophyll content, as measured by SPAD units, is higher in the wastewater-irrigated trees (51 ± 4) compared to the control trees (45 ± 3), suggesting enhanced photosynthetic activity and potentially better overall plant health (Table 2).

Ecological impacts analysis

The study investigated the ecological impacts of recycled wastewater irrigation on critical indicators in the Kyzylorda region, characterized by arid conditions and limited water resources. Comparing conditions using the water from the Syrdarya River as a control to those utilizing recycled wastewater revealed notable shifts in groundwater quality and biodiversity. Groundwater nitrate levels significantly increased under wastewater irrigation (4.5 ± 0.6 mg/L) compared to the control (1.2 ± 0.3 mg/L), indicating substantial nitrogen enrichment likely derived from the applied wastewater.

Table 2. Crop yield and growth

Parameter	Control (Syrdarya River)	Wastewater
Growth parameters		
Tree height (m)	2.5 ± 0.2	3.2 ± 0.3
Trunk diameter (cm)	8 ± 0.5	10 ± 0.6
Leaf area (cm²)	159 ± 14	182 ± 23
Yield parameters		
Biomass yield (kg/tree)	5 ± 0.5	7 ± 0.7
Chlorophyll content (SPAD units)	45 ± 3	51 ± 4

Similarly, groundwater phosphate concentrations were elevated under wastewater irrigation (0.8 ± 0.1 mg/L) relative to the control (0.1 ± 0.02 mg/L), pointing to increased phosphorus loading into groundwater, potentially affecting aquatic ecosystems and water quality.

The impacts on flora were evident in both species richness and biomass. Flora species richness declined from 28 ± 4 species per square meter in the control to 18 ± 3 species per square meter under wastewater irrigation, suggesting a shift in plant community composition and potential implications for ecosystem stability and resilience. Flora biomass also decreased from 255 ± 34 g/m² in the control to 182 ± 25 g/m² under wastewater irrigation, reflecting changes in nutrient availability or soil health influenced by wastewater contaminants. These reductions in flora diversity and biomass highlight the potential ecological consequences, such as altered nutrient cycling and habitat suitability for plant species.

Furthermore, fauna responded to these changes with decreased species diversity and abundance under wastewater irrigation. Fauna species diversity, assessed using the Shannon Index, decreased from 3.5 ± 0.4 in the control to 2.8 ± 0.3 under wastewater irrigation, indicating potential disruptions in ecological interactions and community dynamics. Fauna abundance also declined from 17 ± 2 individuals per transect in the control to 12 ± 1 individuals per transect under wastewater irrigation, suggesting habitat alterations or resource limitations that could impact the predator-prey relationships and overall ecosystem health. These findings underscore the multifaceted impacts of recycled wastewater irrigation on groundwater quality and biodiversity, emphasizing the need for sustainable management practices to balance agricultural demands with environmental conservation in arid regions (Table 3).

Flora species richness

The study in the Kyzylorda region reveals nuanced seasonal dynamics in flora species richness under varying irrigation conditions. From January through March, both control (Syrdarya River) and wastewater-irrigated plots exhibit a decline in species richness, reflecting the region's winter dormancy when fewer plant species actively grow. For instance, in January, the control plots show an average species richness of 23 ± 4 species per square meter, while the wastewater-irrigated plots have 18 ± 3 species per square meter. This reduction continues into February and March, where the control plots maintain an average richness of 22 ± 5 and 21 ± 6 species per square meter, respectively, compared to 17 ± 4 and 16 ± 5 species per square meter in the wastewater-irrigated plots.

As temperatures warm and daylight increases from April to June, both groups experience a gradual increase in species richness. By April, the control plots rebound with an average richness of 25 ± 3 species per square meter, contrasting with 19 ± 2 species per square meter in the wastewater-irrigated plots. This trend continues into May and June, where the control plots reach 27 ± 4 and 29 ± 3 species per square meter, respectively, while the wastewater-irrigated plots lag behind at 21 ± 3 and 23 ± 2 species per square meter. The peak in species richness occurs during the summer months of July and August, with control plots consistently showing higher richness levels, such as 31 ± 2 species per square meter in July and 29 ± 3 species per square meter in August, compared to 22 ± 3 and 21 ± 2 species per square meter in wastewater-irrigated plots.

Throughout the autumn months from September to December, as temperatures cool and daylight hours decrease, both groups experience a decline in species richness as plants enter dormancy. Control plots maintain higher richness

Table 3. Analysis of ecological impacts

Ecological indicator	Control (Syrdarya River)	Wastewater irrigation	International standards
Groundwater nitrate (mg/L)	1.2 ± 0.3	4.5 ± 0.6	< 10 mg/L (WHO)*
Groundwater phosphate (mg/L)	0.1 ± 0.02	0.8 ± 0.1	< 0.1 mg/L (EU Drinking water directive)**
Flora species richness (per m²)	28 ± 4	18 ± 3	-
Flora biomass (g/m²)	255 ± 34	182 ± 25	-
Fauna species diversity (Shannon index)	3.5 ± 0.4	2.8 ± 0.3	-
Fauna abundance (individuals/transect)	17 ± 2	12 ± 1	-

Note: * WHO = World Health Organization, ** EU drinking water directive – maximum concentration for phosphates in drinking water.

levels, ranging from 27 ± 4 to 23 ± 6 species per square meter, whereas the wastewater-irrigated plots show consistently lower richness, varying from 19 ± 3 to 16 ± 6 species per square meter. This seasonal variation underscores the persistent impact of recycled wastewater irrigation on reducing flora diversity compared to natural river water sources, potentially due to altered nutrient availability or residual contaminants affecting plant community dynamics (Figure 3).

Flora biomass

The study highlights seasonal fluctuations in flora biomass under different irrigation conditions in the Kyzylorda region. From January through March, both the control (Syrdarya River) and wastewater-irrigated plots show a gradual decline in biomass, reflecting the winter dormancy period with reduced plant growth. In January, for example, the control plots exhibit an average biomass of 230 ± 35 g/m², whereas the wastewater-irrigated plots show 175 ± 22 g/m². This trend continues into February and March, with biomass values decreasing slightly each month for both groups. The control plots maintain higher biomass levels, such as 225 ± 32 g/m² in February and 220 ± 29 g/m² in March, compared to 170 ± 20 g/m² and 165 ± 18 g/m² in the wastewater-irrigated plots during the same months.

As temperatures rise and daylight increases from April to June, both groups experience a gradual increase in biomass. By April, the control plots show a rebound in biomass with 240 ± 38 g/m², while the wastewater-irrigated plots reach 180 ± 25 g/m². This upward trend continues through May and June, where the control plots peak at 250 ± 42 g/m² and 255 ± 45 g/m², respectively, compared to 190 ± 28 g/m² and 195 ± 32 g/m² in the wastewater-irrigated plots. The peak biomass occurs during the summer months of July and August, with the control plots consistently showing higher values, such as 260 ± 48 g/m² in July and 255 ± 45 g/m² in August, compared to 190 ± 28 g/m² and 185 ± 25 g/m² in the wastewater-irrigated plots.

Throughout the autumn months from September to December, as temperatures cool and daylight hours decrease, both groups experience a decline in biomass as plants prepare for winter dormancy. The control plots maintain higher biomass levels, ranging from 245 ± 42 g/m² to 225 ± 32 g/m², whereas the wastewater-irrigated plots consistently show lower biomass, varying from 180 ± 22 g/m² to 165 ± 16 g/m². This seasonal pattern underscores the persistent impact of recycled wastewater irrigation on reducing flora biomass compared to natural river water sources, possibly due to differences in nutrient availability or contaminants affecting the plant growth dynamics (Figure 4).

Fauna species diversity

From January to March, both the control and wastewater-irrigated plots show a gradual increase in species diversity as temperatures gradually rise

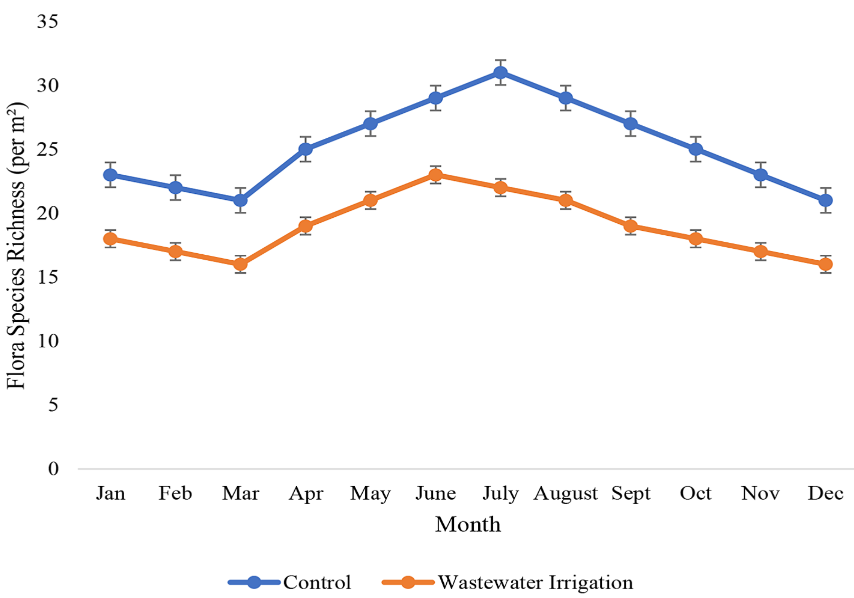

Figure 3. Flora species richness

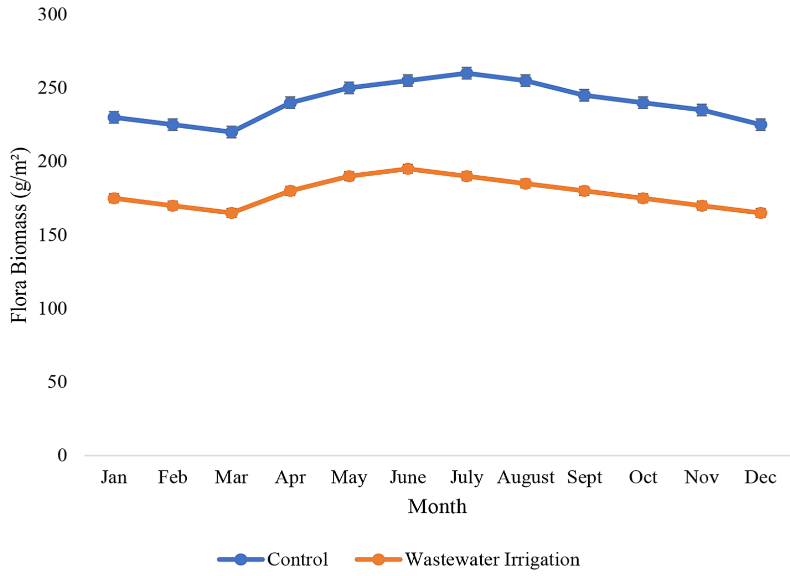

Figure 4. Flora biomass

and environmental conditions become more favorable for fauna activity. In January, for instance, the control plots exhibit an average Shannon Index of 3.48 ± 0.23, whereas the wastewater-irrigated plots have 2.76 ± 0.31. This trend continues into February and March, with diversity values slightly increasing each month for both groups. The control plots maintain higher diversity levels, such as 3.57 ± 0.22 in February and 3.66 ± 0.19 in March, compared to 2.86 ± 0.27 and 2.97 ± 0.34 in the wastewater-irrigated plots during the same periods.

As temperatures continue to warm from April to June, both groups experience a steady rise in species diversity. By April, the control plots demonstrate a Shannon Index of 3.75 ± 0.25, while the wastewater-irrigated plots reach 3.07 ± 0.29. This upward trend continues through May and June, with the control plots peaking at 3.84 ± 0.20 and 3.95 ± 0.23, respectively, compared to 3.17 ± 0.33 and 3.27 ± 0.30 in the wastewater-irrigated plots. The peak diversity occurs during the summer months of July and August, with the control plots consistently showing higher values, such as 3.9 ± 0.23 in July and 3.84 ± 0.20 in August, compared to 3.22 ± 0.30 and 3.17 ± 0.33 in the wastewater-irrigated plots. Throughout the autumn months from September to December, as temperatures cool and daylight hours decrease, both groups experience a decline in species diversity as fauna prepare for winter conditions. The control plots maintain higher diversity levels, ranging from 3.75 ± 0.25 to 3.48 ± 0.15, whereas the wastewater-irrigated plots consistently show lower diversity, varying from 3.07 ± 0.29 to 2.76 ± 0.31. This seasonal pattern underscores the persistent impact of recycled wastewater irrigation on reducing fauna species diversity compared to natural river water sources, potentially influenced by altered habitat conditions or ecological stressors affecting wildlife populations in the region (Figure 5).

Fauna abundance

The study highlights seasonal variations in fauna abundance (individuals/transect) under control (Syrdarya River) and wastewater irrigation conditions in the Kyzylorda region. From January to March, both the control and wastewater-irrigated plots show a gradual increase in fauna abundance as environmental conditions become more conducive to wildlife activity. In January, for example, the control plots exhibit an average abundance of 16.8 ± 1.5 individuals per transect, whereas the wastewater-irrigated plots have 11.9 ± 1.8 individuals per transect. This trend continues into February and March, with abundance values slightly increasing each month for both groups. The control plots maintain higher abundance levels, such as 17.6 ± 1.9 in February and 18.5 ± 2.1 in March, compared to 12.8 ± 1.4 and 13.8 ± 1.7 in the wastewater-irrigated plots during the same periods.

As temperatures warm from April to June, both groups experience a steady rise in fauna abundance. By April, the control plots demonstrate an abundance of 19.4 ± 1.8 individuals

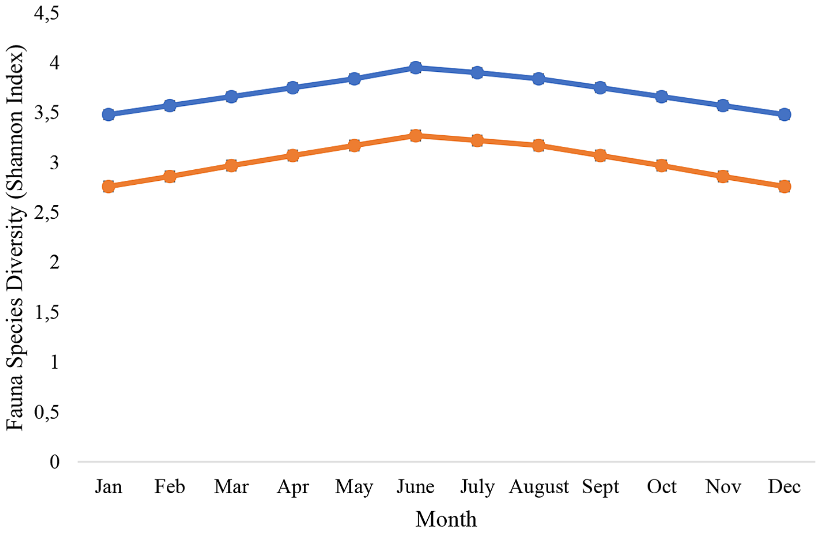

Figure 5. Fauna species diversity

per transect, while the wastewater-irrigated plots reach 14.7 ± 1.9 individuals per transect. This upward trend continues through May and June, with the control plots peaking at 20.3 ± 2.0 and 21.2 ± 2.2, respectively, compared to 15.7 ± 1.6 and 18.7 ± 1.8 in the wastewater-irrigated plots. The peak abundance occurs during the summer months of July and August, with control plots consistently showing higher values, such as 22.2 ± 2.2 in July and 20.3 ± 2.0 in August, compared to 16.7 ± 1.8 and 15.7 ± 1.6 in wastewater-irrigated plots.

Throughout the autumn months from September to December, as temperatures cool and daylight hours decrease, both groups experience a decline in fauna abundance as wildlife adjusts to seasonal changes. The control plots maintain higher abundance levels, ranging from 19.4 ± 1.8 to 16.8 ± 1.5, whereas the wastewater-irrigated plots consistently show lower abundance, varying from 14.7 ± 1.9 to 11.9 ± 1.8. This seasonal pattern underscores the persistent impact of recycled wastewater irrigation on reducing fauna abundance compared to natural river water sources, potentially influenced by habitat quality or ecological stressors affecting wildlife populations in the region (Figure 6).

DISCUSSION

The study revealed notable differences in soil properties between recycled wastewater-irrigated and river water-irrigated soils, highlighting the underlying mechanisms that influenced soil chemistry, physics, and biology. Chemically, the wastewater-irrigated soil showed higher pH and electrical conductivity, indicative of increased alkalinity and salinity, respectively, likely due to dissolved ions and minerals in recycled water. This environment fostered higher organic matter content and nutrient levels, notably nitrogen, phosphorus, and potassium, which enhanced soil fertility and microbial activity. Physically, the lower bulk density of wastewater-irrigated soil suggested improved soil porosity, potentially promoting better root growth and water retention. Biologically, the significant increase in microbial activity in the wastewater-irrigated soil reflected a more dynamic microbial community, driven by enhanced organic substrate availability. While some studies suggest that irrigating with reclaimed wastewater might significantly alter the soil microbiome, a study by Li et al. [12], presents a different perspective. Their research on the soil irrigated with reclaimed wastewater for 40 years showed no major differences in the quantity and composition of microbes compared to soil irrigated with groundwater.

Both water sources and soil types were dominated by *Proteobacteria*, a common soil bacterium. Furthermore, the analysis of four different diversity metrics (observed OTUs, Chao1, Shannon diversity, and Simpson diversity) revealed no significant differences between the two irrigation methods. This suggests that long-term irrigation with reclaimed wastewater might not negatively impact the diversity of the soil microbiome. These findings underscored the dual benefits and challenges of recycled wastewater use in agriculture, emphasizing the need for careful management to mitigate salinity impacts

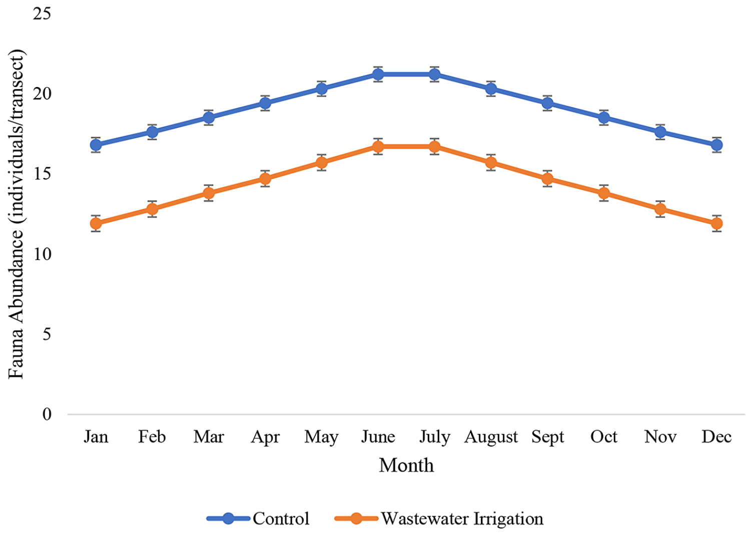

Figure 6. Fauna abundance

and ensure sustainable soil health as well as productivity over the long term [13].

The results of the study indicated significant improvements in growth and yield parameters for the trees irrigated with recycled wastewater compared to those irrigated with the water from the Syrdarya River. In terms of growth parameters, the average tree height in wastewater-irrigated plots was notably higher at 3.2 ± 0.3 meters, compared to 2.5 ± 0.2 meters in the control plots. This increased height can be attributed to the higher nutrient content in recycled wastewater, which provides essential minerals such as nitrogen, phosphorus, and potassium that are crucial for plant growth and development. Additionally, the trunk diameter of the trees irrigated with wastewater was larger, measuring 10 ± 0.6 cm compared to 8 ± 0.5 cm in the control. A larger trunk diameter suggests more robust structural development, likely due to the improved nutrient availability and better overall soil conditions facilitated by the organic matter and nutrients in the wastewater. Leaf area was also significantly greater in the wastewater-irrigated trees, with an average of 182 ± 23 cm^2 versus 159 ± 14 cm^2 in the control group. Larger leaf area enhances the photosynthetic capacity of the trees, allowing them to capture more sunlight and produce more energy, which in turn supports increased growth and biomass production. These enhancements in growth metrics suggested that recycled wastewater provided better support for tree development, likely due to its higher nutrient content and improved soil physical properties, such as lower bulk density and higher porosity. Regarding yield parameters, the trees irrigated with wastewater produced a higher biomass yield, averaging 7 ± 0.7 kg per tree, compared to 5 ± 0.5 kg per tree in the control group. This increase in biomass yield indicated improved overall productivity and health of the trees, which can be linked to the higher availability of essential nutrients in the recycled wastewater, promoting better growth and development. Furthermore, chlorophyll content, as measured by SPAD units, was higher in the wastewater-irrigated trees (51 ± 4) compared to the control trees (45 ± 3), suggesting enhanced photosynthetic activity. Higher chlorophyll content indicates that the trees are more efficient in capturing light energy, leading to better growth and health. Perulli et al. [14], found that irrigating nectarine trees with secondary treated wastewater (STW) provided several benefits compared to using only tap water (TW). The STW-irrigated trees showed improvements in nutrient levels, growth, photosynthetic activity, fruit size, and overall yield. While using tap water supplemented with mineral fertilizer (TW + MF) led to the most vigorous vegetative growth, it also caused signs of water stress in the trees. Importantly, the study found no negative impacts from using STW on any of the measured factors. The researchers concluded that STW can be a valuable resource for improving the health and productivity of nectarine trees due to its inherent nutrient content.

Also, the impacts on flora were evident in both species richness and biomass. Flora species richness declined from 28 ± 4 species per square meter in the control to 18 ± 3 species per square meter under wastewater irrigation, suggesting a shift in plant community composition and potential implications for ecosystem stability and resilience. This decline could result from certain plant species being more sensitive to the chemical composition of wastewater, such as increased salinity or specific contaminants [15], leading to a less diverse plant community. Flora biomass also decreased from 255 ± 34 g/m² in the control to 182 ± 25 g/m² under wastewater irrigation, reflecting changes in nutrient availability or soil health influenced by wastewater contaminants. These reductions in flora diversity and biomass highlight potential ecological consequences, such as altered nutrient cycling and habitat suitability for plant species. Furthermore, fauna responded to these changes with decreased species diversity and abundance under wastewater irrigation. Fauna species diversity, assessed using the Shannon Index, decreased from 3.5 ± 0.4 in the control to 2.8 ± 0.3 under wastewater irrigation, indicating potential disruptions in ecological interactions and community dynamics. This decrease could be due to habitat alterations or changes in food availability caused by the shifts in plant communities. Fauna abundance also declined from 17 ± 2 individuals per transect in the control to 12 ± 1 individuals per transect under wastewater irrigation, suggesting habitat alterations or resource limitations that could impact predator-prey relationships and overall ecosystem health. Chaganti et al. [16], studied the long-term impacts of irrigating bioenergy sorghum with treated urban wastewater. They found that while the wastewater did lead to changes in the composition of the plant biomass over time, these changes were not a direct result of the wastewater itself. Instead, the changes were an indirect consequence of increased salt levels (salinity and sodicity) in the soil, which were more pronounced in the wastewater-irrigated areas. Essentially, the study suggests that long-term wastewater irrigation can lead to soil salinity issues, which in turn affect the quality of the bioenergy sorghum.

Moreover, the study revealed nuanced seasonal dynamics in flora species richness under varying irrigation conditions. From January through March, both the control (Syrdarya River) and wastewater-irrigated plots exhibited a decline in species richness, reflecting winter dormancy when fewer plant species actively grow. In January, the control plots averaged 23 ± 4 species per square meter, while the wastewater-irrigated plots averaged 18 ± 3 species per square meter. This reduction continued into February and March, with control plots maintaining 22 ± 5 and 21 ± 6 species per square meter, respectively, compared to 17 ± 4 and 16 ± 5 species per square meter in the wastewater-irrigated plots. As temperatures warmed and daylight increased from April to June, both groups experienced a gradual increase in species richness. By April, control plots rebounded with 25 ± 3 species per square meter, contrasting with 19 ± 2 species per square meter in wastewater-irrigated plots. This trend continued into May and June, with the control plots reaching 27 ± 4 and 29 ± 3 species per square meter, respectively, while the wastewater-irrigated plots lagged behind at 21 ± 3 and 23 ± 2 species per square meter. The peak in species richness occurred during the summer months of July and August, with the control plots consistently showing higher levels, such as 31 ± 2 species per square meter in July and 29 ± 3 species per square meter in August, compared to 22 ± 3 and 21 ± 2 species per square meter in the wastewater-irrigated plots. Throughout the autumn months from September to December, as temperatures cooled and daylight hours decreased, both groups experienced a decline in species richness as plants entered dormancy. The control plots maintained higher richness levels, ranging from 27 ± 4 to 23 ± 6 species per square meter, whereas the wastewater-irrigated plots consistently showed lower richness, varying from 19 ± 3 to 16 ± 6 species per square meter. This seasonal variation underscored the persistent impact of recycled wastewater irrigation on reducing flora diversity compared to natural river water sources, potentially due to altered nutrient availability or residual contaminants affecting plant community dynamics. However, Helmecke et al. [17], emphasize that the potential risks of using reclaimed wastewater for agricultural irrigation are not universal and depend heavily on context. Factors such as the original composition of wastewater, the treatment it undergoes, the irrigation methods used, the type of crops being grown, the local climate, and the soil characteristics all play a role in determining the potential risks. This highlights the need for case-by-case assessments to ensure responsible and safe water reuse practices in agriculture.

The study in the Kyzylorda region highlighted seasonal variations in fauna abundance (individuals/transect) under the control (Syrdarya River) and wastewater irrigation conditions. From January to

March, both the control and wastewater-irrigated plots showed a gradual increase in fauna abundance as environmental conditions became more conducive to wildlife activity. In January, the control plots exhibited an average abundance of 16.8 ± 1.5 individuals per transect, whereas the wastewater-irrigated plots had 11.9 ± 1.8 individuals per transect. This trend continued into February and March, with abundance values slightly increasing each month for both groups. The control plots maintained higher abundance levels, such as 17.6 ± 1.9 in February and 18.5 ± 2.1 in March, compared to 12.8 ± 1.4 and 13.8 ± 1.7 in the wastewater-irrigated plots during the same periods. As temperatures warmed from April to June, both groups experienced a steady rise in fauna abundance. By April, the control plots demonstrated an abundance of 19.4 ± 1.8 individuals per transect, while the wastewater-irrigated plots reached 14.7 ± 1.9 individuals per transect. This upward trend continued through May and June, with control plots peaking at 20.3 ± 2.0 and 21.2 ± 2.2, respectively, compared to 15.7 ± 1.6 and 18.7 ± 1.8 in wastewater-irrigated plots. The peak abundance occurred during the summer months of July and August, with control plots consistently showing higher values, such as 22.2 ± 2.2 in July and 20.3 ± 2.0 in August, compared to 16.7 ± 1.8 and 15.7 ± 1.6 in wastewater-irrigated plots. Throughout the autumn months from September to December, as temperatures cooled and daylight hours decreased, both groups experienced a decline in fauna abundance as wildlife adjusted to seasonal changes. The control plots maintained higher abundance levels, ranging from 19.4 ± 1.8 to 16.8 ± 1.5, whereas the wastewater-irrigated plots consistently showed lower abundance, varying from 14.7 ± 1.9 to 11.9 ± 1.8. This seasonal pattern underscored the persistent impact of recycled wastewater irrigation on reducing fauna abundance compared to natural river water sources, potentially influenced by habitat quality or ecological stressors affecting wildlife populations in the region.

CONCLUSIONS

This study comprehensively explored the enduring impacts of recycled wastewater irrigation on the physical, chemical, and biological properties of soil, focusing on its implications for hybrid poplar crop yield and quality in the challenging environmental context of the Kyzylorda region. Chemical analyses revealed that the soil irrigated with wastewater exhibited elevated pH (7.5 ± 0.3) and electrical conductivity (2.3 ± 0.2 dS/m), indicating increased alkalinity and salinity levels compared to the control irrigated with the water from the Syrdarya River. Moreover, the wastewater-irrigated soil demonstrated significantly higher organic matter content (3.5 ± 0.4%) and nutrient levels, including nitrogen (45 ± 5 mg/kg), phosphorus (30 ± 4 mg/kg), and potassium (189 ± 16 mg/kg), highlighting the nutrient-rich nature of recycled wastewater. The study also demonstrated substantial improvements in the growth and yield parameters for hybrid poplar trees under wastewater irrigation. The trees irrigated with wastewater exhibited greater average height (3.2 ± 0.3 meters), larger trunk diameter (10 ± 0.6 cm), and increased leaf area (182 ± 23 cm^2) compared to those in the control plots. These enhancements in growth metrics underscored the superior support for tree development provided by recycled wastewater, attributed to its enriched nutrient composition. Yield parameters further confirmed these benefits, with the wastewater-irrigated trees yielding higher biomass (7 ± 0.7 kg per tree) and displaying elevated chlorophyll content (51 ± 4 SPAD units), indicative of enhanced photosynthetic activity and overall plant health. Assessment of seasonal dynamics in flora and fauna underscored shifts in species richness and abundance under both irrigation regimes. From January to March, both the control and wastewater-irrigated plots experienced declines in species richness and fauna abundance, typical of winter dormancy. To be more specific, the seasonal variations in fauna species diversity under the control (Syrdarya River) and wastewater irrigation conditions in the Kyzylorda region showed a gradual increase from January to June, with control plots exhibiting higher diversity levels such as a Shannon Index of 3.66 ± 0.19 in March and peaking at 3.95 ± 0.23 in June, compared to the wastewater-irrigated plots which reached 2.97 ± 0.34 in March and peaked at 3.27 ± 0.30 in June, reflecting temperature-driven changes in environmental conditions and fauna activity. While these dynamics reflected natural seasonal variations, control plots consistently maintained higher species richness and fauna abundance throughout the study period, suggesting potential ecological implications of recycled wastewater irrigation on biodiversity. This study provides comprehensive insights into the complex interactions between recycled wastewater irrigation, soil health, crop performance, and ecological dynamics in arid environments. The findings highlight the potential of recycled wastewater to enhance soil fertility and agricultural productivity, essential for sustainable water management strategies in water-scarce regions. However, careful management practices are imperative to mitigate the potential ecological impacts, emphasizing the need for integrated approaches that balance agricultural needs with environmental conservation goals. Further research is crucial to refine management practices and enhance the sustainability of recycled wastewater use in agriculture.

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