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ORIGINAL ARTICLE

The effect of irrigation with magnetized wastewater on soil heavy metals, water productivity and heavy metals in aerial parts and grains of maize

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Abstract
Rising population strains food resources; reusing wastewater increases but brings microbial and heavy metal pollution, impacting nature and human health. Among environmental pollutants, heavy metals in wastewater are a major concern. Using magnetized water is a method to improve water and soil quality. The aim of this research is to investigate the effect of using treated magnetized wastewater on the chemical properties and tracking of heavy metals in the soil, performance and yield components, water efficiency, and absorption of heavy metals by maize plant. Irrigation treatments consisted of various water and wastewater blending ratios under both magnetic and non-magnetic field application conditions. The results showed that the effect of irrigation water and mixing of water and wastewater on electrical conductivity, soil salts and heavy metals in different depths were significant at 1% probability level. On average, irrigation with magnetized wastewater caused a significant increase in grain yield (9.8%) and biological yield of maize (10.63%) compared to non-magnetized wastewater treatment. Irrigation with magnetized wastewater caused a significant increase in biological (10.92%) and physical (10.13%) productivities compared to non-magnetized wastewater treatment. With applying a magnetic field resulted in a reduction of 17.99%, 23.25%, 17.86%, and 17.12% in the concentration of lead, cadmium, zinc, and nickel in the aerial parts of the plant, respectively, compared to the non-magnetized water treatment. Magnetized water increases the water use efficiency of maize and irrigation management with this technology can be useful in more effective and economical use of limited water resources.

Keywords Water and soil improvement · Water and wastewater mixing · Magnetic field · Heavy metals · Biologic efficiency

Introduction

Due to the increasing daily need for food, agriculture must be developed in terms of production with the available water resources. In this regard, irrigated farming requires more attention, as higher production is achieved per unit area with irrigated farming. New water resources for such development are limited. Due to the limited water resources, there is a strong emphasis on more efficient use of existing water resources and the use of wasted and saline water for irrigation. Therefore, to have a successful agriculture, it is necessary to use these waters properly by implementing appropriate management practices (Hamza et al. 2021; Zhao et al. 2022; Bona et al. 2023; Alessandro et al. 2024). Approximately 75% of the water consumed in cities is turned into wastewater. Neglecting the proper disposal of this wastewater can have abnormal and concerning health consequences. In addition, in some areas, due to the urban layout, traditional disposal of wastewater into absorption wells is not feasible, or this method can cause the groundwater level to rise to the extent that it endangers urban buildings and infrastructure. Therefore, the collection, treatment, and proper disposal of wastewater are also essential for urban development. Research in some areas of Iran and

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other countries has shown that using treated wastewater is a suitable solution to water scarcity and can also meet the irrigation needs of plants (Razanov et al. 2020; Khoshravesh et al. 2021; Latosińska et al. 2021; Azari et al. 2021). Considering the fact that wastewater and sewage have become a major problem in many regions, using treated wastewater or sewage for irrigation purposes has been considered in some countries. In most developing countries, there is no alternative but to use wastewater for irrigation. This is even true for diluted sewage, which can be used to provide nutrients to the soil and reduce the cost of water usage (Alloway 2001; Bolto 1990). However, due to the expansion of agricultural land and the scarcity of water resources, groundwater is being extracted excessively through deep and semi-deep wells, leading to an increase in the level of salinity in the water table. As a result, the quality of water is deteriorating in most areas. Therefore, the use of unconventional water resources such as wastewater has become one of the most important goals in the agricultural sector. Agricultural consumption is one of the main uses of wastewater and return water due to the large amount required. Among the various sources of wastewater and return water, domestic wastewater is considered a higher priority for agricultural use after undergoing treatment processes due to its larger volume and better quality. With the increase in population, urban development, and agricultural production, the need for water resources has increased, along with the expansion of irrigation and the depletion of existing water resources. In most cities in Iran, especially in the north of the country, a significant amount of daily wastewater is produced. Additionally, the existence of fertile lands with the potential to produce agricultural products in these areas makes the use of treated wastewater for agriculture attractive, but heavy metal influx into the soil through wastewater is one of the environmental problems. The accumulation of heavy metals in irrigated soils with wastewater causes soil pollution, and by entering the food chain through plant absorption, it creates toxicity.

Finding faster and cheaper ways to treat and improve these waters is of great importance. Any technology that leads to the purification, recovery, and reuse of unconventional waters, such as wastewater, such as magnetic field technology, is essential and must be examined. Magnetized water has less surface tension and greater permeability and solubility than ordinary water, and it leads to increased activity of enzymes, proteins, chlorophyll, pigments, nucleic acids, and molecular polarity in plant cells. The magnetic field causes an increase in the transfer of ions from cellular channels, the formation of free radicals in the cell, changes in hormone concentrations, changes in the function of ion transporter enzymes in the cell membrane, changes in DNA synthesis and transfer, and the functioning of calcium ion transfer (Rosensweig 2002; Khoshravesh et al. 2018; Ramesh & Ostad-Ali-Askari 2023). These changes due to water passing through a magnetic field depend on factors such as magnetic field intensity, magnetic field direction, exposure time to the magnetic field, solution flow rate, water quality, and pH (Mostafazadeh-Fard et al. 2011; Hamza et al. 2021; Zhao et al. 2022). Therefore, the placement of plants in magnetic fields or passing the water used for their irrigation through a magnetic field and the different responses of plants to different strengths of electromagnetic waves can be a way to increase crop yield and water efficiency. Also, the effect of magnetized water on plant growth can lead to an increase in pigment production, which enhances the color of flowers and fruits (Celik et al. 2008; Pourgholam-Amiji et al. 2022).

Others have reported that magnetized water may increase the permeability of the cellular membrane of the grain, change the pH of both sides of the cellular membrane, increase calcium ion activity, and reduce the activity of harmful microscopic organisms (Biryukov et al. 2005). In a study by Grewal & Maheshwari (2011), the effect of magnetic fields on the performance of chickpeas, celery, and beans under greenhouse conditions was investigated. Their results showed that magnetized water increased celery yield by 12 and 23%, and water use efficiency by 12 and 24%. An increase in crop yield and water use efficiency was also observed in beans in the magnetized water treatment compared to the control treatment. Additionally, Lin and Yotvat (1990) reported an increase in water use efficiency in agricultural crops due to magnetized water.

The use of urban wastewater in agricultural lands leads to an increase in heavy metals in the soil, which also significantly increases their concentration in plants. In irrigated lands with urban wastewater, the total salt concentration has doubled, and the amount of heavy metals has significantly increased up to a depth of 15 cm in the soil, with some elements such as cadmium showing up to 23 times the increase (Sergey and Svetlana 2002). Among heavy metals, cadmium poses particular hazards due to its relatively high mobility in the soil and potential toxicity to living organisms at low concentrations. Cadmium is a non-essential heavy metal that has no metabolic use and naturally accumulates in soil in small concentrations, but large amounts of it have been reported in some soils. Because of its high mobility in soil and toxicity at low concentrations, cadmium poses significant risks. Since cadmium has no metabolic use and has a biological half-life in the human body ranging from 1 to 30 years and cannot be converted into other compounds, it is necessary to reduce its entry into the food chain as much as possible (Naser et al. 2009).

When cadmium enters the body, it accumulates in the kidneys, liver, reproductive organs, nervous, respiratory, digestive systems, and heart muscles. If the amount of cadmium exceeds a certain limit, its long-term effects can cause various diseases. These effects are more severe in children and can lead to more severe consequences (Kabata-Pendias and Pendias 2001). While the human body requires elements such as zinc, copper, nickel, and chromium in very small amounts, even trace amounts of toxic elements such as cadmium and lead are hazardous to human health (Liu et al. 2020). However, the presence of nutritional elements in wastewater reduces the use of chemical fertilizers, but the potential negative effects of these water sources on environmental pollution, plants, and humans must be considered (Abedi-Koupai et al. 2013). The type of irrigation system and the method of distribution of these water sources are also important in water management.

Nickel is an essential metal for plant growth, but its high concentration causes plant toxicity, such as enzyme inhibition, nitrogen metabolism disruption, and growth reduction. The presence of iron and manganese ions causes a decrease in nickel transport to different parts of the plant (Yusuf et al. 2011). Lead toxicity in plants causes damage to the roots, reduces lateral roots, and decreases the concentration of other essential metals such as iron. High concentrations of the essential element iron cause rapid blackening, abnormality, and death of cell tissue. Manganese is an essential element for plant growth, but its high concentration causes disturbance in enzyme activity, absorption and utilization of other minerals, oxidative stress, and reduction in the green color of leaves and their growth (Millaleo et al. 2010). Studies have shown that it generally takes 5 to 10 years for the levels of heavy metals in wastewater-irrigated blue soil to exceed the permissible limit (Smith et al. 1996).

Maize has a great potential in absorbing and removing heavy metals from soil. Besides producing high biomass, it is also known as a hyperaccumulator of heavy metals (Park et al. 2012). In a study, Rezapour et al. (2019) investigated the concentration of heavy metals in winter wheat using treated wastewater. Their results showed the presence of a considerable amount of heavy metals in soil and various parts of wheat. The average concentration of these metals in wheat grain was within the legal limits. Irrigation with treated wastewater led to a significant increase in the concentration of heavy metals in wheat compared to the control treatment, including Zn > Cu > Ni > Cd > Pb. The concentration of heavy metals in wheat roots was significantly higher than in grains and stems, which were in the order of Cu > Zn > Pb > Cd > Ni.

Abedi-Koupai et al. (2001) investigated the effects of wastewater on various plant species using different treatments including regular wastewater, wastewater with 5 times higher heavy metal concentration, and wastewater with 10 times higher heavy metal concentration. The results showed that the total plant biomass decreased with increasing element concentration in the wastewater, to the extent that high concentrations of heavy metals reduced plant production in leaves and stems.

With the reduction of water resources, the use of unconventional water sources such as municipal wastewater, especially where suitable quality water is not available, can reduce pressure on accessible water resources and reduce production costs. In addition to meeting the water requirements of plants, wastewater can also provide a portion of the plant's nutritional needs. On the other hand, magnetizing water can be a suitable option to increase crop yield and the concentration of elements present in the plant parts used. Moreover, magnetizing water can be a suitable option to reduce heavy metals in the soil and ultimately transfer them to plants. Given the existence of treated wastewater sources in Babolsar County and the importance of using treated wastewater, as well as the cultivation of maize in the region, the use of wastewater is essential. So far, studies have been conducted on the effect of magnetized water on soil chemical properties, but no research has been done on the effect of magnetized treated wastewater on soil chemical properties. Also, some research has been done on the effect of magnetized water or wastewater containing heavy metals on crop yield and water use efficiency, but no research has been done on the combined effect of these two, i.e., magnetized treated wastewater, on crop yield and water use efficiency. Studies have been conducted on the effect of magnetized water on soil and plants, but no research has been done on the effect of magnetized treated wastewater on the accumulation of heavy metals in soil and plants. Therefore, the objectives of this study are to investigate the use of magnetized treated wastewater with drip irrigation method on soil chemical properties, crop yield and its components, water use efficiency, and heavy metal absorption in aerial and grain parts of maize plant.

Materials and methods

Study area

The present study was conducted in the years 2021–2022 on a farm located in the village of Armich Kola, Babolsar County (Mazandaran Province), with coordinates of 59° and 39′ north latitude and 36° and 43′ east longitude, at an altitude of − 21 m from sea level. Based on long-term data and De Martonne climatic classification, the region has a humid climate. According to 30-year long-term statistics (1991–2020), the average annual precipitation of the area is 891 mm and the average annual air temperature is 17.5 °C (Pourgholam-Amiji et al. 2021). The geographic location of the study area is shown in Fig. 1.

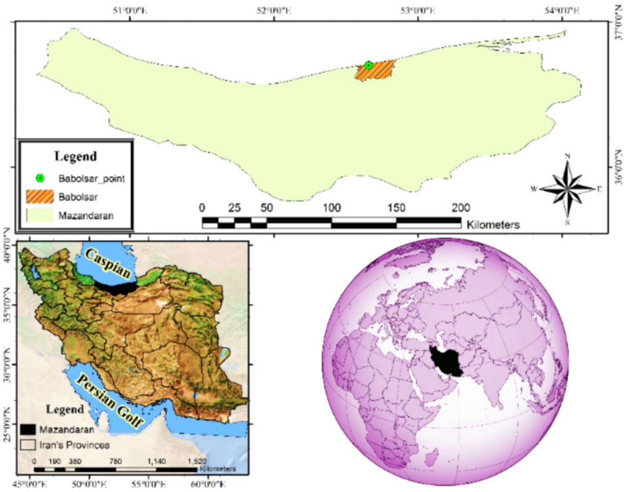
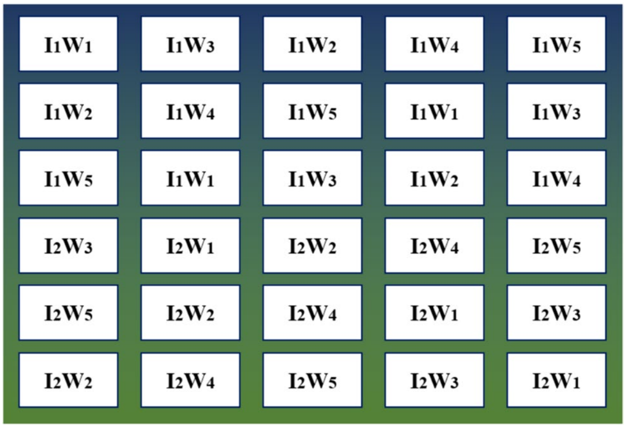


Fig. 1 Geographical location of the experiment site



I_1W_1	I_1W_3	I_1W_2	I_1W_4	I_1W_5
I_1W_2	I_1W_4	I_1W_5	I_1W_1	I_1W_3
I_1W_5	I_1W_1	I_1W_3	I_1W_2	I_1W_4
I_2W_3	I_2W_1	I_2W_2	I_2W_4	I_2W_5
I_2W_5	I_2W_2	I_2W_4	I_2W_1	I_2W_3
I_2W_2	I_2W_4	I_2W_5	I_2W_3	I_2W_1

Fig. 2 Schematic of lysimeters placement

Soil and lysimeter properties

The used lysimeters were made of PVC with a diameter of 60 cm and a height of 100 cm. To remove excess water from the lysimeters, PVC pipes with a diameter of 5 cm and a length of 70 cm were used. Holes with a diameter of two millimeters and a distance of 2.5 cm in 4 rows at 50 cm from the length of the pipe were considered as drainage holes on the pipes. To prevent soil particles from entering the drainage pipes, a geotextile filter was used around the drainage pipes. This filter was sewn as a concentric cover around the pipe and pulled around it. The drainage pipes were placed horizontally on the bottom of the lysimeter, with their blocked end inside and their open end outside of the lysimeter. The connection of the pipes to the lysimeter body was sealed from the inside and outside (Fig. 2) (Khoshravesh and Pourgholam-Amiji 2023).

After obtaining the desired agricultural soil from the farm, filling the lysimeters with the corresponding soil was done in several stages. The soil was poured into the lysimeters in layers of 10 cm high and after leveling, the next layer was added. When the height of the soil reached the middle of the lysimeters, some water was added to the soil for settling and compaction, and adding soil continued until the lysimeters were completely filled. Then, after adding water again and settling, the remaining empty space was filled with soil up to five centimeters below the top edge of the lysimeters. Prior to conducting tests and applying treatments to determine the physical and chemical properties of the soil, sampling was done from the lysimeters. The physical and chemical properties of the soil are given in Table 1.

This experiment was conducted as factorial based on randomized complete block design with three replications. In this design, the treatments consisted of five different irrigation conditions with different ratios of wastewater and well water, under two conditions with (I1) and without (I2) the application of a magnetic field, as follows: irrigation with well water (W1), irrigation with a mixture of 25% wastewater and 75% well water (W2), irrigation with a mixture of 50% wastewater and 50% well water (W3), irrigation with a mixture of 75% wastewater and 25% well water (W4), and irrigation with 100% wastewater (W5). The irrigation water was magnetized using a permanent magnet with a magnetic field intensity of 0.3 Tesla. The chemical properties of the well water and wastewater used in the experiment are shown in Table 2. The SC 704 maize cultivar was grown in the lysimeter.

The strip irrigation method was used for irrigating maize, and the amount and frequency of irrigation were performed according to the plant's needs. The emitters had a flow rate of 1.6 L per hour and a spacing of 20 cm. Considering the Langelier saturation index and the drip irrigation system,

Table 1 Physical and chemical properties of the soil in the lysimeters

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture	ρ_b (g/cm^3)	pH	EC (dS/m)	Ca	Mg	Na	Pb	Cd
								meq/l			mg/kg	
0–30	19.69	45.04	35.27	Loam	1.50	7.5	1.91	9.4	12.3	17.7	1.00	0.020
30–60	19.34	45.16	35.50	Loam	1.53	7.4	1.93	9.6	12.1	17.7	1.02	0.023
60–90	19.55	45.39	35.06	Loam	1.59	7.7	1.92	9.7	12.1	18.2	1.03	0.027

Table 2 Chemical properties of water and wastewater used in the experiment

Water source	EC (dS/m)	pH	Ca meq/l	Mg	Na	Pb µg/l	Cd
well water	0.59	7.3	2.95	2.14	1.67	1.02	0.01
wastewater	1.14	7.7	4.40	41.61	12.20	13.18	0.026

there was no need for leaching. First, wastewater of type 2 from the municipal wastewater treatment plant was obtained and then poured into special containers and sealed to prevent reactions with the outside air. The wastewater was then transferred to the experimental site and used for plant irrigation at different mixing ratios with well water. After approximately one month of maize growth (five to six leaves), the treatments were applied. The amount of irrigation for each treatment was measured using a volumetric flow meter, and the calculations are as follows:

$$\mathrm{Td} = \mathrm{ETc} \times [0.15 + 0.85\mathrm{Pd}] \tag{1}$$

$$d_n = \mathrm{Td} \times F \tag{2}$$

$$d_g = \frac{d_n}{E} \tag{3}$$

$$V = dg \times A \tag{4}$$

In which $\mathrm{ET_C}$ represents the evapotranspiration of maize (mm/day), Td is the maximum daily transpiration of the plant (mm/day), Pd is the shading percentage, F is the irrigation frequency (day), d_n is the net water depth per irrigation (mm), d_g is the gross water depth per irrigation (mm) based on a 90% drip irrigation efficiency, V is the water volume applied to each treatment (m^3), and A is the area of the plot (m^2).

Field measurements

At the end of the experimental period and after completion of irrigation, soil sampling was performed at depths of 0–30 cm, 30–60 cm, and 60–90 cm to investigate the effect of magnetized water and the percentage of different sewage effluent mixtures on some soil chemical properties including electrical conductivity, acidity, calcium, magnesium, sodium, chlorine, and trace metal tracking of lead and cadmium in the soil.

To determine the yield and yield components of maize, each experimental unit was selected for sampling after the growth period and physiological maturity. To do this, traits such as fresh and dry weight of the plant, number of grains per ear, thousand-grain weight, biological yield, grain yield, and harvest index were calculated. Harvesting was done to determine the yield within a certain length range. Also, 20 samples were randomly taken in the desired range to determine the yield components. To measure the weight of the complete plant with the ear, the harvested plants were weighed with their ears in the laboratory. For measuring the weight of the dried plant, the harvested plants were placed inside an oven at a temperature of 105 °C for 24 h and then weighed. To count the number of grains in each ear, the product of the number of grains in a row and the number of rows in an ear was calculated. To measure the weight of a thousand grains, maize grains were separated from the ear, and batches of 100 seeds were prepared, and then the weight of the samples was measured. For measuring biological yield, the plants related to all repetitions of each treatment were cut off (at ground level) and weighed using a scale. Then, the weight of the harvested plants from the mentioned area was calculated in tons per hectare. Finally, to measure the grain yield, the product of the number of plants per unit area, the weight of a thousand grains, and the number of grains per ear was calculated, and so on. The harvest index is calculated using Eq. (5).

$$H_i = \frac{Y}{Y_b} \times 100 \tag{5}$$

where H_i is the harvest index (%), Y and Y_b represent grain yield and biological yield, respectively. The biological and physical productivity, forage yield and dry matter yield were calculated and investigated based on different performances of maize plants and different treatments. Equation (6) was used to calculate maize plant productivity according to Kijne et al. (2003):

$$WP = \frac{\mathrm{Y}}{I} \tag{6}$$

where WP is irrigation water productivity (kg/m^3), Y is yield (kg), and I is irrigation water volume (m^3). Samples were also taken from all treatments and replications, and lead, cadmium, nickel, and chromium were measured in the maize plant and grain.

Atomic absorption spectroscopy (AAS) was used to measure the concentration of heavy metals in the samples, including soil and plants. The AAS technique is used to determine very low concentrations of metals (in the range of ppm) in samples. To prepare the soil samples for reading by the atomic absorption device, 2 g of soil or plant sample were mixed with 15 ml of 4-normal nitric acid and placed in a hot water bath at 80 °C. After 12 h, the sample was filtered. The concentration of heavy metal elements in the obtained extract was read by the atomic absorption device. Finally, the latest version of SAS software (version 9.4) was used for statistical analysis of the data, and the means were compared by the Duncan test.

Results and discussion

Salts and heavy elements of soil

The electrical conductivity and acidity of different depths of soil were measured for different treatments at the end of the experiment period. According to the results of the variance analysis presented in Table 3, the effect of irrigation water (magnetized and non-magnetized) and mixing of water and wastewater (W) on soil electrical conductivity at different depths was significant at 1% probability level. The interactive effect of irrigation water and mixing of water and wastewater on soil electrical conductivity was also significant. However, the effect of irrigation water and mixing of water and wastewater on soil acidity was not significant. In the magnetized water treatment, the electrical conductivity of the soil at all depths was less than that of the non-magnetized water treatment, and this difference was significant. On average, irrigation with magnetized water in the first and second years of cultivation caused a reduction of 30.43% and 33.05% in soil electrical conductivity, respectively (Table 4). The reduction of soil electrical conductivity using magnetized water was more noticeable in the second year. The reduction of soil electrical conductivity in the magnetized water treatment is due to the removal of soluble materials by washing with magnetized water compared to non-magnetized water. Mohamed (2013) showed that using magnetized saline water had a significant effect on soil and tomato plants. He observed that the use of magnetized water had a significant effect on reducing soil electrical conductivity after harvesting.

The highest level of soil electrical conductivity was related to the second year of cultivation at depth of 60–90 cm in the treatment irrigated with 100% wastewater, with a value of 4.42 dS/m. The lowest value was observed in the treatment irrigated with well water, with a value of 1.96 dS/m. The higher electrical conductivity in treatments irrigated with a higher percentage of wastewater was due to the higher electrical conductivity of the wastewater and an increase in soil salinity in these treatments. In fact, with repeated cultivation in the second year, the soil salinity also increased. Kaboosi (2017) showed that mid-term irrigation

Table 3 Analysis of variance the effect of various factors on the electrical conductivity and acidity

Variations source	Degrees of freedom	EC			pH		
		0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
Block	2	0.030^{ns}	0.033^{ns}	0.036^{ns}	0.034^{ns}	0.039^{ns}	0.044^{ns}
I	1	13.14**	15.21**	16.45**	39.60^{ns}	40.55^{ns}	41.08^{ns}
W	4	20.03**	23.59**	27.94**	39.98^{ns}	40.08^{ns}	40.32^{ns}
I×W	4	6.87**	7.32**	8.19**	1.34^{ns}	1.59^{ns}	1.67^{ns}
Error	18	0.406	0.437	0.466	0.741	0.783	0.798
Coefficient of variation	-	7.37	6.44	6.21	2.45	1.96	1.74

**, and ^{ns} indicate statistical significance at one% level, and no significant difference, respectively

Table 4 Comparison of the mean values of electrical conductivity and acidity at different soil depths

Treatment	EC (dS/m)			pH		
	0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
I						
I1	2.20 b	2.35 b	2.70 b	7.31 a	7.36 a	7.52 a
I2	3.38 a	3.61 a	3.80 a	7.38 a	7.42 a	7.57 a
W						
W1	1.96 e	2.05 e	2.23 e	7.31 a	7.33 b	7.36 d
W2	2.42 d	2.61 d	2.77 d	7.33 a	7.35 b	7.42 cd
W3	2.69 c	2.96 c	3.14 c	7.34 a	7.42 a	7.47 c
W4	3.09 b	3.38 b	3.69 b	7.36 a	7.43 a	7.60 b
W5	3.79 a	3.90 a	4.42 a	7.38 a	7.42 a	7.87 a

In each column, means with the same letter are not significantly different at $P = 0.05$ level with treated wastewater (for 7 years) increases soil salinity. Mostafazadeh-Fard et al. (2012) investigated that the effect of magnetized water on soil salinity at different depths in drip irrigation and found that the use of magnetized water reduced soil salinity compared to non-magnetized water. They stated that an increase of 5.7% in soil moisture due to magnetized water resulted in leaching of soil salts.

The results of the analysis of variance in Table 5 indicate that the effect of irrigation water and the mixing of water and wastewater on soil calcium and magnesium at different soil depths is significant at 1% probability level. Additionally, the interaction effect of irrigation water and the mixing of water and wastewater on soil calcium and magnesium is significant. The amount of soil calcium and magnesium at all depths (30–0, 60–30, and 90–60 cm) in the magnetized water treatment was lower than that in the non-magnetized water treatment, and this difference was significant. On average, irrigation with magnetized water in the first and second years of cultivation resulted a reduction of 36.33% and 36.92% in soil calcium and a reduction of 30.77% and 31.36% in soil magnesium, respectively (Table 6). In treatments with higher percentages of wastewater mixing, the amounts of calcium and sodium increased at all depths due to the higher levels of these elements in the irrigation wastewater. The findings of this study are in agreement with the results of Mostafazadeh-Fard et al. (2012), who observed that soil calcium and sodium decreased by 35.2% and 33.6%, respectively, in the magnetized water treatment compared to the non-magnetized water treatment. Saliha (2005) conducted a study on the physical and chemical properties of soil under the influence of a magnetic field and showed that the values of EC, pH, and $CaCO_3$ in the soil solution were significantly reduced in the magnetized water treatment. He attributed the high potential of magnetized water in washing soil salts to its effective role in increasing soil permeability.

The highest amounts of calcium and magnesium, equal to 17.39 and 18.34 meq/l respectively, were observed at a depth of 60–90 cm in soil irrigated with 100% treated wastewater. The increase in soil calcium content in wastewater-irrigated soils compared to well water is due to the higher amount of this element in the wastewater calcium (4.35 meq/l) compared to normal water (2.92 meq/l).

The results of the analysis of variance in Table 7 indicate that the effect of irrigation water and the mixing of water and wastewater on sodium and chloride at different soil depths is significant at 1% probability level. Additionally, the interaction effect of irrigation water and the mixing of water and wastewater on sodium and chloride is significant. The amount of soil sodium and chlorine at all depths (30–0, 60–30, and 90–60 cm) in the magnetized water treatment

Table 5 Analysis of variance the effect of various factors on the calcium and magnesium

Variations source	Degrees of freedom	Calcium			Magnesium		
		0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
Block	2	0.066^{ns}	0.069^{ns}	0.074^{ns}	0.061^{ns}	0.068^{ns}	0.079^{ns}
I	1	65.91**	74.48**	76.77**	79.42**	84.21**	90.08**
W	4	78.90**	86.44**	90.30**	86.77**	91.49**	92.96**
I×W	4	6.93**	9.02**	9.98**	7.70**	8.96**	10.39**
Error	18	0.488	0.542	0.598	0.672	0.703	0.782
Coefficient of variation	–	9.90	9.59	9.32	9.67	8.34	8.14

**, and ^{ns} indicate statistical significance at one% level, and no significant difference, respectively

Table 6 Comparison of the mean values of calcium and magnesium at different soil depths

Treatment	Ca (meq/l)			Mg (meq/l)		
	0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
I						
I1	9.40 b	10.09 b	10.55 b	12.39 b	12.47 b	12.45 b
I2	15.49 a	15.82 a	16.31 a	18.04 a	18.11 a	18.20 a
W						
W1	9.40 d	9.47 d	9.64 e	12.60 d	12.61 d	12.63 e
W2	10.01 d	11.25 c	11.43 d	13.48 d	14.02 c	13.65 d
W3	12.30 c	11.99 c	13.29 c	15.76 c	15.19 b	14.89 c
W4	14.58 b	15.73 b	15.90 b	16.93 b	16.93 a	17.11 b
W5	15.93 a	16.33 a	16.89 a	17.30 a	17.70 a	18.34 a

In each column, means with the same letter are not significantly different at P = 0.05 level was lower than that in the non-magnetized water treatment, and this difference was significant. On average, irrigation with magnetized water in the first and second years of cultivation resulted a reduction of 22.49% and 21.97% in soil sodium and a reduction of 26.48% and 28.64% in soil chloride, respectively (Table 8). Mostafazadeh-Fard et al. (2012) investigated the effect of magnetized water on soil salts at different depths under drip irrigation. They found that the sodium and chloride content in the magnetized water treatment decreased by 33.6% and 32.5%, respectively, compared to non-magnetized water. In treatments with higher wastewater mixing percentages, the sodium and chloride content increased in the soil at different depths due to the higher amounts of these elements in the wastewater used. The highest amount of sodium and chloride was observed at 22 and 17.30 meq/l per liter, respectively, at a soil depth of 60–90 cm in the treatment with 100% wastewater irrigation.

The results of the analysis of variance in Table 9 indicate that the effect of irrigation water and the mixing of water and wastewater on lead and cadmium at different soil depths is significant at 1% probability level. Additionally, the interaction effect of irrigation water and the mixing of water and wastewater on lead and cadmium is significant. The average amount of soil lead at the beginning and end

Table 7 Analysis of variance the effect of various factors on the sodium and chloride

Variations source	Degrees of freedom	Sodium			Chloride		
		0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
Block	2	0.069^{ns}	0.072^{ns}	0.077^{ns}	0.053^{ns}	0.059^{ns}	0.068^{ns}
I	1	88.99**	90.12**	92.78**	80.72**	82.66**	85.09**
W	4	95.03**	98.00**	99.85**	83.58**	86.81**	89.90**
I × W	4	11.05**	11.89**	12.73**	6.44**	7.50**	9.23**
Error	18	0.710	0.758	0.835	0.619	0.678	0.692
Coefficient of variation	–	17.68	18.11	15.02	15.45	15.30	13.76

**, and ^{ns} indicate statistical significance at one% level, and no significant difference, respectively

Table 8 Comparison of the mean values of sodium and chloride at different soil depths

Treatment	Na (meq/l)			Cl (meq/l)		
	0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
I						
I1	17.75 b	17.38 b	17.40 b	12.40 b	12.55 b	12.48 b
I2	22.34 a	22.45 a	22.53 a	17.32 a	17.36 a	17.74 a
W						
W1	17.06 d	17.12 d	17.15 c	12.35 c	12.45 d	12.20 e
W2	19.01 c	19.44 c	19.42 b	13.91 b	14.05 c	14.02 d
W3	19.39 c	20.09 bc	19.90 b	14.72 b	15.16 b	15.39 c
W4	20.95 b	21.98 a	21.36 a	16.35 a	16.38 a	16.44 b
W5	23.81 a	20.86 b	22.00 a	16.97 a	16.73 a	17.50 a

In each column, means with the same letter are not significantly different at $P = 0.05$ level

Table 9 Analysis of variance the effect of various factors on the lead and cadmium

Variations source	Degrees of freedom	Pb			cd		
		0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
Block	2	0.022^{ns}	0.029^{ns}	0.035^{ns}	0.0062^{ns}	0.0065^{ns}	0.0078^{ns}
I	1	13.28**	13.71**	15.18**	0.95**	1.02**	1.39**
W	4	20.22**	21.13**	21.88**	1.83**	1.96**	2.44**
I × W	4	4.58**	4.43**	5.19**	0.52**	0.59**	0.74**
Error	18	0.061	0.069	0.066	0.0059	0.0067	0.0078
Coefficient of variation	–	9.71	9.38	8.46	8.49	7.87	7.60

**, and ^{ns} indicate statistical significance at one% level, and no significant difference, respectively

Table 10 Comparison of the mean values of lead and cadmium at different soil depths

Treatment	Pb (mg/kg)			cd (mg/kg)		
	0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
I						
I1	2.21 b	2.23 b	2.26 b	0.021 b	0.021 b	0.021 b
I2	3.54 a	3.49 a	3.66 a	0.049 a	0.049 a	0.049 a
W						
W1	1.80 d	1.84 d	1.84 d	0.019 b	0.020 b	0.022 c
W2	2.11 cd	2.05 d	2.09 d	0.023 b	0.025 b	0.031 c
W3	2.51 c	2.71 c	2.73 c	0.034 ab	0.036 ab	0.044 b
W4	3.39 b	3.51 a	3.50 b	0.046 a	0.050 a	0.066 a
W5	4.56 a	4.19 b	4.64 a	0.053 a	0.061 a	0.069 a

In each column, means with the same letter are not significantly different at $P = 0.05$ level

of the experiment was 1.01 and 2.88 mg/kg, respectively (Table 10). Additionally, the average entry of lead from well water and treated wastewater into the soil was 1.02 and 13.15 µg/lit, respectively (Table 2). According to the World Health Organization's standard for soils contaminated with heavy metals, soil containing 36 mg/kg or less of lead is classified as low-pollution soil (Bull et al. 2020). Table 10 indicates that the use of treated wastewater has led to an accumulation of lead in the subsoil layers. Due to the toxicity of lead to humans and the resulting risks, limitations on the use of this wastewater for irrigation are mandatory, and its use must be managed. In other words, the use of alternate irrigation with well water and wastewater can prevent the accumulation of this toxic metal in the soil profile, enabling longer use of the soil for agriculture without the need for leaching.

In the magnetized water treatment, the amount of lead in the soil at all depths was less than that of the non-magnetized water treatment, and this difference was significant. On average, irrigation with magnetized water in the first and second years of cultivation led to a reduction of 35.25% and 37.45% in the amount of lead in the soil profile, respectively. The highest amount of lead, equal to 4.69 mg/kg, was observed in the surface layer of soil in the treatment with 100% irrigation with wastewater. The level of cadmium in both well water and wastewater sources were 0.01 and 0.025 µg/lit, respectively. Irrigation with various percentages of wastewater in all three depths caused an increase in cadmium accumulation in the soil, and this difference was statistically significant (Table 10). The reason for this could be the higher concentration of this element in the treated wastewater compared to well water. Chen et al. (2010) stated that irrigation with municipal wastewater leads to an increase in the accumulation index of soil pollutants such as copper, cadmium, lead, nickel, and zinc. They also stated that heavy metals such as cadmium and lead accumulate in soil over time due to their low mobility. The amount of cadmium in the soil at all depths was lower in the magnetized water than in the non-magnetized water, and this difference was statistically significant. On average, irrigation with magnetized water in the first and second years of cultivation resulted a reduction of 56.11% and 65.28% in cadmium content in the soil profile, respectively. The highest amount of cadmium, equal to 0.069 mg/kg, was observed in the subsoil layer of the 100% wastewater irrigation treatment.

It is true that irrigating with municipal wastewater leads to an increase in the accumulation index of heavy metal pollution in the soil, but heavy elements like cadmium, due to their low mobility, accumulate over time in the deeper layers of the soil, which has been the view of other researchers as well. However, just like lead, under conditions of using cadmium, irrigation with magnetized water also reduces the presence of cadmium in all depths of the soil. This is attributed to the magnetic field itself and was one of the objectives of the present study. It should also be noted that magnetized water has less surface tension and greater permeability and solubility than ordinary water, and this may have been the reason for the present occurrence. The amount of mobile heavy elements in the soil is a function of pH, clay content, organic matter, and cation exchange capacity, and as pH, carbonate, and soil organic matter increase, the mobility of heavy elements decreases. Therefore, acidic soils show very little ability to absorb and retain cadmium compared to neutral soils.

Maize yield and yield components

Weight of plant

According to the results of the analysis of variance (Table 11), the effect of irrigation water (magnetized and non-magnetized) on plant weight and the effect of water and wastewater mixing on plant weight were significant at the 1% and 5% probability levels, respectively, in both years of cultivation. The interaction effect of irrigation water and mixing water and wastewater on plant weight was not significant.

Table 11 Analysis of variance the effect of various factors on maize yield components

Variations source	Degrees of freedom	Weight of plant	Dry plant weight	Number of seed per ear	1000 grain weight
Block	2	24.96^{ns}	18.10^{ns}	19.85^{ns}	19.39^{ns}
I	1	354.49**	296.03**	311.40**	293.77**
W	4	43.55**	32.19*	39.08**	36.87*
I×W	4	30.08^{ns}	27.56^{ns}	29.11^{ns}	22.49^{ns}
Error	18	5.79	4.81	5.65	5.29
Coefficient of variation	-	16.52	18.09	17.33	16.28

*, **, and ^{ns} indicate statistical significance at one%, five% level, and no significant difference, respectively

The maximum plant weight was 848.99 gr obtained from the treatment with 100% wastewater, which showed an increase of 30.96% compared to the control treatment. Also, the application of magnetic field increased the fresh weight of the plants in magnetically treated wastewater by 12.1% and 13.62% in the first and second years of cultivation, respectively, compared to non-magnetized water treatments. The reason for the effect of magnetized water may be related to root growth and conductance, which increases nutrient uptake. Algozari and Yao (2006) reported that magnetized water leads to increased water penetration into the cell membrane and increased water and nutrient uptake in root cells.

Dry plant weight

The results of the analysis of variance presented in Table 11 indicate that the effect of irrigation water on dry plant weight was significant at 1% probability level; while, the effect of mixing water and wastewater on dry plant weight was significant at 5% probability. However, the interaction effect between irrigation water and mixing of water and wastewater on dry plant weight was not significant. The highest dry plant weight equal to 213.02 gr was obtained from the treatment of 100% wastewater, which had a 47.55% increase compared to the control treatment. Similar to the effect of wastewater on plant weight, the trend of dry plant weight was expected to be consistent with plant weight, as dry plant weight is derived from plant weight. The best performance was observed in the treatment of 100% wastewater, followed by mixing 75% wastewater and 25% well water, and mixing 50% wastewater and 50% well water, which had similar dry plant weights in one experimental group (Table 12).

Table 12 Comparison of the mean values of maize yield components

Treatment	Weight of plant (gr)	Dry plant weight (gr)	Number of seed per ear	1000 grain weight (gr)
I				
I1	798.06 a	185.43 a	670.71 a	271.09 a
I2	702.38 b	162.71 b	623.40 b	250.88 b
W				
W1	648.25 d	144.37 e	577.28 d	225.32 d
W2	709.23 c	159.71 d	614.09 c	241.07 c
W3	754.55 b	171.23 c	649.51 bc	256.44 c
W4	790.08 b	182.02 b	671.13 b	278.03 b
W5	848.99 a	213.02 a	723.26 a	304.06 a

In each column, means with the same letter are not significantly different at $P=0.05$ level

Number of seed per ear

The application of magnetic field increased the dry plant weight in magnetized treatments compared to non-magnetized treatments by 11.07% and 13.96% in the first and second years of cultivation, respectively. The comparison of the mean values of mixed water and wastewater treatments showed no significant difference between the 25% wastewater and 75% well water treatment and the 50% wastewater and 50% well water treatment in the first year. Additionally, there was no significant difference between the 50% wastewater and 50% well water treatment and the 75% wastewater and 25% well water treatment, but there was a significant difference between the rest of the mixed wastewater treatments. However, in the second year of cultivation, there was a significant difference between all treatments (Table 12). The use of wastewater led to an increase in biomass and green coverage in maize plants, and this increase was more evident in the 100% wastewater treatment than in other wastewater mixtures.

Number of seed per ear

According to the results of the analysis of variance, the effect of irrigation water on the number of seed per ear was significant at a 1% probability level, and the effect of mixing water and wastewater on the number of seed per ear was significant at a 5% probability level. Additionally, the interaction effect of irrigation water and mixing water and wastewater on the number of seed per ear was significant at a 1%

probability level. The maximum number of seed per ear was obtained from the treatment with 100% wastewater (723.26 gr), which showed a 25.28% increase compared to the control treatment. Moreover, by applying a magnetic field, the number of seed per ear in magnetized treatments increased by 7.54% and 7.59% in the first and second years of cultivation, respectively, compared to non-magnetized treatments. Magnetized water enhances the solubility of water, resulting in increased photosynthesis and growth of irrigated seeds with magnetized water and increased nutrient absorption from the soil. Podleoeny et al. (2004) reported an increase in pod number and yield of beans with the application of magnetized water. The results of the comparison of the mean effect of the treatments of mixing water and wastewater on the number of seed per ear showed that there was no significant difference between the treatments of 25% wastewater and 75% well water and 50% wastewater and 50% well water. Also, there was no significant difference between the treatments of 50% wastewater and 50% well water and 75% wastewater and 25% well water, but there was a significant difference between the other treatments of mixing water and wastewater (Table 12). The use of wastewater increased the number of seed per ear, and this increase was more evident in the treatment of 100% wastewater than in other water and wastewater mixtures. The use of wastewater and magnetic field during the growth and germination stages affected the potential for maize grain production during these stages, and by increasing the number of grains per row and the number of rows in maize, it directly affected the yield of the maize.

1000 grain weight

The results of the analysis of variance showed that the effect of irrigation water on the 1000 grain weight was significant at 1% probability level, and the effect of mixing water and wastewater on the 1000 grain weight was significant at 5% probability level (Table 11). Additionally, the interaction effect of irrigation water and mixing water and wastewater on the 1000 grain weight was also significant at 5% probability level. The highest 1000 grain weight, which was equal to 304.06 gr, was related to the treatment with 100% wastewater, showing a 34.94% increase compared to the control treatment. The comparison of the mean results showed that wastewater irrigation significantly increased the 1000 grain weight. The increase in the 1000 grain weight, as one of the main components of yield, led to an increase in crop yield under wastewater irrigation and the application of magnetic field. While under conditions without the use of wastewater and magnetic field, a lower 1000 grain weight was obtained. By applying the magnetic field, the 1000 grain weight in the magnetized treatments increased by 8.26% and 8.05% in the first and second years of cultivation, respectively, compared to non-magnetized treatments, and this increase was significant. The comparison of the mean of mixing water and wastewater treatments showed that the treatments with 25% wastewater and 75% well water and 50% wastewater and 50% well water did not have a significant difference, but the other treatments had significant differences with each other (Table 12). Mousavi and Shahsavari (2014) reported that the richness of treated wastewater in nitrogen, phosphorus, potassium, calcium, zinc, and iron elements compared to well water increased the 1000 grain weight of maize.

Biological yield

Based on the results of the analysis of variance, it is evident that the effect of irrigation water and the mixture of water and wastewater had a significant effect on biological yield at 1% probability level (Table 13). The interaction effect of irrigation water and the mixture of water and wastewater was significant on biological yield at a 5% probability level. According to Table 14, the highest biological yield was observed in the treatment with 100% wastewater, which had an increase of 30.14% compared to the control treatment, with a maximum yield of 44.68 tons per hectare. Since the highest components of biomass yield were obtained in the treatment with 100% wastewater and then in other percentages of wastewater mixed with well water, the biological yield, which includes all of them, followed this trend and is consistent with it. The results of the comparison of the mean effect of water and wastewater mixture treatments on

Table 13 Analysis of variance the effect of various factors on maize yield

Variations source	Degrees of freedom	Biological yield	Grain yield	Harvest index
Block	2	4.98^{ns}	0.49^{ns}	13.32^{ns}
I	1	14.21**	3.37**	2.09^{ns}
W	4	6.55**	0.89**	16.51*
I×W	4	6.98**	0.98*	20.32^{ns}
Error	18	1.88	0.25	4.01
Coefficient of variation	–	8.76	8.05	8.69

*, **, and ^{ns} indicate statistical significance at one%, five% level, and no significant difference, respectively

Table 14 Comparison of the mean values of maize yield

Treatment	Biological yield (ton/ha)	Grain yield (ton/ha)	Harvest index (%)
I			
I1	41.68 a	23.72 a	56.93 a
I2	37.49 b	21.48 b	57.29 a
W			
W1	34.33 e	19.73 d	57.47 d
W2	37.25 d	20.36 d	54.65 d
W3	39.76 c	22.60 c	56.84 c
W4	41.90 b	24.29 b	57.97 b
W5	44.68 a	26.02 a	58.23 a

In each column, means with the same letter are not significantly different at $P = 0.05$ level

biological yield showed that there was a significant difference between all treatments (Table 14).

Grain yield

The results of the analysis of variance showed that the effect of irrigation water and the mixing of water and wastewater on grain yield were significant at 1% probability level (Table 13). Additionally, the interaction effect of irrigation water and mixing of water and wastewater on grain yield was also significant at 5% probability level. The highest grain yield of 26.02 tons per hectare was related to the treatment of 100% wastewater, which showed a 31.88% increase compared to the control treatment. The comparison of mean results showed that irrigation with wastewater significantly increased grain yield. The comparison of mean treatments of mixing water and wastewater showed that there was no significant difference between the 25% wastewater mixed with well water treatment and the 75% well water treatment, but there was a significant difference between other treatments (Table 14). Applying a magnetic field resulted in a significant increase in grain yield in magnetized treatments compared to non-magnetized treatments in the first and second years of cultivation by 9.18% and 10.42%, respectively. In other words, the use of a magnetic field increased soil moisture and reduced soil profile salinity, which ultimately led to an increase in crop yield (Mostafazadeh-Fard et al. 2011; Hamza et al. 2021).

Harvest index

The results of the analysis of variance on harvest index show that the effect of irrigation water was not significant, but the effect of mixing water and wastewater was significant at 5% probability level (Table 13). The interaction effect between irrigation water and mixing water and wastewater on the harvest index was not significant. The highest harvest index of 58.23% was obtained in the treatment with 100%wastewater. This treatment showed a 1.32% increase compared to the control treatment (Table 14). Treatments with higher percentages of wastewater had higher biomass production and higher grain yield compared to other treatments, leading to differences in the harvest index. This difference may be due to a greater allocation of photosynthetic materials to the grain in these treatments.

Water use efficiency in maize

The results of the analysis of variance on various productivity of maize showed the effect of irrigation water and the mixing of water and wastewater were significant at 1% probability level (Table 15). The interaction effect of irrigation water and the mixing of water and wastewater on various productivity of maize was not significant. Grewal & Maheshwari (2011) investigated the effect of magnetic field on the yield of celery and beans under greenhouse cultivation conditions and showed that magnetized water increased the yield of celery by 23% and water use efficiency by 2%. The effect of magnetized water on bean also increased crop yield and water use efficiency compared to the control treatment. Similarly, Lin & Yotvat (1990) reported an increase in water use efficiency in various agricultural crops due to the magnetic field effect.

Table 15 Analysis of variance the effect of various factors on maize productivity

Variations source	Degrees of freedom	Biological productivity	Physical productivity	Productivity of wet fodder	Productivity of dry fodder
Block	2	3.11^{ns}	2.08^{ns}	1.15^{ns}	0.98^{ns}
I	1	12.03**	7.94**	3.96**	1.68**
W	4	5.12**	2.97**	1.59**	0.77*
I×W	4	5.33^{ns}	2.74^{ns}	0.95^{ns}	0.42^{ns}
Error	18	1.87	1.12	0.45	0.10

*, **, and ^{ns} indicate statistical significance at one%, five% level, and no significant difference, respectively

Biological productivity

The results of the comparison of the mean biological productivity of the water and wastewater mixing treatments show that all treatments have a significant difference with each other. The use of wastewater increased the green cover weight in maize plants, and this increase was more noticeable in the 100% wastewater treatment compared to other water and wastewater mixing percentages. The maximum amount of biological productivity, equal to 3.66 kg/m^3, was achieved in the 100% wastewater treatment, which showed a 32.13% increase compared to the control treatment (Table 16).

Using a magnetic field breaks hydrogen bonds and van der Waals forces between water molecules, which reduces surface tension and increases water solubility. As a result, the necessary mineral salts for plant growth dissolve well in water, leading to improved plant growth and yield. Applying a magnetic field increased the biological productivity of magnetized treatments by 10.33% in the first year and 11.51% in the second year compared to non-magnetized treatments. Due to magnetization, changes in the physical and chemical properties of water occur, and the molecules become smaller, leading to increased water absorption by the plant, resulting in increased water productivity. The results of this study are agreement with El Sayed (2014), showed that using magnetized water increases the leaf surface of lima beans and peas, which can increase biological productivity.

Physical productivity

The results of the comparison of the mean physical productivity of the water and wastewater mixing treatments show that all treatments have significant differences with each other. The maximum physical productivity of 2.03 kg/m^3 was achieved in the 100% wastewater treatment, which showed a 28.48% increase compared to the control treatment (Table 16). In the wastewater treatment, the amount of chlorophyll in the leaves increased, resulting in increased production of sap and the speed of grain filling, ultimately increasing the yield. Additionally, an increase in the leaf area index led to an increase in photosynthesis and transfer of materials to the grains during the filling stage, resulting in increased weight (Asgari et al. 2007). The use of wastewater and magnetic fields during the growth and development stages of maize has the potential to affect grain production, increasing the number of grains per row and thus directly increasing the yield and physical productivity. By applying magnetic fields, the average physical productivity in magnetized treatments increased by 9.35% and 10.92% in the first and second years of cultivation, respectively, compared to non-magnetized treatments. Magnetized water increases the solubility of water, leading to increased photosynthesis and growth of irrigated seeds. During this process, nutrient absorption from the soil is also increased, resulting in increased physical productivity. These findings are consistent with those of Belyavskaya (2004), reported that applying magnetic fields makes water molecules more regular and occupies less space, leading to an increase in the plant's water absorption capacity and water use efficiency.

Productivity of wet fodder

The results of the comparison of the mean productivity of wet fodder of the water and wastewater mixing treatments show that the treatments of mixing wastewater and well water in the ratio of 50% wastewater and 50% well water, 75% wastewater and 25% well water, and 25% wastewater and 75% well water did not have a significant difference. However, the rest of the treatments showed a significant difference. The maximum amount of productivity of wet fodder, equal to 1.70 kg/m^3, was obtained from the treatment of 100% wastewater, which showed a 45.23% increase

Table 16 Comparison of the mean values of maize productivity

Treatment	Biological Productivity (kg/m^3)	Physical productivity (kg/m^3)	Productivity of wet fodder (kg/m^3)	Productivity of dry fodder (kg/m^3)
I				
I1	3.39 a	1.93 a	1.50 a	1.02 a
I2	3.04 b	1.74 b	1.33 b	0.89 b
W				
W1	2.77 e	1.60 d	1.17 d	0.79 e
W2	3.03 d	1.69 c	1.34 c	0.86 d
W3	3.21 c	1.86 b	1.37 c	0.93 c
W4	3.40 b	2.01 a	1.49 b	1.05 b
W5	3.66 a	2.02 a	1.70 a	1.14 a

In each column, means with the same letter are not significantly different at $P = 0.05$ level compared to the control treatment (Table 16). The increase in productivity of wet fodder in the wastewater treatment compared to the control treatment is due to the provision of necessary plant nutrients by wastewater. Tavassoli et al. (2010) showed that productivity of wet fodder under wastewater irrigation conditions had an 8.25% increase compared to control treatment. Also, applying a magnetic field in the first and second years of cultivation increased the productivity of wet fodder by 10.07% and 12.78%, respectively, compared to non-magnetized treatments. The magnetic field reduces the surface tension and viscosity of water, resulting in faster water penetration into the seed. Additionally, it helps to mitigate the effects of drought and salinity stress. (Yao et al. 2005).

Productivity of dry fodder

The results of the comparison of the mean productivity of dry fodder of the water and wastewater mixing treatments show that the treatment of mixing wastewater and well water with a ratio of 50% wastewater and 50% well water did not have a significant difference compared to the treatment of 25% wastewater and 75% well water or 75% wastewater and 25% well water. However, there was a significant difference in the productivity of dry fodder between the other treatments. In the second year of cultivation, there was a significant difference among all treatments. The maximum productivity of dry fodder of 1.14 kg/m^3 was obtained from the treatment of 100% wastewater, which showed a 44.3% increase compared to the control treatment. Similarly, to the effect of wastewater on the productivity of wet fodder, the productivity of dry fodder also followed a similar trend. This is because the productivity of dry plants is derived from the productivity of wet plants, and the yield changes proportionally.

The percentage increase in the parameters of maize yield in the magnetized treatment compared to the non-magnetized treatment in different mixtures of wastewater and well water is presented in Table 17. The minimum increase in physical productivity was related to the well water treatment, which showed an 8.63% increase in magnetized conditions compared to non-magnetized conditions. The maximum increase in productivity was related to productivity of dry fodder, which showed a 12.71% increase in magnetized conditions compared to non-magnetized conditions. The application of a magnetic field, by increasing plant yield, leads to an increase in productivity.

Table 17 Percentage increase in corn product productivity in magnetic treatment compared to non-magnetic treatment in different mixtures of water and wastewater

Treatment	Biological Productivity (kg/m^3)	Physical productivity (kg/m^3)	Productivity of wet fodder (kg/m^3)	Productivity of dry fodder (kg/m^3)
W1	9.67	8.64	9.12	10.38
W2	9.99	8.90	9.53	10.86
W3	10.41	9.33	10.01	11.56
W4	10.70	9.88	10.69	12.19
W5	11.18	10.31	11.20	12.71

Heavy metal absorption by maize

The concentration of heavy metals in the aerial parts of maize plant

Based on the results of the analysis of variance presented in Table 18, the effect of irrigation water and the effect of water and wastewater mixing on the concentration of lead, cadmium, zinc, and nickel in the aerial parts of maize plants were significant at 1% and 5% probability levels, respectively, in both years of cultivation. The interaction effect of irrigation water and mixing water and wastewater on the concentration of lead, cadmium, zinc, and nickel in the aerial parts of maize plants was not significant.

Comparison of the mean values of magnetized and non-magnetized treatments revealed that the concentration of all heavy metals was lower in magnetized treatments and this difference was significant at 5% probability level (Table 19). In the first year of cultivation, applying a magnetic field resulted in a reduction of 17.84%, 15.9%, 14.22%, and 13.92% in the concentration of lead, cadmium, zinc, and nickel in the aerial parts of the plant, respectively, compared

Table 18 Analysis of variance the effect of various factors on the concentration of heavy metals in the aerial parts of maize

Variations source	Degrees of freedom	Lead	Cadmium	Zinc	Nickel
Block	2	24.09^{ns}	10.56^{ns}	38.02^{ns}	19.97^{ns}
I	1	373.17**	245.68**	490.21**	286.39**
W	4	33.12*	19.15*	51.33*	29.05*
I×W	4	21.09^{ns}	9.39^{ns}	22.40^{ns}	15.91^{ns}
Error	18	6.39	3.82	7.45	4.98

*, **, and ^{ns} indicate statistical significance at one%, five% level, and no significant difference, respectively

Table 19 Comparison of the mean values of heavy metals in the aerial parts of maize

Treatment	Lead	Cadmium	Zinc	Nickel
I				
I1	11.01 b	0.34 b	48.03 b	2.98 b
I2	13.45 a	0.49 a	61.19 a	3.74 a
W				
W1	3.76 e	0.11 d	18.81 e	1.05 e
W2	6.68 d	0.23 c	36.33 d	1.98 d
W3	11.49 c	0.42 b	55.27 c	3.33 c
W4	17.87 b	0.64 a	74.19 b	4.72 b
W5	21.35 a	0.68 a	88.45 a	5.72 a

In each column, means with the same letter are not significantly different at $P=0.05$ level

to the non-magnetized treatment. In the second year, the concentration of lead, cadmium, zinc, and nickel in the aerial parts of the plant also showed a reduction of 18.14%, 30.61%, 21.5%, and 20.32%, respectively, compared to the non-magnetized treatment. As it is evident, the greatest and lowest effects of the magnetic field were related to lead and nickel. The lower amount of heavy metals present in the aerial parts of the plant in the magnetized treatment compared to the non-magnetized treatment was due to the leaching of salts and heavy metals from the magnetized wastewater.

The results of the comparison of the mean values of mixing water and wastewater indicate that there is a significant difference between all mixing treatments at 5% probability level. The maximum concentration value of zinc was found to be 93.19 mg/kg, which was 3.94% higher than the control treatment. The increase in soil organic matter by wastewater has led to an increase in the absorption of lead, cadmium, zinc, and nickel by plant. The results of this section of the study are agreement with the findings of Ahmad et al. (2011). They found that an increase in the percentage of wastewater in irrigation water in Pakistan caused an increase in the amount of chromium, cadmium, and lead in the aerial parts of canola. Lead accumulated in canola between 0.08 and 1.52 mg/kg, which was within the permissible limit. The lowest heavy metal absorption concentration in the aerial parts of the plant was related to cadmium, which had the highest amount in the treatment with 100% wastewater and was 6.08 times higher than the control treatment (Table 19). Marchiol et al. (2004) with the study of phytoremediation of heavy metal-contaminated soil using canola and turnip, reported that the nickel concentration in the aerial parts of turnip was higher than canola. The transfer factor for zinc and cadmium was higher than lead and chromium, and for copper and nickel, it was moderate.

Table 20 Analysis of variance the effect of various factors on the concentration of heavy metals in maize grains

Variations source	Degrees of freedom	Lead	Cadmium	Zinc	Nickel
Block	2	24.87^{ns}	20.45^{ns}	36.08^{ns}	14.93^{ns}
I	1	391.20**	352.14**	402.36**	191.44**
W	4	30.85**	31.06**	42.55**	26.97**
I×W	4	22.11^{ns}	16.89^{ns}	15.44^{ns}	8.74^{ns}
Error	18	6.19	4.30	4.28	3.09

*, **, and ^{ns} indicate statistical significance at one%, five% level, and no significant difference, respectively

The concentration of heavy metals in maize grains

The results of the analysis of variance on the effects of irrigation water and the mixing of water and wastewater on the concentration of heavy metals in maize grain are presented in Table 20. According to the results of Table 20, the effects of irrigation water and mixing of water and wastewater on the concentration of lead, cadmium, zinc, and nickel in maize grain were significant at 1% probability level. However, the interaction effect of irrigation water and mixing of water and wastewater on the concentration of these metals in maize grain was not significant.

Based on Table 21, the results of the comparison of the mean values between magnetized and non-magnetized treatments showed that the concentration of lead, cadmium, zinc, and nickel in the magnetized treatments was lower than in the non-magnetized treatments, and this difference was significant at 5% probability level. By applying a magnetic field in the first year of cultivation, the concentration of lead, cadmium, zinc, and nickel in the grains decreased by 13.97%, 14.52%, 12.95%, and 13.71%, respectively, compared to the non-magnetized treatment. In the second year of cultivation,

Table 21 Comparison of the mean values of heavy metals in maize grains

Treatment	Lead	Cadmium	Zinc	Nickel
I				
I1	24.11 b	4.02 b	40.55 b	1.84 b
I2	30.08 a	5.01 a	47.98 a	2.39 a
W				
W1	9.19 e	1.04 e	15.10 e	0.66 d
W2	21.59 d	2.85 d	28.70 d	1.43 c
W3	27.43 c	4.69 c	44.01 c	2.28 b
W4	34.29 b	6.40 b	60.26 b	2.99 a
W5	42.97 a	7.59 a	73.34 a	3.21 a

In each column, means with the same letter are not significantly different at $P=0.05$ level the concentration of these metals in the grains decreased by 19.84%, 19.76%, 15.48%, and 23.01%, respectively, compared to the non-magnetized treatment. The maximum and minimum effects of the magnetic field were related to cadmium and zinc metals. Magnetized water reduces the absorption of elements in the grains by reducing the salts present in the soil.

The results of the comparison of the mean values between magnetized and non-magnetized treatments showed that there is a significant difference among all treatment groups at 5% probability level (Table 21). The absorption of all elements in maize grains was highest in the 100% wastewater treatment. With an increase in the percentage of wastewater used for irrigation, the biological yield and grain yield also increased, and as a result, the absorption of heavy metals also increased proportionally. The maximum concentration of zinc was found to be 74.32 mg/kg, which was 4.93 times higher than the control treatment. The lowest absorption concentration of heavy metals in maize grains was for nickel, which had the highest concentration in the 100% wastewater treatment, and was 5.64 times higher than the control treatment. The absorption of heavy metals in the aerial parts and grain of maize showed that the concentration of lead and cadmium in the grain was higher than in the aerial parts, but the concentration of the zinc and nickel in the aerial parts was higher than in the grain.

The maximum allowable amount of lead in plants for human consumption is 5 mg/kg (Alloway 1990), which, based on the results of Tables 19 and 21, exceeds the allowable limit in all water and wastewater mixtures. The amount of lead in contaminated plants is 30–300 mg/kg. The permissible amount of cadmium in plants for human consumption is 0.1 mg/kg, in which case the soils should not contain more than 1.5–2 mg/kg of the cadmium element, which is less in sandy soils.

The allowable limit of zinc in plants for human consumption is 200 mg/kg, which based on the concentration of aerial parts and grains obtained in this study, is within the permissible limit. The amount of zinc in contaminated plants is 100–400 mg/kg (Alloway 1990), and according to the results of this study, using more than 25% of wastewater for maize plants causes contamination of maize plants with zinc. The average amount of nickel that daily enters the human body through nutrition is 400–500 µg.

The amount of nickel in contaminated plants is 10–100 mg/kg, which according to the values in Tables 19 and 21, indicates that the concentration of the nickel is within the permissible limit.

Overall, the results indicate that, contrary to the low concentration of heavy metals in wastewater, the amounts of these elements have increased in the aerial parts and grains of the plant, and the concentration of some elements has exceeded the permissible limit for human consumption in plants. Soils with high concentrations of heavy metals and low acidity pose the greatest risk to humans. As long as the acidity does not decrease, the risk of dissolution and movement of heavy metals and their absorption by plants is low. Therefore, the environmental hazards of using wastewater for plant irrigation should be taken into account.

Conclusion

1. The use of unconventional water sources, especially wastewater, is one of the main solutions to alleviate the water shortage in developing countries for increasing the cultivated area and ensuring food security. However, one of the fundamental environmental challenges is the gradual increase in the concentration of heavy metals in soil and the consequent contamination of crops with these metals. The results showed that irrigation with various mixing ratios of well water and wastewater under magnetic field conditions had different effects on the chemical properties and heavy metal concentrations of soil. The use of magnetized water led to a significant reduction in soil salts and heavy metals at different depths. On average, irrigation with magnetized water resulted in a reduction of 31.74% in electrical conductivity, a reduction of 36.62% in calcium, a reduction of 31.06% in magnesium, a reduction of 22.23% in sodium, a reduction of 27.56% in chlorine, a reduction of 36.35% in lead, and a reduction of 60.69% in cadmium in the soil profile. Therefore, it is recommended to use magnetized water technology to control salinity in soils that are constantly irrigated with wastewater, considering the type of crop and its salt tolerance threshold.
2. In recent years, the increase in demand and decrease in the supply of water resources has put immense pressure on water resources and caused irreversible damage to surface and groundwater resources. This has resulted in limitations on drinking water, agriculture, and industrial use. Under such circumstances, reuse of wastewater and unconventional water sources is essential as a primary solution to address the water scarcity challenge in the agriculture sector. Wastewater can be used as a source of irrigation in the region due to its richness in plant nutrients such as nitrogen, phosphorus, and other high and low-consuming elements. The second objective of this study was to investigate the effect of irrigation with magnetically treated wastewater on the yield and yield components of maize plants. The results showed that irrigation with magnetically treated wastewater increased the yield of maize, with the highest and lowest increases in the weight of plant and number of grains per ear being 12.86% and 7.56%, respectively. The use

of wastewater also increased all yield components of maize, with the highest and lowest increases in dry plant weight and number of grains per ear being 47.55% and 25.28%, respectively. By applying a magnetic field, better absorption of soil nutrients can reduce the use of fertilizers.

3. Using wastewater can increase plant-accessible water by changing the physical properties of soil, which will lead to water and soil resource sustainability. This study was conducted with the aim of investigating the effect of magnetic-treated wastewater irrigation on various yield indices of maize. The results showed that irrigation with different mixtures of well water and wastewater, under magnetic field conditions, significantly increased all yield indices of maize. Moreover, irrigation with magnetic-treated wastewater increased water use efficiency of maize, with the highest and lowest increases in productivity of dry fodder and physical productivity, respectively, at 13.04% and 10.13%. Also, using wastewater increased all yield indices of maize, with the highest and lowest increases in productivity of wet fodder and biological productivity, respectively, at 31.03% and 27.69%. By applying a magnetic field, better absorption of soil nutrients and improved water holding capacity in soil can increase water use efficiency of maize and improve irrigation management using magnetized water technology for more effective and economical use of limited water resources.
4. Finally, the fourth objective of this study was to investigate the effect of magnetically treated wastewater irrigation on heavy metal uptake by maize plants. The results showed that irrigation with different water and wastewater mixtures, under the influence of magnetic field in field conditions, significantly reduced heavy metal concentration in maize plants. Also, the use of wastewater led to an increase in lead, cadmium, zinc, and nickel, with the highest levels observed in the 100% wastewater treatment. The uptake of heavy metals by plants in large amounts leads to contamination of the human and animal food chain.

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Data availability The data presented in this study are available in the article. Also, the datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the author.

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