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CHARACTERIZATION AND RISK ASSESSMENT OF WASTEWATER FOR AGRICULTURAL IRRIGATION: A STUDY OF JHELUM DISTRICT, PUNJAB, PAKISTAN

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Abstract

Over the last decade, the rapid growth of population, urbanization, industrialization, increased demand for water and energy for a better quality of life, has been the talk of the town these days, which illustrates the future of wastewater in developing countries. The sudden growth in population and the mismanagement of water put stress on the supply of water, resulting in the reuse of untreated wastewater for agriculture. This will affect other life activities, posing a significant risk to global food security. The wastewater itself contain the nutrient which can be used by the plant for their growth but it also contain the chemicals and heavy metals which pose a greater negative impact on environment and human health. The food irrigated by the wastewater is consumed by human, and then it becomes a part of the food chain and causes health issues. Present research is carried out for the characterization and risk assessment of wastewater at different locations of Jhelum district, Punjab, Pakistan. Different parameters were analyzed which show that majority of samples have a concentration of pH from (7.96-8.74), temperature (31-38°C), which is under acceptable limit by the national environment quality standard of Ph (6.5-10) and temp (40°C) respectively, Sodium (139.75-172.50mgL-1), and heavy metals such as iron (0.273-0.473 mgL-1), manganese (0.048-1.35 mgL-1) within standard limits. However, due to the contamination and leakage of the sewage system and mixing of different solvents in water, resulting in an increase in the concentration of residual sodium carbonate, heavy metals such as lead, and total dissolved solids, more than the accepted limits of the national environmental quality standard. Due to the contamination of water the prevalence risk of waterborne diseases like cholera, typhoid, dysentery, and diarrhea increases. Regular monitoring of the quality of water using physicochemical parameters will provide a better quality of public health and the environment.

Keywords: *Heavy metals, Jhelum, Risk assessment, Waste water*

INTRODUCTION

Water is the only common substance naturally found in all three states of matter, and it is essential for all life on Earth. Water usually makes up 55% to 78% of the human body (1). Water is the part and parcel of universe. A prominent Quranic verse about water, emphasizing its role in creation, is "And We created from water every living thing" (Surah Al-Anbiya, 21:30). Similarly, "Water is mentioned numerous times in the Quran. Allah SWT categorizes water into its different properties. He differentiates the rain that falls from the sky as purified water, water from the spring as sweet, seawater as salty and bitter and mentions of water that flows from rocks. He speaks of the barrier between freshwater and salt water as well.

The global shortage of freshwater and its contamination by various pollutants have emerged as critical concerns due to their significant socioeconomic implications. In light of escalating freshwater scarcity, especially in arid and semi-arid regions, farmers are increasingly turning to wastewater for agricultural purposes. Wastewater often contains vital inorganic and organic nutrients that support plant growth and metabolism. However, its use also raises serious concerns related to hygiene, environmental safety, and public health, primarily due to the presence of toxic elements such as heavy metals. Pakistan is currently grappling with a severe freshwater crisis, leading to the widespread use of untreated wastewater in agriculture (2).

Currently, over 75% of groundwater is used for irrigation, and the ongoing depletion of these water resources poses a significant threat not only to economic stability but also to national food security. Freshwater consumption has been increasing at nearly 1% per year, driven by socio-economic development and shifts in consumption patterns, including changes in diets. Agriculture accounts for about 70% of global freshwater withdrawals, while industrial (around 20%) and domestic (approximately 10%) uses are becoming increasingly important contributors to rising water demand. As economies industrialize, populations urbanize, and water supply and sanitation systems expand, the demand for water continues to grow. However, the impact of population growth is less pronounced in regions with the lowest per capita water use, which are often the regions experiencing the fastest population increases (2). In countries such as China, India, Pakistan, Egypt, and Morocco, the practice of using wastewater for irrigation is common, especially in areas facing water scarcity. In these regions, where freshwater resources are limited, farmers often turn to wastewater as a viable alternative to meet their irrigation needs. Wastewater contains various nutrients, such as nitrogen, phosphorus, and potassium, which are essential for plant growth. As a result, it provides an additional source of fertilizer, reducing the need for expensive chemical fertilizers. However, while wastewater can be a valuable resource, it also carries significant risks. The water may contain harmful pathogens, heavy metals, and other toxic substances that can contaminate the soil, crops, and ultimately, the food supply. Consuming crops irrigated with contaminated wastewater can lead to health problems, including gastrointestinal diseases, exposure to carcinogens, and other long-term health effects. In regions with limited access to clean water, the use of wastewater for irrigation represents a complex trade-off between addressing immediate water needs and managing the potential health and environmental risks associated with contamination (3).

Toxic heavy metal contamination in water is a significant public health issue in Pakistan. The country ranks 80th out of 122 countries in terms of access to safe drinking water, with both surface and groundwater resources increasingly contaminated, often exceeding the safety limits established by the World Health Organization (WHO) and the Pakistan Environmental Protection Agency (Pak EPA). Health risk indicators, such as Chronic Daily Intake (CDI) and the Health Risk Index (HRI), frequently surpass recommended safety thresholds. The primary contributors to water contamination are industrial effluents, improper waste disposal, and the extensive use of agrochemicals. The buildup of heavy metals in water sources poses severe risks to both human health and the surrounding ecosystems (4).

The problem of heavy metal pollution is becoming more widespread worldwide. Heavy metals are naturally occurring elements found in the Earth's crust. However, when present in excessive quantities, they can pose serious risks to both human health and the environment. Some heavy metal compounds are resistant to degradation and can accumulate in living organisms when they enter the food chain. These metals can enter the environment through natural processes, as well as human activities such as waste disposal, industrial manufacturing, and mining (5, 6). Heavy metals are naturally occurring elements that, when present in elevated concentrations, can cause substantial harm to human health, even with limited exposure. These metals are termed "heavy" due to their high atomic mass and density, which often correlates with their toxicological potential. The most concerning heavy metals in drinking water include cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and chromium (Cr). These metals can negatively impact various physiological systems, such as the nervous, renal, and cardiovascular systems. Prolonged exposure to certain heavy metals may also lead to carcinogenic effects and impair developmental, neurological, and immune system functions (7, 8).The rapid expansion of human activities, including industrialization, urbanization, agriculture, and other commercial ventures, has created significant pressure on water supply demands. Industrial wastewater contamination presents a major risk to both human and environmental health, particularly in developing countries (9, 10).

In agricultural areas irrigated with industrial wastewater, the soils often accumulate high concentrations of heavy metals, which then bio accumulate in plants. These metals are transferred through the food chain, leading to considerable health risks for consumers. While the average concentrations of heavy metals such as chromium, copper, lead, and nickel in soils generally remain within permissible limits, the significant transfer of these metals from soil to plant, driven by biological magnification, raises serious concerns regarding their long-term health impacts (11, 12). The present study was conducted for Jhelum district, where sewage disposal is a main problem.

The objectives of this study were to characterize wastewater through physicochemical analysis and to assess the health risks associated with water contamination based on the perceptions of local residents in the Jhelum region.

MATERIALS AND METHODS

TARGET AREA AND SAMPLING SITES

The target area for this study was Jhelum, a city located approximately 120 km from Islamabad, situated on the banks of the Jhelum River. With a population of around 1,382,308, Jhelum spans an area of approximately 3,587 square kilometers (13). This region is an ideal location for studying wastewater due to its population density and proximity to the river, which plays a crucial role in the water quality and wastewater management of the area.

SAMPLE COLLECTION

Water samples were collected from various locations within Jhelum, as detailed in Table I. The waste water samples which have been collected from the different sites of Jhelum are abbreviated as "A" (Table I). Each sample was stored in 500mL polystyrene bottles, which were labeled with a unique identification code. Two samples were collected from each site: Sample No.1 for the analysis of basic parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS), and Sample No. 2 for the analysis of heavy metals. To prevent contamination, the bottles used for heavy metal sample collection were thoroughly washed with distilled water, then treated with a 5% nitric acid (HNO_3) solution for preservation, particularly of trace elements crucial for heavy metal analysis (10, 14).

The preliminary preparation of the water samples for basic parameter analysis was conducted at the Soil and Water Testing Laboratory in Jhelum. Following this, the samples were sent to the Soil and Water Testing Laboratory in Mandi Baha ud Din for the determination of heavy metal concentrations. Each sample was carefully labeled with its unique code. After collection, the samples were refrigerated at 4°C in an ice bag to prevent any changes in chemical composition and ensure the integrity of the samples.

To maintain quality control during sample collection and handling, all necessary precautions were taken to minimize contamination. Equipment was regularly calibrated, and the accuracy of analytical results was censured by analyzing blank and replicate samples under identical conditions. All chemicals and reagents used were of analytical reagent grade. Glass and plastic ware were thoroughly cleaned by soaking in 14% HNO_3 overnight, followed by multiple rinses with deionized water. During transport, samples were kept in insulated containers to avoid contamination or evaporation, and all samples were analyzed within 24 hours of collection (15).

Table I. Sampling sites of Jhelum

Jehlum cantonment A1	Phulery Sydan A6	Pandori A11	Bishan daur A16,
Kalan gujran A2	Nagial A7	Nara A12	Nakka Kalan A17
Muftian A3	Khukha A8	Kohali A13	Chakri rajgan A18
Dina city A4	Sanghoi A9	Dharyala Jalap A14	Mamyan A19
Domeli A5	Fariq A10	Garh Mahal A15	Aima bari A20

LABORATORY ANALYSIS

The collected wastewater samples were analyzed in the laboratory for physicochemical parameters according to the guidelines set by the Soil Fertility Research Institute (SFRI), Punjab, Lahore. Key parameters such as pH were measured using a pH meter (Thermo Scientific) following standard methods. Total dissolved solids (TDS) and electrical conductivity (EC) were determined using a portable EC meter (Orion Star A0151). Additionally, parameters including sodium, carbonate, calcium, magnesium, bicarbonate, and chloride were analyzed using the water corrosion mineral scale residual sodium carbonate (RSC) method and the sodium adsorption ratio (SAR), as per the SFRI Guide (16).

For the determination of various metal ions, such as copper (Cu), manganese (Mn), lead (Pb), iron (Fe), zinc (Zn), and aluminum (Al), an Atomic Absorption Spectrophotometer (AAS, iCE 3000 Series Thermo Scientific with VP 100 Vapor System) was used. Specific hallow cathode lamps were used for each metal e.g, Copper (Cu) at 324.8 nm, Cadmium (Cd) at 228.8 nm, Lead (Pb) at 217.0 nm, Zinc (Zn) at 213.9 nm, Mercury (Hg) at 253.6 nm, Chromium (Cr) at 257.9 nm, Iron (Fe) at 248.3 nm, and Nickel (Ni) at 232.0 nm (Thermo Fisher, 2011) (17).Due to budgetary constraints, only a subset of randomly selected water samples were analyzed for heavy metals.

STATISTICAL ANALYSIS

The data obtained on physicochemical properties and heavy metal concentrations from the collected wastewater samples were statistically analyzed using Minitab statistical software (MINITAB® Release 14.1, Minitab Inc., State College, PA, USA).

RESULTS AND DISCUSSIONS

The water samples from various sites exhibited a color range from yellow to light yellow (Table II). The pH levels of the samples ranged from 7.95 to 9.22, which fall within the acceptable standard range of 6-10 for water pH, as set by the Pakistan National Environmental Quality Standards and the World Health Organization. The highest pH (9.22) was recorded at site A13 (Kohali), which may be attributed to factors such as agricultural runoff, the percolation of sewage water, the use of artificial fertilizers, alkaline detergents in wastewater, leaching of waste, and elevated nutrient levels due to the use of chemical solvents like cleansing agents. In contrast, the lowest pH of 7.95 was observed at site A20 (Aima Bari), possibly due to the use of phosphoric fertilizers.

The temperature of the analyzed water samples ranged from 31°C to 38°C, which is within the acceptable limit of 40°C according to the Pakistan National Environmental Quality Standards and the World Health Organization. The highest temperature, 38°C, was recorded at sites A4 (Dina City), A7 (Nagial), A12 (Nara), A13 (Kohali), and A19 (Mamyan). The lowest temperature, 31°C, was noted at site A10 (Faqir), with similar temperatures observed at sites A1, A5, A6, A10, and A18.

Electrical conductivity (EC) measures the amount of dissolved salts and minerals in water, indicating its ability to conduct electricity. The EC values of the water samples from the city of Jhelum ranged from 905.5 to 1421.75 µS/cm, as shown in Table II. These values exceed the standard limit of 1000 µS/cm, as defined by the Pakistan National Environmental Quality Standards. The highest EC value, 1421.75 µS/cm, was recorded at site A13 (Kohali), which may be due to factors such as agricultural runoff, percolation of sewage water, rainfall, the disposal of municipal wastewater in open areas without prior treatment, or leaching of waste into groundwater (18). In contrast, the lowest EC value of 905.5 µS/cm was observed at site A1 (Jhelum Cantonment).

The majority of the samples had total dissolved solids (TDS) within the standard range of approximately 3500 mgL^{-1}, as set by the Pakistan National Environmental Quality Standards and the World Health Organization for irrigation and other purposes. The highest TDS value, 2799.25 mgL^{-1}, was reported at site A13 (Kohali), while the lowest TDS value, 816.5 mgL^{-1}, was recorded at site A8 (Khukha). Several studies (12) have suggested that elevated TDS values in wastewater samples can result from activities such as the cleaning of reactors, softeners, and the backwashing of filters. In agricultural fields, TDS plays a vital role in plant growth and crop yield. However, higher TDS levels can negatively impact crop production, leading to stress on food production systems (18).

Table II. Analysis of physico-chemical properties of sewage water samples of target areas of Jhelum

Sample Sites	Color	Odor	tem. (°C)	pH	EC (μs/cm)	TDS	HCO3	Na+	K+	Ca+	Mg+	SAR	RSC (meL^{-1})
						(mgL^{-1})							
A1	L/Yellowish	NO	31	8.52	905.50	1783.75	474.75	161.75	6.775	335.50	181.50	5.638	1.148
A2	L/Yellowish	NO	32	8.15	1004.50	961.75	524.25	139.75	11.450	252.25	156.75	5.625	2.905
A3	L/Yellowish	NO	34	8.25	1050.00	1955.00	547.00	149.25	11.600	262.75	156.50	5.710	3.650
A4	L/Yellowish	NO	38	8.32	1107.00	990.75	575.50	158.25	14.425	265.00	169.25	6.333	4.208
A5	Blackish	Offensive	31	8.42	1172.50	1883.75	608.25	172.50	14.875	279.50	179.75	5.750	1.050
A6	Blackish	Offensive	31	8.32	1064.00	944.75	554.00	144.25	12.250	259.25	160.25	5.638	1.250
A7	L/Yellowish	Offensive	38	8.47	1153.00	1939.25	598.50	162.25	12.175	281.25	176.50	4.853	-2.428
A8	L/Yellowish	NO	36	8.72	1011.00	816.50	277.50	159.75	5.125	143.50	100.00	4.975	-3.193
A9	Blackish	Offensive	37	8.85	1100.50	1819.25	322.25	172.25	3.025	168.50	119.50	5.275	-1.710
A10	Yellowish	NO	31	8.95	1049.00	841.50	296.50	163.00	4.475	134.50	92.25	4.423	0.938
A11	L/Yellowish	NO	32	8.90	1159.50	833.25	323.00	177.00	5.175	154.50	105.75	3.708	-0.233
A12	Yellowish	NO	38	9.07	990.50	1801.25	267.25	173.00	4.625	132.50	81.50	3.438	-3.548
A13	Yellowish	NO	38	9.22	1087.50	2799.75	315.75	184.50	5.375	157.00	101.25	3.750	-2.328
A14	Yellowish	NO	34	8.02	1184.50	2581.00	364.25	141.25	3.650	132.50	66.25	3.873	-0.585
A15	Blackish	Offensive	36	8.12	1268.50	1576.25	406.25	155.00	2.375	155.50	75.50	3.805	2.385
A16	Yellowish	NO	35	8.17	1226.50	2606.75	385.25	149.75	3.475	143.75	67.50	3.925	2.433
A17	Yellowish	NO	35	8.25	1421.75	1600.75	438.00	163.00	4.525	157.00	80.00	4.053	2.843
A18	L/Yellowish	NO	31	8.22	1196.00	1561.00	370.00	147.00	3.250	147.25	65.00	4.905	-2.393
A19	L/Yellowish	NO	38	8.25	1337.50	1859.50	440.75	161.25	3.825	175.25	84.25	4.688	-1.945
A20	L/Yellowish	NO	32	7.95	1288.50	2709.00	416.25	166.50	3.050	113.00	68.25	4.350	-1.710

To better understand the environmental impact of disposing high salt concentration effluents, the levels of various cations, including sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca), were analyzed. The analysis of wastewater samples from different sites in Jhelum revealed that the sodium concentration (Na) ranged from 139.75 to 184.5 mgL^{-1}, which is within the permissible limit of 200 mgL^{-1} for irrigation purposes. However, high concentrations of sodium can lead to soil toxicity, altering the soil structure and negatively affecting plant growth and crop yield, potentially even causing plant death.

The Sodium Adsorption Ratio (SAR) indicates the amount of sodium in water, which can contribute to soil toxicity, alter soil structure, and affect the water-holding capacity of soil. Table II presents the SAR values for different sampling sites in the city of Jhelum. According to the analysis, the SAR values were greater than 0.2, making the wastewater unsuitable for irrigation purposes (16). The evaluation of the Sodium Adsorption Ratio (SAR) indicates the amount of sodium adsorbed by the soil. When high sodium levels come into contact with soil, they can replace salts such as magnesium (Mg) and calcium (Ca) ions, leading to the degradation of soil structure. This change negatively impacts the soil's ability to retain air and water. The amount of bicarbonates in water is described using Residual Sodium Carbonate (RSC). The acceptable limit for bicarbonates is less than 1.25 meqL^{-1}, the marginal acceptable limit ranges from 1.25 to 2.5 meqL^{-1}, and values above 2.5 meqL^{-1} are considered intolerable.

In this research, the RSC values of wastewater samples ranged from -3.193 to 4.208 meqL^{-1}. This shows that approximately 10% of the samples exceed the unacceptable limit, while 28% are within the permissible limit, and 62% fall within the marginally acceptable range, making them suitable for reuse in irrigation. Wastewater with high RSC levels can still be reused for irrigation purposes, but this requires special irrigation management techniques and continuous monitoring of soil health through laboratory testing (19, 20). The physicochemical parameters of the sewage water samples are further illustrated in Fig. 1(a, b) and Fig. 2.

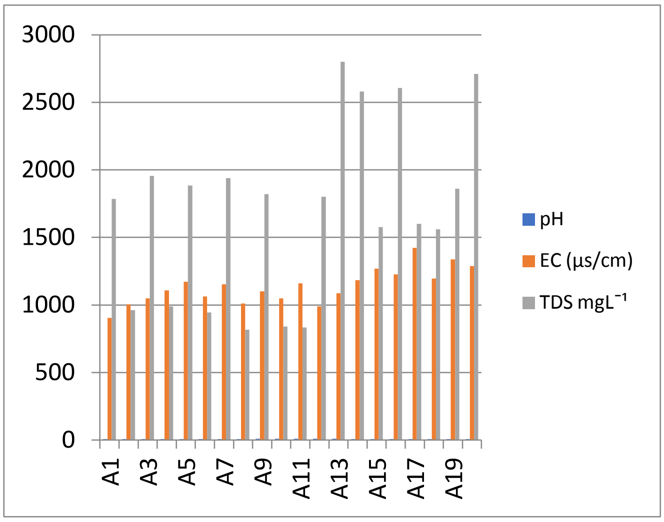

Fig. 1(a). Values of pH, EC & TDS in waste water samples of Jhelum

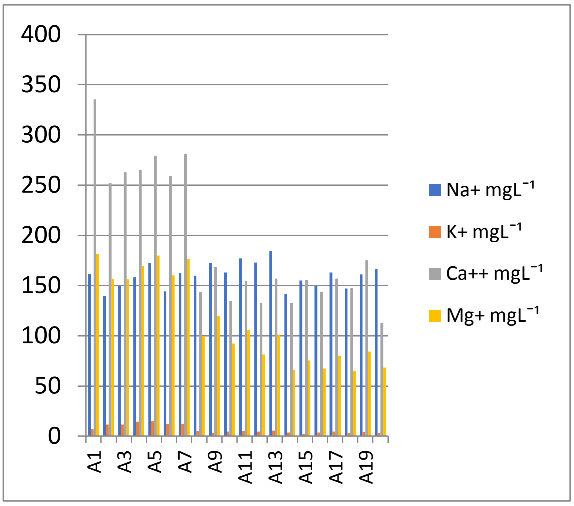

Fig. 1(b). Values of Na, K, Ca & Mg in waste water samples of Jhelum

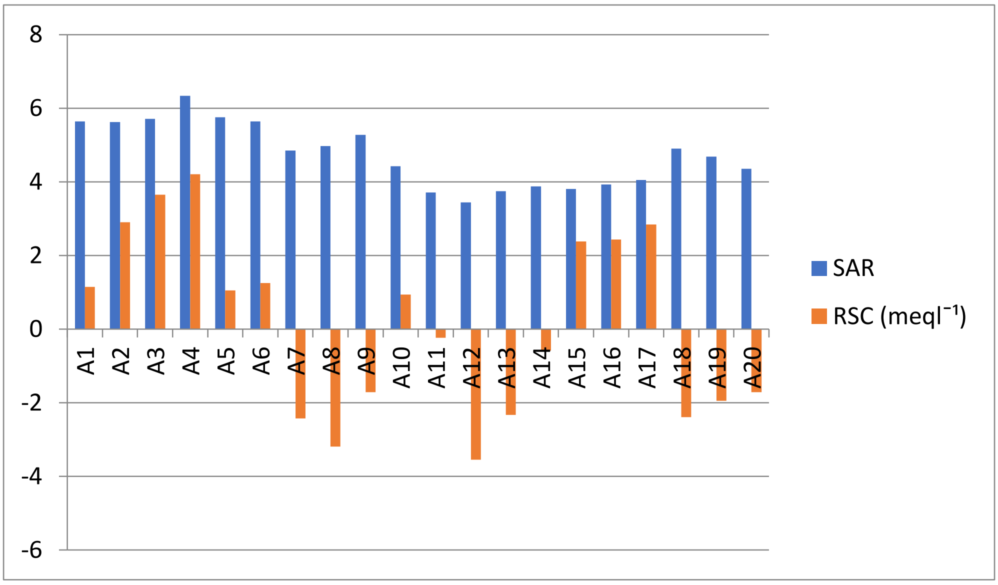

Fig. 2. Values of SAR and RSC in samples of waste water of Jhelum

Table III. Irrigation water quality standards interpreted by SFRI, Punjab, Lahore

Water Quality Indicator	Status	Guide line value
EC(µS/cm)	Suitable	<1000
	Marginal	1000-1200
	Unsuitable	>1200
SAR	Suitable	<6
	Marginal	6-10
	Unsuitable	>10
RSC(me/L)	Suitable	<1.25
	Marginal	1.25-2.5
	Unsuitable	>2.5
Cl^{-1}(me/L)	Suitable	<4.5
	Unsuitable	>4.5
TDS(mgL^{-1})	Suitable	≤640
	Marginal	641-800
	Unsuitable	>800

To better understand the environmental impact of disposing of high salt concentration effluents, an analysis was conducted on the levels of various cations, including sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}). The wastewater samples collected from different sites in Jhelum revealed that sodium concentrations ranged from 139.75 to 184.5 mgL^{-1}, which fall within the permissible limits for irrigation as outlined by WWF guidelines (2007). However, elevated sodium levels can increase soil sodicity, leading to changes in soil structure that may negatively affect plant growth, reduce crop yields, and potentially result in plant mortality. The formula used to calculate SAR of water is:

$$SAR = Na [(Ca + Mg)/2]^{1/2}$$

According to Qazi *et al.* (2021) (16), the Sodium Adsorption Ratio (SAR) is categorized based on groundwater quality for irrigation purposes. As shown in Table 1, the SAR range of the wastewater samples collected in this study varies from 3.438 to 6.333, indicating that approximately 95% of the samples fall within the acceptable or marginally acceptable range for irrigation as depicted in table III devised by Soil Fertility Research Institute, Punjab, Lahore. The only exception is the wastewater sample from Dina City (A4), which falls into the marginally acceptable category. All other sewage water samples are suitable for irrigation, in accordance with the guidelines set by the Soil Fertility Department, Punjab, Lahore (21).The evaluation of the Sodium Adsorption Ratio (SAR) indicates the concentration of sodium relative to the calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in wastewater. High sodium concentrations, when in contact with soil or sludge, can replace magnesium and calcium ions, leading to the degradation of soil structure. This process, known as soil sodicity, impairs the soil's ability to retain air and water. Elevated sodium levels can negatively impact plant growth, reduce crop yields, and even cause plant mortality. Furthermore, the increased sodium concentrations can result in a decrease in heavy metal levels and an alteration of the pH range, which ultimately affects soil fertility (22). High levels of bicarbonates in water can increase the pH by suspending organic matter, which in turn can raise the concentration of sodium ions (Na^+) in the soil. In this research, the Residual Sodium Carbonate (RSC) values of the wastewater samples ranged from -3.193 to 4.208 meqL^{-1}. This shows that 70% of the samples exceed the unacceptable limit, while 30% fall within the permissible and marginally acceptable ranges, making them suitable for irrigation. Wastewater with high RSC levels can still be used for irrigation purposes, but it requires specialized irrigation management practices, including continuous monitoring of soil conditions through laboratory testing (21).These findings could be better understandable when Table II and Table III are collectively and comparatively analyzed.

DESCRIPTION OF HEAVY METALS PRESENT IN WATER OF JHELUM

Cadmium was not detectable in the wastewater samples. However, other toxic metals, including Fe, Cu, Zn, Mn, Pb, and Al, were analyzed. Due to budget constraints and limited availability of reagents for heavy metal analysis, only selected samples were tested. Among these metals, aluminum was the most polluting, with a concentration range of 12.910±0.159 to 13.845±0.14 mgL^{-1}, several magnitudes higher than the WHO standard (0.01 mgL^{-1}) and the PAK-EPA standard (0.05 mgL^{-1}) for wastewater. The second-highest concentration was lead, ranging from 0.078±0.030 to 0.270±0.057 mgL^{-1}, which exceeds the WHO limit of 0.5 mgL^{-1}. The concentration of iron (Fe) in the wastewater samples ranged from 0.340±0.029 to 0.445±0.025 mgL^{-1}, which is within the permissible limit according to WHO standards (2008). The concentrations of other heavy metals were as follows: copper (Cu) ranged from 0.048±0.017 to 0.210±0.028 mgL^{-1}, manganese (Mn) ranged from 0.048±0.013 to 0.248±0.022 mgL^{-1}, and zinc (Zn) ranged from 0.078±0.030 to 0.270±0.057 mgL^{-1}. If the concentration of these metals exceeds standard limits, they can enter the food chain through the irrigation process, especially when wastewater is used for irrigation or when these metals are discharged into water bodies. These metals are then absorbed by plants and animals, ultimately affecting human health through the consumption of contaminated food and water, potentially leading to waterborne diseases. Furthermore, they pose a significant threat to the ecosystem by disrupting the quality of the food chain and harming aquatic life (23, 24). The concentration of different heavy metals of different wastewater samples which have been analyzed are shown in Table IV.

Table V shows the concentration of heavy metals analyzed in the wastewater samples, which were used to assess the interaction between these metals and various physicochemical parameters using the Pearson correlation coefficient matrix (r). Certain metal pairs, such as Fe/Mn and Fe/Zn, were examined for their correlations. A correlation coefficient close to 1 indicates a positive relationship, suggesting that the elements share a common source or chemical process. In contrast, a correlation further from 1 indicates a negative relationship. For instance, the Fe/Mn pair ($r = 0.03466$) is positively correlated, implying that these elements have similar sources and processes, while the Pb/Mn pair ($r = -0.44886$) shows a negative correlation, suggesting a reverse relationship. Gul et al 2025 observed the same findings (10).

Table IV. Mean and standard deviation of concentration of metals in wastewater sample analyzed for different sites of Jhelum

Sampling sites	Fe (mgL-1)	Cu	Zn	Mn	Pb	AI
Kala Gujran(A2)	0.440±0.029	0.055±0.007	0.160±0.010	0.048±0.013	0.270±0.057	13.295±0.3 23
Fariq(A10)	0.440±0.123	0.145±0.007	0.165±0.007	0.055±0.017	0.245±0.021	13.268±0.289
Pandori(A11)	0.340±0.029	0.168±0.010	0.087±0.021	0.088±0.025	0.158±0.057	13.085±0.159
Nara(A12)	0.438±0.025	0.048±0.017	0.117±0.015	0.055±0.019	0.115±0.024	12.910±0.159
Bishan daur(A16)	0.445±0.031	0.210±0.028	0.215±0.049	0.248±0.022	0.78±0.030	13.845±0.141

Table v. Pearson correlation matrix (r) of analyzed wastewater sample of Jhelum to describe the interaction among physiochemical parameters (n - 20)

Variables	Fe	Mn	Zn	Al	Cu	Pb	pH	EC	TDS
Fe	1								
Mn	0.03466	1							
Zn	0.01615	0.264	1						
Al	0.122775	0.655396	0.305791	1					
Cu	0.019118	0.19665	0.114896	0.26266	1				
Pb	0.41463	-0.44886	-0.20334	-0.26587	-0.11328	1			
pH	0.077436	-0.24294	-0.44909	-0.34357	0.226313	0.059058	1		
EC	-0.1855	0.621869	0.402385	0.488805	-0.05351	-0.63154	-0.48469	1	
TDS	0.28525	-0.44617	-0.14716	-0.68381	-0.17485	0.59117	0.307319	-0.62027	1

CONCLUSION

Due to the rapid growth of industrialization, urbanization, and population, the demand for water has increased, putting pressure on both the supply and quality of water. As a result, the reuse of water for irrigation and other purposes has become more common. The water samples analyzed in this study revealed a pH range of 7.95 to 9.22 and temperatures between 31°C and 38°C, which fall within the standards set by the National Environmental Quality Standards (NEQS) and the World Health Organization (WHO).

However, water with high sodium levels can contribute to soil sodicity over time. Based on the analysis of sodium, calcium, magnesium, and residual sodium carbonate (RSC), it was found that 10% of the wastewater samples exceeded acceptable limits, 28% were within the permissible limit, and 62% were within the marginally acceptable limit. Among the toxic metals analyzed, lead (Pb) was present in nearly all samples, which is quite alarming. The Pearson correlation coefficient matrix was used to assess the interaction between metals and various physicochemical parameters, helping to characterize the wastewater. The direct discharge of untreated wastewater into water bodies and the leakage of untreated sewage into the ground pose significant risks to human health, leading to waterborne diseases like diarrhea, dysentery, cholera, and typhoid fever, which result in the deaths of millions of people.

In summary, while treating industrial wastewater in Pakistan presents significant challenges, it also offers an opportunity for innovation and sustainable practices. By integrating various treatment technologies, adopting more efficient methods, and implementing robust regulatory frameworks, Pakistan can mitigate the environmental and health risks associated with industrial wastewater contamination. This will require a collaborative effort from industries, government, and communities to develop long-term solutions to this growing issue.

FUTURE RECOMENDATIONS

There are some recommendations for sustainable wastewater management:

Integrated Treatment Approaches:

Combining multiple treatment methods can indeed be an effective strategy for treating industrial wastewater. For example: Pre-treatment with physical methods (filtration, sedimentation) could be used to remove larger particles before moving on to chemical treatment or adsorption, which targets dissolved contaminants like heavy metals. Biological treatment could be employed after physical and chemical treatments to further degrade organic contaminants, improving overall water quality and reducing operational costs. Phyto remediation: The use of plants to remove or degrade contaminants from wastewater could offer a sustainable and cost-effective method for heavy metal removal, especially for industries located near agricultural zones.

Regulatory Measures and Incentives:

Governments and local authorities could play a critical role in reducing the impact of industrial wastewater through Implementing and enforcing stricter regulations on wastewater discharge can encourage industries to invest in cleaner treatment technologies and adopt sustainable practices. Establishing safe discharge limits for heavy metals and other contaminants is crucial. Public-Private Partnerships (PPPs) can help fund large-scale wastewater treatment projects, combining public policy with private sector efficiency.

Conflict of interest:

There is no conflict of interest among authors regarding this article.

Authors` contribution:

AA,AW,SA & MSA conducted the research work; MS composed the paper; WI performed proof reading and editing; AH conceptualized and supervised the research work; NG & AU critically reviewed the manuscript; ZHT & MSA conducted the analysis of Water samples, HRA technically reviewed the paper; SUK & AA analyzed the data statistically.

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