Dijlah Journal of Agricultural Sciences
Journal homepage: https://djas.uowasit.edu.iq/index.php/djas/en

Research article

Impact of Treated Wastewater Irrigation on Soil Chemical Properties, Potato Yield, Tuber Quality, and Heavy Metal Accumulation under Semi-Arid Conditions

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A R T I C L E I N F O

Keywords:
Treated wastewater,
Potato,
Soil salinity,
Tuber quality,
Heavy metals,
Bioaccumulation,
Microbial contamination,
Sustainable irrigation

Article history:
Received: 18th May 2026
Accepted: 23 May 2026
Online: 30 Jun 2026

A B S T R A C T

Treated wastewater is becoming a source of water for agriculture in arid and semi-arid regions where freshwater supplies are scarce. The aim of this study was to assess the effects of wastewater-treated irrigation on the water quality, soil chemical properties, growth and yield of potato (Solanum tuberosum L.), tuber quality, microbial contamination, and accumulation of heavy metals under field conditions in Al-Shuwaija, Wasit Governorate, Iraq. Randomized complete block design (RCBD) with two irrigation water sources (river water and treated wastewater) was used. Standard laboratory methods were used to analyze the water, soil and plant samples, and analysis of variance (ANOVA) at $p \leq 0.05$ was used to assess the effects of the treatments. Both treated wastewater and river water were found to have significantly higher electrical conductivity, TDS, COD, BOD, total nitrogen, sodium, chloride, bicarbonate, sodium adsorption ratio, sodium percentage, and cadmium and nickel concentrations than treated wastewater. The use of treated wastewater for irrigation increased the soil fertility by raising both the organic carbon and organic matter, cation exchange capacity, total nitrogen, and nutrient availability, and increased soil salinity and the level of trace metals. Irrigating potato plants with treated wastewater resulted in better vegetative plant growth, such as height, biomass, and number of leaves. River water irrigation, however, produced significantly more tubers, weight of tubers, total yield, marketable yield, and marketable yield percentage. The quality parameters of tubers, such as dry matter, starch, and specific gravity, were lower under TW irrigation. In addition, treated wastewater resulted in higher Cd, Ni, Pb, Cr, Zn, and Cu content in tubers and higher counts of coliform bacteria and Escherichia coli in treated wastewater. Hence, treated wastewater can be used as an alternate source of irrigation water, but it must be monitored for salinity, microbial contamination, and heavy metal accumulation.

1. Introduction

Agricultural sustainability is hindered by many constraints, water scarcity being one of the most prominent in arid and semi-arid areas, where population growth, climate fluctuations, urbanization, and competition between the domestic, industrial, and agricultural sectors all have an impact on water resources (Wang et al., 2022). The demand for conventional water sources for agriculture continues to shift as there is a growing need to find other water sources to sustain crop cultivation without further impacting the river and groundwater resources. In this context, the use of treated wastewater has gained increasing attention as a non-conventional water source that could help

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conserve water and recycle nutrients, as well as promote sustainable water-intensive agriculture (Savari et al., 2025). Wastewater can serve two purposes in an agricultural system: First, it provides irrigation water in water-scarce regions (Mishra et al., 2023). Second, it can be used as an augmenting source of nutrients and organic matter since treated effluents may contain nitrogen, phosphorus, potassium, dissolved organic matter, and other mineral substances. These inputs can increase soil fertility, make nutrients more available, increase organic carbon, and decrease the use of mineral fertilizers. Thus, wastewater reuse can be regarded as a significant aspect of the circular water management, especially in water-stressed areas where the costs and availability of fertilizer are significant issues to farmers (Ukoha-Onuha & Horsfall, 2026).

Although the benefits of agricultural use of treated wastewater are noted, some potential risks are associated with such use (Mokhtari et al., 2012). The effluents from the treatment processes can contain high levels of soluble salts, sodium, chloride, bicarbonate, organic matter, heavy metals, and pathogenic bacteria. The prolonged use of this water can lead to soil electrical conductivity, soil pH changes, soil sodium problems, soil physical degradation, and an increase of potentially hazardous elements in the soil–plant system. These risks are particularly high in arid and semi-arid environments, as water evaporation is a high-risk factor, and not enough natural leaching can cause salt accumulation in the root zone. Thus, the safe reuse of treated wastewater demands an integrated assessment of the quality of the irrigation water, soil chemical response, crop growth, yield performance, edible product quality, microbial contamination, and heavy metal transfer (Ibrahim & Hammad, 2024). Potato (Solanum tuberosum L.) is one of the most vital food crops in the world, and therefore is extensively grown due to its nutritional and economic value (Xu et al., 2023). The production of potatoes is especially vulnerable to the quality of irrigation water due to the fact that the initiation of tubers, bulking, dry matter content, and the final marketable yield can be strongly influenced by salinity, nutrient imbalance, and soil chemical conditions. Potato tubers do not grow above ground like most other crops, which means they are exposed to soil-borne contaminants, residues of irrigation water, microbes, and accumulated metals within the soil from which they grow. For this purpose, the effects of wastewater irrigation on potato cultivation should not be evaluated solely based on plant growth and yield, but also on the quality of the tubers and parameters of food safety (Akkamis & Caliskan, 2023).

In the past, it has been found that treated wastewater can enhance the vegetative growth and soil fertility due to its nutrient and organic matter content (Ferreira et al., 2023). But, the same water source can also cause yield and quality losses when salinity, sodicity, microbial content, or trace metal content is too high for the crop-soil combination. This dual effect raises questions about the appropriateness of the treated wastewater in the case of potato irrigation. In many instances, treated wastewater might be beneficial when only vegetative growth is considered; however, its beneficial effect may be reduced if any of the following are reduced: tuber yield, marketable production, dry matter, starch content, or edible-tuber safety. Thus, a thorough evaluation is required to investigate the potential use of treated wastewater for safe and productive potato farming (Abou Jaoude et al., 2025). The scarcity of water and the occasional reduction in fresh water availability in Iraq have made treated wastewater a critical resource to evaluate for irrigation purposes (Al-Rikabi et el., 2025). The al-Shuwaija area is part of Wasit Governorate, which is a region of great agricultural importance and is known for growing potato, wheat, barley, and onion crops. But the sustainability of crop production in this region relies on the availability and quality of irrigation water. The potential application of treated wastewater from local treatment plants may provide an alternative source of water, but the impacts of treated wastewater on soil properties, potato productivity, soil tuber quality, microbial risks, and heavy metal accumulation have not been thoroughly documented under local field conditions (Er, 2025).

Thus, the present study was carried out to assess the effect of using treated wastewater for potato production under field conditions with the aim of comparing the effect with water from the river, at Al-Shuwaija, Wasit Governorate, Iraq. The specific objectives were to (i) characterize the physicochemical, salinity, sodicity, heavy-metal and microbiological quality of river water and treated wastewater; (ii) quantify the changes in soil chemical properties due to irrigation with the treated wastewater including pH, EC, organic carbon, organic matter, CEC, total nitrogen, Cd, Ni; (iii) evaluate effects of irrigation water type on vegetative growth, yield components, total yield, marketable yield and quality of potato; (iv) examine heavy metal accumulation in potato tubers and bioaccumulation behavior; and (v) determine the overall benefits and limitations of the use of treated wastewater in potato production. The results will be scientifically used for safe management of treated wastewater irrigation in water-constrained agricultural systems.

2. Materials and Methods

2.1 Study area and experimental site

The field experiment was carried out in Al-Shuwaija Agricultural Zone - Wasit Governorate - Iraq, east of Al-Kut city. It is an area of high-intensity irrigated agriculture and is typically planted with strategic and/or vegetable crops such as wheat, barley, onion, and potato. The proximity of the study site to both river water and the Al-Shuwaija wastewater treatment plant was the selection criterion in order to compare the conventional irrigation water with treated wastewater under the same field conditions. The treated wastewater was collected from the Al-Shuwaija wastewater treatment plant (WWTP), which is situated at 32°36′16.6″N and 45°55′38.1″E. The plant is a secondary treatment plant with a design capacity of about 24,000 m^3 day^{-1}. The effluent obtained from the treatment is released towards the Al-Shuwaija depression. The water from the river was considered to be the control irrigation source and was taken from the local river irrigation source used by the farmers in the same agricultural area.

Representative soil samples were taken from the experimental field at 0–15 cm soil depth before planting to measure the physical and chemical characteristics of the soil. The soil was found to consist of a clay loam type soil with 24% sand, 34% silt, and 42% clay. The initial soil had a pH of 7.90, EC of 5.334 dS m^{-1}, CEC of 24 $cmol^{+}$ kg^{-1}, organic carbon of 0.10%, organic matter of 0.17%, total nitrogen of 19 ppm, Cd of 0.00493 mg kg^{-1}, and Ni of 0.002 mg kg^{-1}.

2.2 Experimental design and treatments

The experiment was designed as a randomized complete block design (RCBD) with two irrigation-water treatments and three replications. The watering programs were:

1. Control Irrigation with water from the river.

2. Treated wastewater irrigation wastewater treated in the secondary treated effluent from Al-Shuwaija wastewater treatment plant.

The effect of field variability was minimized by randomly allocating each treatment within each block. The same agronomic practices were used for all experimental units, with the exception of the source of irrigation water. Irrigation is applied as per crop water demand during the crop growth period. For all treatments, water was added at the same time and in the same quantity to minimize the influence of irrigation amounts on the differences observed, and to emphasize the effect of water quality.

2.3 Land preparation and crop cultivation

Before planting, the experimental field was plowed, leveled, and prepared. Plowing, leveling, and field preparation were done before planting in the experimental field. Potato cultivar Arizona was chosen for planting due to its suitability for production in the local environment, with certified and disease-free potato tubers being used. Planting of potato tubers was done in ridges with 75 cm spacing between ridges. The experimental units were each a single ridge, 5 m long. Common crop practices such as field maintenance and weed control were used equally on all treatments throughout the growing season. No other treatment differences, except irrigation-water source, were added. Fertilizer use should be reported as practiced in the field by the authors. If fertilizers have been used, antecedent information about the type, rate, timing, and application method of fertilizer should be provided prior to submission in this section.

2.4 Irrigation-water sampling and analysis

Samples of water were taken from the two sources of irrigation water, namely the river and treated wastewater. Samples were collected in clean polyethylene bottles, taken to the laboratory, and analyzed using conventional methods. The parameters of the irrigation water that were measured were pH, electrical conductivity (EC), total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand after five days (BOD_5), total nitrogen, sodium (Na), chloride (Cl), bicarbonate (HCO_3^-), cadmium (Cd), nickel (Ni), and microbiological indicators. PH and EC of water were measured by using a calibrated digital pH and EC meter, respectively. The gravimetric method was used to determine the total dissolved solids. COD was measured by using the dichromate oxidation method, and BOD_5 was measured by the standard water and wastewater examination method after 5 days of incubation. The total nitrogen was measured by the Kjeldahl digestion, distillation, and titration method. The concentrations of Cd and Ni in irrigation water were measured via AAS following specific sample treatment. Standard analytical techniques were used to determine the concentrations of sodium, chloride, and bicarbonate. Sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and sodium percentage were computed to determine the salinity and sodicity hazards of irrigation water use.

The sodium adsorption ratio was calculated as:

$$SAR = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+})/2]}$$

where Na^+, Ca^{2+}, and Mg^{2+} are expressed in meq L^{-1}.

Residual sodium carbonate was calculated as:

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$$

where all ions are expressed in meq L^{-1}.

Sodium percentage was calculated as:

$$\text{Na percentage} = [Na^{+} / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})] \times 100$$

where all cations are expressed in meq L^{-1}.

The total coliforms, fecal coliforms, Escherichia coli, and helminth eggs were used to check the microbiological quality of irrigation water. Coliforms and E. coli were reported as the number of organisms per 100mL (MPN/100mL) and helminth eggs as the number of eggs L^{-1}.

2.5 Soil sampling and chemical analysis

Before planting and after harvest, soil samples were taken from 0–15 cm in depth. Soil samples were taken from each experimental unit, air-dried, crumbled carefully, and crushed through a 2 mm sieve prior to laboratory analysis. The effect of irrigation-water type on soil chemical properties was judged by conducting soil analyses. The hydrometer method was used to determine soil texture. A soil–water suspension pH and EC were measured with a calibrated pH and EC meter. The cation exchange capacity was determined by using the methylene blue method. Soil organic carbon was measured by the Walkley–Black wet oxidation technique, and soil organic matter was estimated as 1.72 times soil organic carbon. The Kjeldahl method was used to determine total nitrogen. Diethylenetriaminepentaacetic acid (DTPA) extraction was used to remove available heavy metals (Cd, Ni), followed by their quantification by Atomic Absorption Spectrophotometry. From the pre-planting to post-harvesting soil properties, the treatment-induced change was worked out by subtracting the initial pre-planting property from the post-harvesting property for each soil parameter. The magnitude of the soil chemical alteration produced by each irrigation-water source was determined by these changes.

2.6 Plant growth measurements

At maturity, representative plants were randomly sampled from each experimental unit for growth and yield measurements. Three plants were chosen from each plot, excluding the border effects. The vegetative growth traits measured were plant height, plant weight, and number of leaves per plant. The height of plants was calculated from the soil surface to the top of the plants and was expressed in cm. The weight of plants was expressed in terms of fresh plant biomass (g $plant^{-1}$). The number of leaves was counted manually and expressed as leaves per $plant^{-1}$.

2.7 Yield and marketable yield measurements

The potato tubers were harvested from each experimental unit. Yield components measured were the number of tubers per plant and tuber weight per plant. The number of tubers was estimated by hand and recorded as tubers per $plant^{-1}$. The weight of tubers was determined using a digital balance and then reported as g plant-1. The total yield was determined and expressed in t ha^{-1}. The marketable yield was calculated after discarding diseased, damaged, and non-marketable tubers and is also given as t ha^{-1}. The marketable yield percentage was defined as:

$$\text{Marketable yield (\%)} = (\text{Marketable yield} / \text{Total yield}) \times 100$$

Diseased tubers were counted and expressed as a percentage of total tubers.

2.8 Tuber quality analysis

Quality of the tubers was determined by dry matter content, starch content, and specific gravity. Representative samples of tubers were dried to constant weight, and the weight of the dry matter was expressed as a percentage of the fresh weight. Starch content was determined using standard analytical procedures suitable for potato tubers and expressed as a percentage. The specific gravity was used as an index of the quality of the tubers. The parameters were added because dry matter, starch content, and specific gravity are significant potato quality, processing suitability, and market value parameters.

2.9 Heavy-metal analysis in potato tubers

After harvest, representative samples (tubers) were taken from each experimental unit to assess the level of heavy metal accumulation in the edible part of the crop. The samples were washed thoroughly in order to clean soil particles, rinsed with distilled water, and sent to the laboratory for analysis. The samples were then dried and ground, and subjected to an appropriate acid digestion procedure followed by determination of Cd, Ni, Pb, Cr, Zn, and Cu by atomic absorption spectrophotometry. Tuber contents of heavy metals were reported in mg kg^{-1} fresh weight. To assess the transfer of metals from soil to potato tubers, the bioaccumulation factors have been calculated from the selected metals. Bioaccumulation Factor (BAC) was computed as follows:

$$BAF = \text{Metal concentration in tuber} / \text{Metal concentration in soil}$$

The concentrations of metals in both tuber and soil were reported in similar concentration units. The relative transfer efficiency of the metals from the soil environment to the edible portion of the tuber was evaluated using the bioaccumulation factors.

2.10 Statistical analysis

Analysis of variance (ANOVA) was used to analyze the data of a randomized complete block design (RCBD). Treatment means were compared at a significance level of $p \leq 0.05$. If significant differences were found, then the least significant difference test was applied to separate treatment means. Independent two-sample t-tests were also performed to compare the water quality parameters of river water and treated wastewater. The values are expressed as mean ± Standard error. Based on the p-values obtained, the levels of significance were reported as non-significant, significant at $p < 0.05$, highly significant at $p < 0.01$, and very highly significant at $p < 0.001$. The relationship between different soil chemical changes and growth traits, yield traits, tuber quality, and heavy-metal uptake was investigated through the use of correlation analysis. Pearson correlation coefficients were calculated to determine associations between variables, and for the integrated interpretation of soil–plant responses. Prior to manuscript submission, all statistical analyses should be reported exactly as performed by the authors, specifying the software used. If the analysis was carried out in R, Python, SPSS, GenStat, SAS, or another package, add the following information in this paragraph: Analysis software name, version, and relevant packages.

2.11 Quality control and data reliability

Everything was done according to standard laboratory practice and by the use of calibrated equipment. Water, soil, and plant samples were collected and analyzed in replicates to increase the reliability and decrease the sampling error. To prevent contamination of the sample, laboratory glassware and sampling containers were cleaned prior to use. To prevent external contamination, samples were handled during preparation and digestion with care for the analysis of heavy metals. Replicated field data were used for statistical analysis, and appropriate significance tests were used for comparing treatment effects.

2.12 Methodological limitations

This experiment was made in one growing season with two sources of irrigation water. Thus, results indicate a clear short-term effect of treated wastewater irrigation, but should be treated with caution for the long-term reusers. Multi-season studies are required to assess the salt load, sodicity build-up, heavy-metal accumulation, microbial persistence, and changes in the safety of the tubers during multiple wastewater irrigation cycles.

3. Results and Discussion

3.1 Irrigation water quality and reuse suitability

The physicochemical and microbiological properties of the two sources of irrigation water were distinctly different from each other, as were the salinity, sodicity, and heavy metals. The pH of river water was slightly alkaline (7.876 ± 0.012), while treated wastewater had a lower value of pH (7.400 ± 0.011).

Table 1. Irrigation water quality, salinity/sodicity indicators, and microbiological parameters of river water and treated wastewater.

Parameter	Unit	River water mean ± SE	Treated wastewater mean ± SE	p-value	Significance
pH	–	7.876 ± 0.012	7.400 ± 0.011	<0.001	***
EC	dS m^{-1}	0.972 ± 0.009	1.432 ± 0.014	<0.001	***
TDS	mg L^{-1}	630.20 ± 5.09	930.00 ± 8.65	<0.001	***
COD	mg L^{-1}	40.00 ± 0.71	53.60 ± 0.93	<0.001	***
BOD_5	mg L^{-1}	13.40 ± 0.51	19.20 ± 0.58	<0.001	***
Total N	mg L^{-1}	2.00 ± 0.07	3.00 ± 0.07	<0.001	***
Cd	mg L^{-1}	0.00204 ± 0.00005	0.00400 ± 0.00007	<0.001	***
Ni	mg L^{-1}	0.01400 ± 0.00032	0.01680 ± 0.00037	<0.001	***
Na	mg L^{-1}	107.67 ± 1.45	168.33 ± 2.03	<0.001	***
Cl	mg L^{-1}	139.67 ± 1.20	219.33 ± 2.96	<0.001	***
HCO_3	mg L^{-1}	214.00 ± 2.31	268.33 ± 2.03	<0.001	***
SAR	index	2.78 ± 0.03	3.79 ± 0.03	<0.001	***
RSC	meq L^{-1}	−2.15 ± 0.05	−3.05 ± 0.04	<0.001	***
Na percentage	%	46.37 ± 0.37	50.86 ± 0.11	<0.001	***
Total coliform	MPN 100 mL^{-1}	130.00 ± 5.77	883.33 ± 20.28	<0.001	***
Fecal coliform	MPN 100 mL^{-1}	32.33 ± 1.45	195.00 ± 8.66	0.002	**
E. coli	MPN 100 mL^{-1}	13.33 ± 0.88	77.67 ± 4.33	0.003	**
Helminth eggs	eggs L^{-1}	0.00 ± 0.00	0.00 ± 0.00	NS	NS

Values are means ± SE. SAR = sodium adsorption ratio; RSC = residual sodium carbonate; NS = not significant. ** and *** indicate significance at $p < 0.01$ and $p < 0.001$, respectively.

The electrical conductivity was found to be 0.972 ± 0.009 dS m^{-1} for river water and 1.432 ± 0.014 dS m^{-1} for treated wastewater, which showed that the treated wastewater had a higher salt load in the soluble form. The concentrations of total dissolved solids, COD, BOD_5, total nitrogen, Cd, and Ni were also significantly higher in treated wastewater than in river water, as shown in Table 1.

The salinity and sodicity also supported the higher ionic content of treated wastewater. Sodium increased from 107.67 ± 1.45 mg L^{-1} in river water to 168.33 ± 2.03 mg L^{-1} in treated wastewater, while chloride increased from 139.67 ± 1.20 to 219.33 ± 2.96 mg L^{-1}. SAR increased from 2.78 ± 0.03 to 3.79 ± 0.03, and sodium percentage increased from 46.37 ± 0.37% to 50.86 ± 0.11%. The RSC values for both the water sources were negative, indicating that the sodicity hazard was not the limiting factor for carbonates. The higher EC, SAR, Na%, Cl, and HCO_3 values under treated wastewater, however, suggest that long-term reuse will need to have regular salinity and sodicity monitoring. Even the microbiological indicators were also higher in treated wastewater. Total coliforms increased from 130.00 ± 5.77 MPN 100 mL^{-1} in river water to 883.33 ± 20.28 MPN 100 mL^{-1} in treated wastewater. The number of fecal coliforms and E. coli was also significantly higher in treated wastewater, and no helminth eggs were detected in either water source. The findings in this report suggest that treated wastewater can have more nutrients and increased microbial and salt risks.

3.2 Soil chemical changes after irrigation

The soil chemical properties after harvest were different, with the amount of change greatly related to the irrigation-water type in Figure 1. Under both treatments, the soil pH had declined, but more so under the treated wastewater treatment. It is observed that pH has decreased more under treated wastewater irrigation (TWW) as compared to river water irrigation (RWI); the change in pH at TWW was −0.083 ± 0.020, compared to −0.397 ± 0.015 under RWI in Table 2.

Table 2. Treatment-induced changes in soil chemical properties after harvest under river water and treated wastewater irrigation.

Soil change variable	River water mean ± SE	Treated wastewater mean ± SE	p-value	LSD 0.05	Significance
ΔpH	−0.083 ± 0.020	−0.397 ± 0.015	0.008	0.132	**
ΔEC	0.317 ± 0.019	1.500 ± 0.042	0.002	0.281	**
ΔCEC	0.567 ± 0.088	1.933 ± 0.033	0.008	0.576	**
ΔOC	0.057 ± 0.003	0.577 ± 0.009	<0.001	0.058	***
ΔOM	0.100 ± 0.006	0.993 ± 0.012	<0.001	0.083	***
ΔTotal N	0.800 ± 0.115	2.067 ± 0.176	0.021	1.077	*
ΔCd	0.00020 ± 0.00006	0.00103 ± 0.00007	0.020	0.00070	*
ΔNi	0.00283 ± 0.00009	0.02797 ± 0.00113	0.002	0.00702	**

Values are means ± SE. EC is expressed as dS m^{-1}, CEC as $cmol^{+}$ kg^{-1}, OC and OM as %, total N as ppm, and Cd and Ni as mg kg^{-1}. *, **, and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Irrigation led to an increase in the soil EC, and a significantly higher increase under treated wastewater. The EC increase was 0.317 ± 0.019 dS m^{-1} under river water and 1.500 ± 0.042 dS m^{-1} under treated wastewater. This outcome shows that treated wastewater resulted in higher salinization of the soil. Consequently, treated wastewater proved to have a positive effect on some fertility-related parameters, while an increase in soil EC was a significant drawback for long-term reuse. The treated wastewater resulted in significant increases in soil organic carbon and organic matter. Under river water, the increase in organic carbon was 0.057 ± 0.003% while the increase under treated wastewater was 0.577 ± 0.009%. In river water, the increase of organic matter was 0.100 ± 0.006% and 0.993 ± 0.012% in treated wastewater. Nitrogen enrichment and increased nutrient-retention capacity were also seen in treated wastewater; CEC and total nitrogen increased more under the treated wastewater. Also, treated wastewater led to an accumulation of trace metals in the soil. Soil Cd increased by 0.00103 ± 0.00007 mg kg^{-1} under treated wastewater compared with 0.00020 ± 0.00006 mg kg^{-1} under river water. Soil Ni increased by 0.02797 ± 0.00113 mg kg^{-1} under treated wastewater and by only 0.00283 ± 0.00009 mg kg^{-1} under river water. Nitrogen and phosphorus were low in this data set, but the treated wastewater showed a larger increase, suggesting that long-term monitoring is needed.

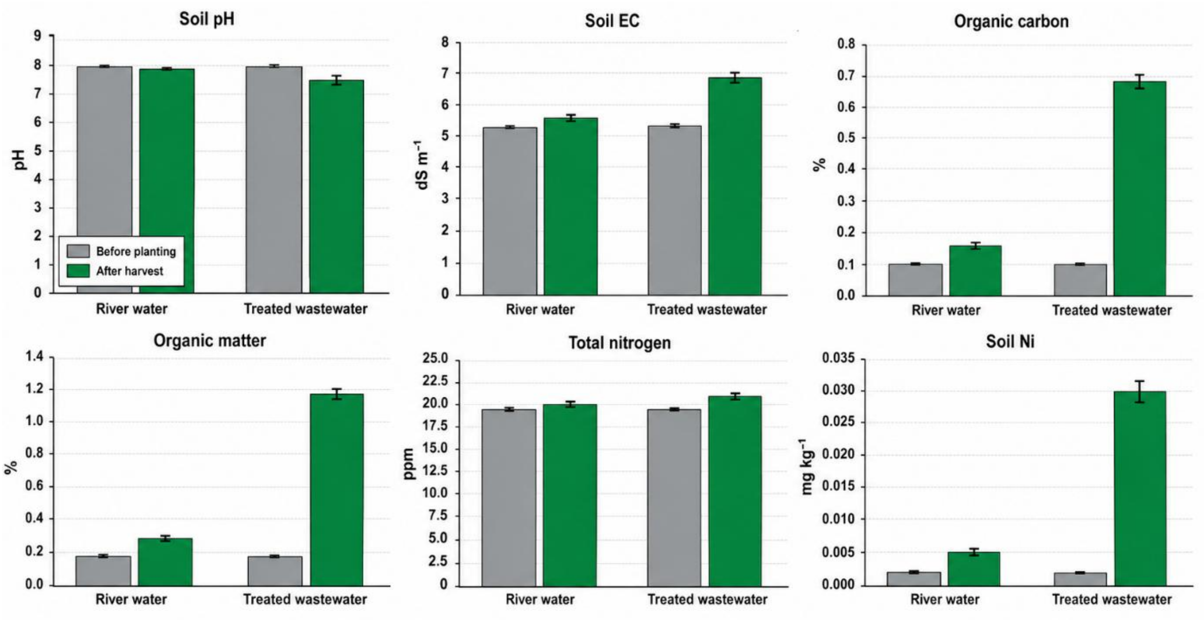

Figure 1. Soil chemical properties before planting and after harvest.

3.3 Potato vegetative growth, yield, and tuber quality

Vegetative growth of potato was improved by the treated wastewater irrigation. The height of the plants was found to be greater in treated wastewater (68.21 ± 0.28cm) than in river water (61.61 ± 0.24cm). Plant weight increased from 30.99 ± 0.46 to 35.00 ± 0.40 g plant^{-1}, and leaf number increased from 30.00 ± 0.58 to 34.11 ± 0.68 leaves plant^{-1}. The results show that treated water fosters growth of the vegetational parts, which may be due to its higher nutrient and organic content, as shown in Figure 2.

Yield-related traits, however, under-treated wastewater decreased. Tuber number decreased from 7.00 ± 0.19 to 5.00 ± 0.19 tubers per plant^{-1}. Under river water, tuber weight was 820.22 ± 3.11g plant^{-1} while under treated wastewater it was 650.67 ± 3.24 g plant^{-1}. Total yield decreased from 21.91 ± 0.12 to 17.47 ± 0.08 t ha^{-1}, and marketable yield decreased from 20.00 ± 0.15 to 15.42 ± 0.12 t ha^{-1}. The marketable yield percentage was also reduced in the treated wastewater treatment.

Tuber quality was the same as the yield. Dry matter decreased from 20.93 ± 0.09% under river water to 19.70 ± 0.06% under treated wastewater, while starch content decreased from 14.63 ± 0.09% to 13.60 ± 0.06%. Specific gravity also decreased from 1.084 ± 0.001 to 1.076 ± 0.001. The number of tubers with disease was greater under treated wastewater, although the differences were not significant.

The results demonstrate a substantial difference between vegetative growth and economic yield. The treatment of wastewater led to a reduction in the number and quality of tubers and stimulated the growth of aboveground biomass. This response can be related to higher EC and salt buildup in soils and to changes in assimilate partitioning during the growth of the tubers.

Table 3. Potato vegetative growth, yield, and tuber quality under river water and treated wastewater irrigation.

Trait	Unit	River water mean ± SE	Treated wastewater mean ± SE	p-value	LSD 0.05	Significance
Plant height	cm	61.61 ± 0.24	68.21 ± 0.28	<0.001	0.90	***
Plant weight	g plant^{-1}	30.99 ± 0.46	35.00 ± 0.40	0.002	2.06	**
Leaves	number plant^{-1}	30.00 ± 0.58	34.11 ± 0.68	<0.001	1.77	***
Tubers	number plant^{-1}	7.00 ± 0.19	5.00 ± 0.19	<0.001	0.72	***
Tuber weight	g plant^{-1}	820.22 ± 3.11	650.67 ± 3.24	<0.001	12.49	***
Total yield	t ha^{-1}	21.91 ± 0.12	17.47 ± 0.08	<0.001	0.42	***
Marketable yield	t ha^{-1}	20.00 ± 0.15	15.42 ± 0.12	<0.001	0.55	***
Marketable yield	%	91.28 ± 0.24	88.29 ± 0.30	<0.001	1.05	***
Dry matter	%	20.93 ± 0.09	19.70 ± 0.06	<0.001	0.32	***
Starch	%	14.63 ± 0.09	13.60 ± 0.06	0.001	0.32	**
Specific gravity	value	1.084 ± 0.001	1.076 ± 0.001	0.002	0.003	**
Diseased tubers	%	2.67 ± 0.33	4.67 ± 0.33	0.074	2.38	NS

Values are means ± SE. NS = not significant. ** and *** indicate significance at $p < 0.01$ and $p < 0.001$, respectively.

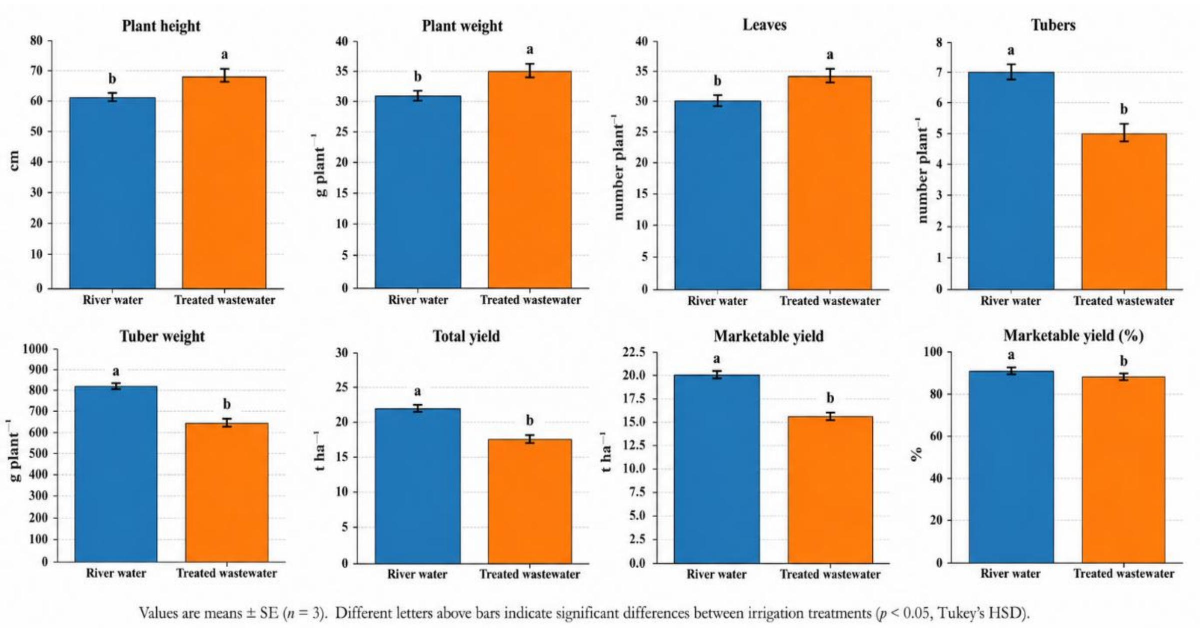

Figure 2. Potato growth and yield response to irrigation water type.

3.4 Heavy metal accumulation in potato tubers and bioaccumulation factors

Heavy metal uptake in potato tubers was greater with treated wastewater. Under the influence of river water, the concentration of Cd in the tubers of Cd increased from 0.0063 ± 0.0003 mg kg^{-1} fresh weight, while under the influence of treated wastewater, the concentration of Cd in the tubers of Cd increased to 0.0103 ± 0.0003 mg kg^{-1} fresh weight. Tuber Ni increased from 0.0357 ± 0.0012 to 0.0617 ± 0.0012 mg kg^{-1} fresh weight. The same is true for the treated wastewater, where levels of Pb and Cr also rose. The levels of essential trace elements such as Zn and Cu were also significantly higher in the treated wastewater-irrigated tubers in Table 3.

Table 3. Heavy metal concentrations in potato tubers and bioaccumulation factors under river water and treated wastewater irrigation.

Parameter	Unit	River water mean ± SE	Treated wastewater mean ± SE	p-value	Significance
Tuber Cd	mg kg^{-1} FW	0.0063 ± 0.0003	0.0103 ± 0.0003	<0.001	***
Tuber Ni	mg kg^{-1} FW	0.0357 ± 0.0012	0.0617 ± 0.0012	<0.001	***
Tuber Pb	mg kg^{-1} FW	0.0190 ± 0.0006	0.0270 ± 0.0006	<0.001	***
Tuber Cr	mg kg^{-1} FW	0.0123 ± 0.0003	0.0183 ± 0.0003	<0.001	***
Tuber Zn	mg kg^{-1} FW	4.93 ± 0.09	5.93 ± 0.09	<0.001	***
Tuber Cu	mg kg^{-1} FW	1.63 ± 0.03	2.03 ± 0.03	<0.001	***
BAF Cd	ratio	1.24 ± 0.05	1.73 ± 0.04	<0.001	***
BAF Ni	ratio	7.38 ± 0.05	2.06 ± 0.06	<0.001	***

Values are means ± SE. FW = fresh weight; BAF = bioaccumulation factor. *** indicates significance at p < 0.001.

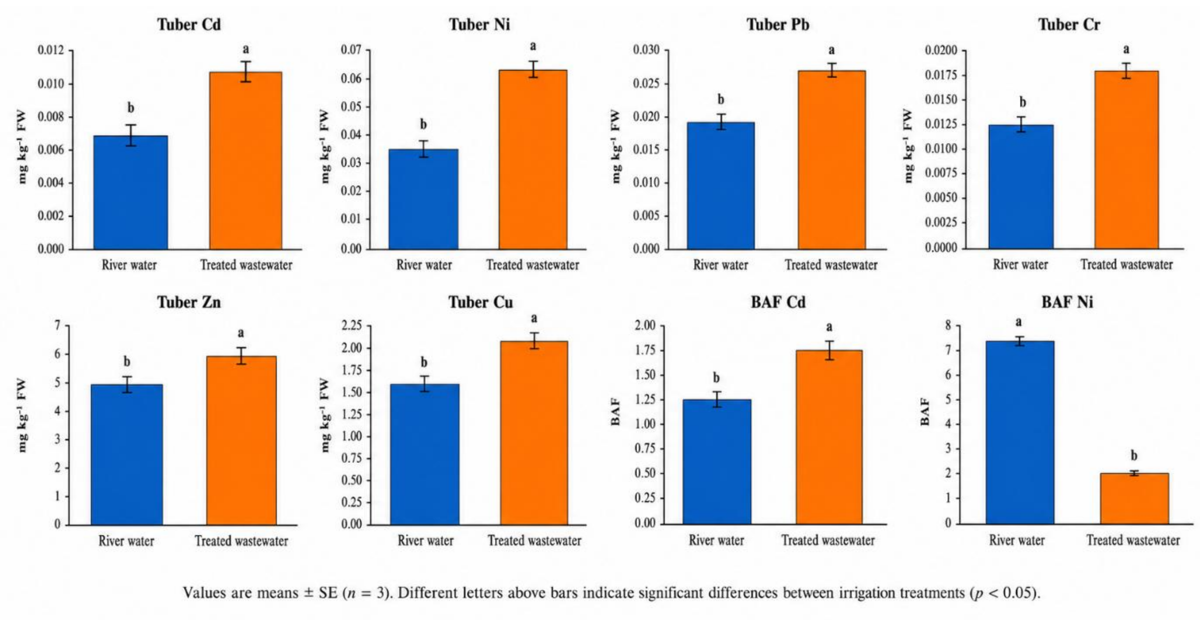

Figure 3. Heavy metal accumulation in potato tubers and bioaccumulation factors.

The bioaccumulation factor for Cd was higher in treated wastewater than in the river water, rising from 1.24 ± 0.05 to 1.73 ± 0.04. However, it is noteworthy that the bioaccumulation factor of Ni was higher when irrigated with river water than with treated wastewater, although the Ni concentration was higher in soils and tubers irrigated with wastewater, as shown in Figure 3. This means that the transfer from soil to tubers was variable among metals, and the metal concentration in the soil is not adequate to predict the concentration in the edible portion of the tuber.

The results are relevant to the interpretation of food safety. A treated wastewater cannot be considered fully safe, using only water and soil measurements. The levels of metals in edible tubers have to be reported and compared to relevant food safety standards before making consumer-safety decisions.

3.5 Integrated relationships among soil changes, growth, yield, and tuber metals

Correlation analysis revealed significant relationships between the soil chemical changes and the plant growth, yield, and metal accumulation in tubers. Plant height, leaf number, organic carbon change, organic matter change, soil Ni change, and tuber metal accumulation are positively correlated with soil EC change. In Figure 4, however, soil EC change was negatively associated with the tuber weight, total yield, and marketable yield.

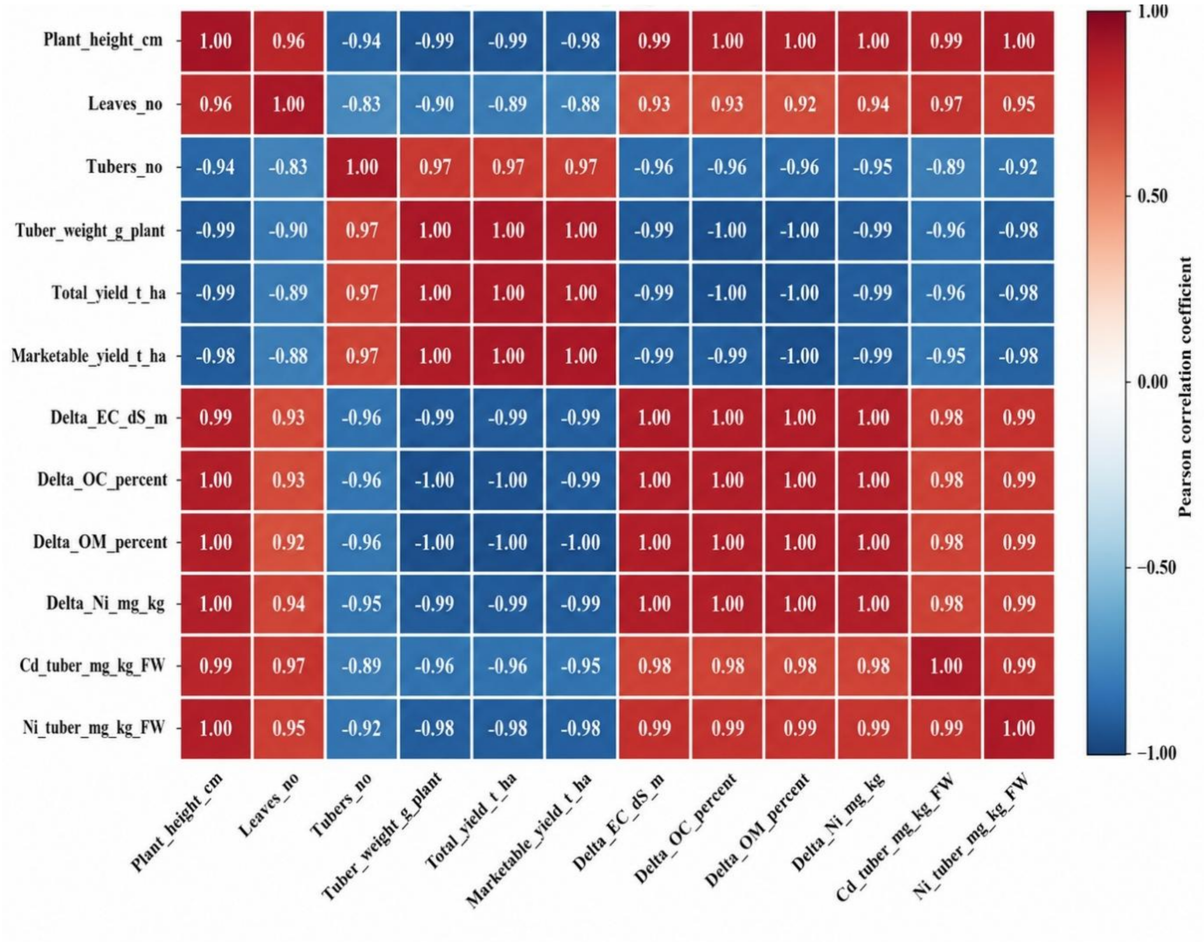

Figure 4. Correlation among soil change, growth, yield, and tuber metals.

The vegetative growth and metal uptake into the tubers were positively associated with the changes of organic carbon and organic matter, while the yield traits were negatively associated with the changes of the two. The pattern confirms the hypothesis that treated wastewater affected soil fertility-related parameters and vegetative growth positively, but also raised salinity and the concentration of trace metals, negatively affecting tuber productivity.

There was a positive correlation between soil Cd change and soil EC change, soil OM change, and soil Ni change, respectively. The relationships indicate that the soil chemical alteration that occurred due to treated wastewater resulted in higher metal levels in tubers intended for human consumption. Correlation analysis is performed on limited observations from the plots and may not be the main evidence for making causal inferences.

3.6 Overall treatment response

The overall results show that the treated wastewater had both positive and negative impacts. It increased soil organic carbon, organic matter, CEC, TN, plant height, plant weight, and leaf number. The answers indicate that the treated wastewater is also fertilizing and that it could increase the vegetative growth.

Treated wastewater, however, also showed to add to the EC, Cd, Ni, microbial indicators, and heavy metal accumulation in potato tubers. It also decreased tuber number, tuber weight, total yield, marketable yield, dry matter, starch content, and specific gravity values. Thus, treated wastewater may not be considered to be completely safe or agronomically superior without qualification.

For this dataset, treated wastewater can be considered as an alternative source of water for irrigation in areas where water is limited, but only if its use is managed carefully. Salinity, sodicity, soil heavy metals, and food tuber metal concentrations, as well as microbial indicators, should be regularly monitored for long-term re-use. To minimize risk and maximize the nutrient benefit of treated wastewater, blended irrigation, better drainage, leaching management, and periodic soil and tuber testing may be required.

The present study aimed to integrate an assessment of treated wastewater reuse for irrigation of potato crop, relating the quality of irrigation water, soil chemical changes, crop growth, yield of potato tubers, quality of potato tubers, presence of microbial indicators, and accumulation of heavy metals. The results indicated that the treated wastewater was also significantly different than river water on beneficial and potentially restrictive attributes. The higher salts, nutrients, organic load, sodium, chloride, bicarbonate, and trace metals in treated wastewater compared to river water were supplied. The dual response seen in the field is attributed to these characteristics, namely increased soil fertility indicators and vegetative growth, decreased yield and quality of tubers, and increased risk from microbial and metal contamination. The EC, TDS, COD, BOD_5, total N, Cd, Ni, Na, Cl, HCO_3^-, SAR, and sodium percentage values of the treated wastewater were much higher than those of the river water. This is a normal trend as secondary treated effluents typically have a higher concentration of soluble ions, organic residues, and nutrients than surface water. As for the pH of treated wastewater, it was not the main limitation in this study, as the pH was within the acceptable limit for irrigation. The values of EC and TDS, however, were higher, which means that more salt is entering the soil per irrigation.

The measured salinity and metal concentrations were relatively low and might be considered for short-term agricultural applications, but they are additive. Potato is moderately sensitive to salinity, and moderate increases in soil EC can cause a decrease in tuber initiation, bulking, and yield. Thus, water quality values for a single season should not be used to assess the suitability of treated wastewater. Rather, repeated testing of soil EC, soil SAR, sodium percentage, chloride, bicarbonate, and heavy metals should be conducted to evaluate their long-term use. As can be seen from the negative RSC values registered for both the irrigation sources, the sodicity hazard due to the presence of carbonate was not the predominant issue. But the treated wastewater produced higher SAR and sodium percentage, which means sodium accumulation may be a problem in repeated irrigation, particularly in clay loam soils with limited drainage and leaching (Salah et al., 2025). Microbiological results are especially relevant regarding crop safety. River water had significantly fewer total coliforms, fecal coliforms, and E. coli than treated wastewater (no helminth eggs were found). This suggests that the treated effluent remained contaminated with microbial contamination after treatment. Potato tubers grow in direct contact with the soil, and potentially excessive amounts of microorganisms in irrigation water may result in increased pathogen transfer to the soil–tuber environment. Hence, treated wastewater might need further disinfection or controlled irrigation practices, or a shorter pre-harvest irrigation period, prior to being deemed safe for edible crops.

Soil analysis showed that treated wastewater had a high impact on the chemical properties of the soil following harvest of vegetation. The increase in soil EC was greater under treated wastewater than under river water, which suggests salt accumulation in the root zone under treated wastewater. The rise in all these parameters is in tune with the higher EC, TDS, Na, Cl, and HCO_3^- levels of the treated wastewater. Noticeable increase of EC is an alarming symptom, though one season's exposure may not result in serious salinization. Repeated application can cause a gradual buildup of salts, especially in arid and semi-arid climates, with high evapotranspiration and low natural leaching.

Meanwhile, treated wastewater benefited a number of fertility-related soil characteristics. Organic carbon, organic matter, CEC, and total nitrogen were found to have been higher under treated wastewater than under river water. This is because treated wastewater has the ability to introduce dissolved and suspended organic matter and mineral nutrients to the soil, which account for the fertilizing value of treated wastewater. There could be an increase in organic carbon and organic matter, which can help to retain nutrients and increase microbial activity and soil structure. The rise of CEC also suggests better exchange capacity, thus enhancing the soil's ability to hold on to necessary nutrients. These changes prove that treated wastewater can serve as an irrigation source and as a nutrient source as well (Obijianva et al 2025).

But the positive fertility effect coincided with the soil's accumulation of Cd and Ni. The specific concentrations were low in the present data set, but the substantial rise due to treated wastewater suggests that trace metals were deposited from treated wastewater to the soil. This is significant because heavy metals are not biodegradable and can build up. Thus, the short-term results with low metal levels should not be taken as indication of long-term safety of the product. Irrigation over multiple seasons can lead to increases in soil metal pools and subsequently metal uptake, particularly under conditions that enhance metal mobility in soil such as low pH, organic matter, salinity, and redox conditions. Plant height, plant weight, and number of leaves of potato plants were higher in the treated wastewater-irrigated group as compared to the river water-irrigated group. This response suggests that the treated wastewater favored aboveground vegetative growth, likely because of the higher amount of nitrogen and contribution of organic nutrients supplied by the treated wastewater. Nitrogen is one of the most important factors influencing leaf growth, shoot growth, and canopy growth. Thus, the increase in vegetative growth when treated wastewater was used could be taken as a direct result of the nutrient enrichment.

This rise in soil organic matter and CEC may also be a factor in retaining and making nutrients more available. In the clay loam soil, additional organic matter can increase the ability of the soil to provide nutrients to the plants when growing. This could be the reason for the difference in vegetative development between treated wastewater and river water. But in potato production, overgrowth is not always desirable. Potato yield is not only related to shoot growth, but also to successful tuber initiation, partitioning of assimilates, tuber bulking, and quality development of the tubers. Thus, the positive impact of treated wastewater on vegetative characteristics needs to be discussed in conjunction with its effects on yield and tuber quality (Alvarez-Holguin et al., 2022).

Even though the vegetative growth was improved, treated wastewater resulted in a decrease in tuber number, tuber weight, total yield, marketable yield, and marketable yield percentage. This implies a good distinction between vegetative growth and economic yield. The most probable cause was the osmotic and ionic stress during the development of the tubers caused by the higher salinity and ionic load from treated wastewater. Raised EC can also decrease the uptake of water by the soil, disrupt the nutrient balance in the soil profile, and decrease translocations of assimilates from the leaf to the developing tuber. Consequently, plants can have higher aboveground growth but have reduced carbohydrate allocation to tuber bulking and formation. Reduced tubers in the lower part of the crop indicate that the initiation of tubers could have been impaired. Environmental stress (such as salinity, nutrient imbalance, and water-quality constraints) can affect tuber initiation. The tuber weight and total yield were also reduced further, indicating that the bulking of the tubers was also limited. Thus, the use of treated wastewater did not enhance the productivity of potatoes in the present experiment despite its positive effect on vegetative growth (Abbas et al., 2014).

The discovery is of agronomic significance. This indicates that treated wastewater can't be called superior just because it can make the plant grow taller or have more leaves. Marketable potato tuber yield and quality are most important. River water yielded better yields as treated wastewater increased vegetative growth and decreased economic productivity in this study. Hence, any measures for the practical application of treated wastewater for the irrigation of potatoes should prioritize measures that minimize salt stress and excessive vegetation growth, including: dilution of water with river water, improvement of drainage, irrigation scheduling control, periodic leaching, and balanced fertilizer adjustment. Treated wastewater irrigation also had a negative impact on the quality of the tubers. The specific gravity, starch content, and dry matter were lower in treated wastewater than in river water. These are critical quality parameters, particularly when processing potatoes. Generally, good processing quality, better texture, and higher economic value are achieved with higher dry matter and starch content. The decrease in these qualities with treated wastewater suggests that treated wastewater may have an impact on market and processing suitability.

The loss in dry matter and starch content might be linked to the change in carbohydrate metabolism and the partitioning of assimilates in the salinity stress. With salt stress, plants invest more resources into osmotically adjusting and resisting stress, potentially lowering tuber carbohydrate reserves. Also, more nitrogen availability can lead to increased vegetative growth and delay or decrease dry matter accumulation in the tubers. The slightly higher diseased tuber percentage (not significant) may also be relevant, as this treated wastewater had higher microbial indicators. This implies careful monitoring of the health of tubers in future research, especially when treated wastewater is applied near harvest, or tubers are consumed fresh or stored for extended periods (Shi et al., 2025).

The treated wastewater led to the uptake of Cd, Ni, Pb, Cr, Zn, and Cu in potato tubers. This indicated that the treated wastewater and soil irrigated with wastewater resulted in a higher metal content, which was also observed in the edible part of the plants. The increase in the measured concentrations was consistent along treated wastewater, but low in concentration, which is important from a food safety point of view. Potato tubers are eaten directly, and repeated exposure to low levels of toxic metals (Cd and Pb) could be a long-term health risk if the risk increases over the seasons. The behavior of the metals was different with respect to the bioaccumulation factor. The bioaccumulation factor was higher for Cd under treated wastewater, thus suggesting higher soil-to-tuber transfer under this treatment. However, the Ni bioaccumulation factor was higher under river water, although a higher concentration of Ni was observed in the treated wastewater-irrigated soil and tubers. Metal uptake does not only depend on the total soil concentration, but also on the metal speciation, soil pH, organic matter, salinity, competition of metal ions, and plant physiology regulation. Hence, the consideration of heavy metal risk should not be based only on water concentration or soil concentration, but also incorporate the bioaccumulation properties of the metal (He et al., 2025).

The results also suggest that if treated wastewater is considered safe, the levels of metals in tubers should be compared to the relevant food-safety standards. Crop safety is not determined by water-quality compliance, particularly for crops whose edible portions grow in close contact with the soil. The discussion should clearly differentiate between the two, "short-term concentrations below critical limits" and "long-term safety under repeated wastewater irrigation", for future publications.

The positive relationship between vegetative growth and tuber metal accumulation with changes in organic carbon and organic matter was seen to be negatively related to yield traits. This is not an indication that the reduction in yield was a result of the organic matter. Instead, organic matter increases co-occurred with the application of treated wastewater, which also brought an increase in salts, sodium, chloride, microbial load, and metals. Thus, the correlation pattern is not caused by the sole influence of organic matter on the treated wastewater, but by the combined influence. The correlation analysis used is only based on a small number of observations, it is used as supporting evidence, not as the primary basis for causal inference (Hammerton & Munafo, 2021).

The results of this research indicated that treated wastewater may be a resourceful irrigation water for potato production under water-limited conditions, but needs to be controlled. The main benefit is the improvement of soil fertility indicators and vegetative growth. The significant constraints are increased soil salinity, microbial contamination, the accumulation of trace metals, decreased tuber production, and reduced quality of the tubers. Hence, treated wastewater might be better applied with a controlled or mixed irrigation system, instead of being applied as a single water source.

Treated wastewater may be applied safely and sustainably when irrigation water quality is monitored regularly, soil EC, SAR, sodium percentage, chloride, heavy metals, microbial indicators, and tuber metal concentrations are monitored regularly. Other management practices may involve mixing treated wastewater with fresh water, leaching fractions, better drainage, drip irrigation rather than surface irrigation, avoiding irrigation with wastewater near harvest, and modifying fertilizer programs based on input from wastewater. Proper practices could help farmers obtain the nutrient content of treated wastewater without compromising the health of the soils, crop yields, and food safety (Karef et al., 2025).

The overall findings of the study show the potential and challenges of treated wastewater reuse in potato production. It can have positive effects on soil nutrient status and vegetative growth, but in the present situation, it caused decreases in yield and tuber quality and increases in metal and microbial issues. It is important to note that the treated wastewater is not a limitless alternative to river water, but a controlled alternative irrigation source.

5. Conclusion

The present study showed that the irrigation using treated wastewater had a significant effect on the water quality, soil properties, potato growth and yield, potato tuber quality, and heavy metal accumulation as compared to river water irrigation. The wastewater treatment composition had higher levels of dissolved salts, nutrients, organic matter, and microbial contaminants, which are indicated by higher EC, TDS, BOD_5, COD, TN, sodium-related indices, and coliform levels. Helminth eggs were not found, but microbial contamination was an issue. After irrigation, treated wastewater-irrigated soils showed higher levels of EC, organic carbon, organic matter, total N, Cd, and Ni concentrations, which signify higher availability of nutrients as well as increased salinity and trace metal levels. The vegetative growth (plant height, biomass, and leaf production) of potato plants was enhanced when they were irrigated with treated wastewater. But these improvements did not lead to increased productivity. The irrigation water from the river resulted in better tuber number, tuber weight, total yield, marketable yield, and marketable yield percentage. Treated wastewater negatively influenced tuber quality, reducing the dry matter, starch content, and specific gravity, and increasing the percentage of tubers with disease. Moreover, treated wastewater resulted in higher levels of Cd, Ni, Pb, Cr, Zn, and Cu in the tubers of potato. In general, treated wastewater is a possible alternative irrigation source and may be used to supply nutrients in addition to other water sources under water-deficient conditions; however, for potatoes, water use should be carefully managed, monitored, and assessed to reduce salinity, microbial, and heavy metal risks.

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