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EXAMINATION OF THE POTENTIAL OF USING TREATED WASTEWATER WITH DIFFERENT CHEMICAL QUALITIES FOR IRRIGATION AS GOVERNED BY STANDARDS AND LEGISLATION

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ABSTRACT

The research investigates the application of treated wastewater in agricultural practices in Jordan, spanning from the Al-Samra Wastewater Treatment Plant to the King Talal Dam. The chemical properties of water fluctuate with time, impacting human health. The cultivation of crops utilising treated water is regulated by Jordanian guidelines for the application of treated wastewater in irrigation (JS 893/2006). The study seeks to assess the chemical quality and adherence to the utilisation of treated water in accordance with Jordanian requirements, investigating the feasibility of employing treated wastewater with diverse chemical qualities for irrigation, while highlighting the impact of regulations and legislation on this practice. The research highlights the urgent necessity for sustainable water management in agriculture, especially in arid locations. By examining definitions of wastewater quality, regulatory frameworks, and pertinent case studies, I illustrate how comprehending these elements can enhance the safe and efficient use of treated wastewater in irrigation. The quality of treated wastewater affects land use and the availability of agricultural land. Three scenarios are proposed the existing water quality will remain unchanged, water quality will enhance, or water quality will deteriorate. These possibilities impact irrigated crops within the research region. The chemical assessment of treated water and proposed scenarios can assist decision-makers in selecting appropriate crops and identifying available agricultural land based on varying qualities of treated wastewater. The Jordanian Standards (JS) 893:2006 delineate precise regulations for the quality of treated wastewater intended for agricultural purposes. This standard categorises wastewater according to its chemical makeup and potential effects on crops and soil. The classifications encompass no to minimal restrictions, moderate restrictions, and severe restrictions. Each category specifies the allowable concentrations of various pollutants, including salt, heavy metals, and pathogens, that may be present in treated wastewater. The findings demonstrated that treated wastewater is applicable for irrigating all crops with minimal to no restrictions. Approximately 8.6%

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of the study area was deemed highly suitable, while around 28% was categorised as moderately suitable for agricultural utilisation under similar water quality conditions. The agricultural area decreased from 51,900 hectares with no to minimal restrictions to 31,070 hectares under moderate restrictions, and further to 9,340 hectares under severe restrictions regarding water quality. Certain soil-mapping units were designated as slightly or unsuited for rainfed crops due to rainfall constraints, while classed as highly or moderately acceptable for irrigated crops; this land may be irrigated with treated wastewater provided the water quality presents only modest or moderate restrictions. Therefore, to enhance the efficiency of land and water resource utilisation, the quality of treated wastewater must be elevated to comply with Jordanian Standards for use as an irrigation source for all cultivated crops. In conclusion, analysing treated wastewater with varying chemical properties is crucial for comprehending its environmental and public health implications. By acknowledging the importance of monitoring and chemical properties, we may advance sustainable management of treated wastewater and safeguard natural ecosystems and human populations.

KEYWORDS: Treated Wastewater Quality, Jordanian Standards, Irrigation, Water Management, Sustainable Agriculture Land.

1. INTRODUCTION

The As-Samra Wastewater Treatment Plant is the primary source of reclaimed water in Jordan and serves as the main treatment facility for the cities of Amman and Zarqa. Treated effluent from As-Samra is discharged into Wadi Zarqa for various agricultural and non-agricultural applications.

The irrigation methods reliant on treated wastewater along the Zarqa River encompass: (1) direct application for the irrigation of tree crops and forage, (2) indirect utilisation following the discharge of treated water into the environment to enhance quality, and (3) illicit use of water for irrigation that contravenes established laws or regulations. The prospects for developing new freshwater sources in Jordan are costly and entail significant running expenses. Treated wastewater should be regarded as a resource that, with appropriate attention to health and environmental concerns, ought to be repurposed for agricultural and other non-domestic use.

Treated wastewater denotes water that has undergone processing to eliminate impurities and pathogens, rendering it suitable for many applications, such as agricultural irrigation. The quality of treated wastewater is contingent upon the treatment technology employed and the specific pollutants it contains [1]. These contaminants, comprising chemicals and microbes, adversely impact farmed crops and soil. Given the water constraint in Jordan, treated water has been designated as a primary source for agriculture irrigation. Upon considering the Jordanian guidelines (893:2006) that govern the utilisation of treated water in agriculture [5]. Treated water is utilised for irrigation of many crops along the Zarqa River, owing to the scarcity of freshwater in Jordan. The use of treated wastewater for irrigation presents agronomic and economic benefits; nevertheless, it also has certain disadvantages. The primary concern with the use of treated wastewater in agriculture is the inherent health risks associated with wastewater containing bacteria, viruses, and different parasite organisms [9]. Salinity can lead to soil issues and negatively impact yield quality. The value of Electrical Conductivity (EC) fluctuates between summer and winter. In the summer months, the average electrical conductivity (EC) values of treated water from the Zarqa River (2.5 dS/m) exceed the average values seen in winter months (2.1 dS/m), necessitating minor to moderate tolerance in agricultural crops. As wastewater is categorised as a non-conventional water source, its utilisation in agriculture requires specialised management to guarantee that its appropriate usage does not endanger the environment, flora, soils, or surface and subsurface water supplies. Pescod (1992) evaluated the advantages and disadvantages of different irrigation methods for wastewater application and determined that drip gardening is the sole strategy that effectively mitigates the unique challenges of utilising wastewater. The implementation of surface and subsurface drip irrigation has demonstrated efficacy in promoting root development, enhancing water absorption, and facilitating nitrate movement [8]. A separate study found that employing a combination of surface and subsurface drip irrigation reduces soil pollution. The below drip irrigation approach is anticipated to enhance maize output, effectively addressing the particular challenges associated with wastewater use [11]. The total volume of water produced in the Amman-Zarqa basin is projected to increase from the current 61 MCM per year to around 180 MCM per year by 2025.The concentration of trace elements in the effluent is markedly below the specified requirements, with the exception of Zinc and Boron. Other metrics do not conform to the relevant Jordanian Standards, specifically BOD5, COD, TSS, FOG (fats, oils, greases), NH4+, total nitrogen, PO4-3, Cl-, HCO3-, and total coliforms [6, 7]. While treated wastewater serves as a viable irrigation water source, stringent and often costly treatment processes are necessary to comply with quality standards, particularly for high-value crops [12]. Standards such as the Jordanian Standards (893:2006) are essential in directing the utilisation of treated wastewater for agricultural purposes. They establish a standard for evaluating wastewater quality and guarantee that its utilisation does not jeopardise environmental safety or public health. Highlight that existing requirements for treated wastewater usage largely focus on mitigating negative impacts on the environment and public health, emphasising the significance of regulatory adherence in enhancing wastewater reclamation.

A multitude of characteristics are assessed to evaluate the quality of treated water and promote its sustainable application in agriculture [14]. Although the utilisation of treated water in agriculture is essential, it presents several obstacles [15]. Particularly in regions where water is inadequately treated and utilised for irrigating crops consumed raw without cooking [16]. Wastewater quality criteria must be perpetually revised due to alterations in pollutant quality or the introduction of previously unmeasured contaminants [17]. The standard governing irrigation water quality in

Jordan is 893:2006, promulgated by the Jordanian government [18]. The rationale is that the reuse of treated water in agriculture necessitates stringent regulation to avert chemical and microbiological contamination of soil and plants. While treated water is blended with freshwater for irrigation reuse in Jordan, ongoing monitoring of this practice is advisable to safeguard environmental integrity [24].

This research examined the feasibility of utilising treated water for crop irrigation under three scenarios: the existing water quality, the types of crops suitable for irrigation, and the available cultivation areas; the implications of improved water quality on both crop types and cultivation areas; and the consequences of deteriorating water quality on crop types and cultivation areas. This is essential in areas where food security is jeopardised by water scarcity, as the safe utilisation of treated wastewater can augment crop yield and diminish dependence on freshwater resources. The results indicate that compliance with established criteria enhances agricultural productivity and fosters environmental sustainability. Ultimately, proponents of enhanced legislation and increased research into optimising wastewater treatment techniques to facilitate the sustainable reuse of water resources

2. METHODOLOGY

A level two soil map (scale 1:50,000) served as the foundational map for creating land suitability maps for the chosen land utilisation types. Soil data was obtained from observation stations recorded in the Jordan Soil and Climatic Information System. The data encompasses climatic information, specifically mean annual rainfall and winter growth potential, defined as the cumulative degree-days exceeding 8 degrees.

Celsius during the coldest months. Additionally, it includes soil characteristics such as depth and available water holding capacity, erosion type and classification, topography in terms of slope, and the presence of rock outcrops and stones. This information was utilised to compute the properties of soil mapping units. The Jordanian regulations for the use of treated wastewater in irrigation (893:2006) encompass irrigation water parameters (EC, BOD5, COD, TSS, FOG, NH4+, Total Nitrogen, PO4-, Cl-, HCO3-, and Total Coliforms) employed to assess the extent of usage restrictions (Table 1). Arcview 3.2 was employed to create land suitability maps, subsequently preparing suitability maps for agricultural use based on treated wastewater quality.

Table 1: Jordian Standards for Reclaimed Domestic Wastewater for Irrigation Purposes, (893:2006).

Standard and Properties	Maximum Permissible Limits			
Group A	**Cut Flowers**	**Cooked Vegetables, Parks. Playgrounds. and Roadsides within Cities**	**Fruit trees, External roadsides, and Green landscapes**	**Field crops. Industrial crops, and Forest trees**
BOD5	30	30	200	300
COD	100	100	500	500
DO	>2	>2	-	-
TSS	15	50	200	300
pH	(6-9)	(6-9)	(6-9)	(6-9)
NO3	45	30	-	-
T-N	70	45	45	70
E.coli	<1.1	100	1000	-
Intestinal Helminthes Eggs	≤1	≤1	≤1	≤1
FOG	2	8	8	8

2.1. Definition and Classification of Treated Wastewater Quality

When properly managed, treated wastewater serves as a sustainable and viable alternative water source for irrigation, particularly in arid and semi-arid countries. Jordanian Standards 893:2006 serves as a framework for assessing the quality of treated water utilised for crop irrigation, evaluated through many factors, including pH, salinity, mineral and heavy metal concentrations, as well as pathogen presence. Treated water is categorised into three primary classifications based on its levels.

- **Rejection of Minor Limitation:** treated wastewater is suitable for irrigating a diverse array of crops, including those eaten raw.
- **Moderate Restriction:** treated wastewater is appropriate for irrigating crops that are not consumed raw or for application in regions with elevated soil and crop tolerance levels.
- **Severe Restriction:** Treated wastewater may include elevated concentrations of salts, minerals, or pollutants, rendering it

inappropriate for most agricultural applications; it is utilised just for irrigating non-food crops.

2.2. *Irrigation Water Quality Criteria*

Several criteria must be considered when assessing treated water for crop irrigation [25], specifically:

2.2.1. Salinity

The FAO has established recommendations for the utilisation of treated water in irrigation, with salinity being the paramount factor in evaluating treated water quality. Treated wastewater frequently possesses high salinity, which can adversely affect agricultural development, necessitating the establishment of salinity regulations.

Salinity is generally quantified using electrical conductivity (EC). The influence of salinity on agricultural growth differs according to the specific crop species. Irrigation water with an EC of 700 µS/cm typically does not impede crop growth, however values above 3000 µS/cm can inflict significant harm.

2.2.2. Nutrients

Phosphorus (P) and Nitrogen (N) are vital elements for agricultural development. Nevertheless, elevated doses can produce adverse effects. Excessive nitrogen and phosphorus in paddy rice might result in rampant growth and lodging.

2.2.3. Organic Matter

Biochemical oxygen demand (BOD) is frequently utilised as a measure of organic matter. Increased BOD levels diminish oxygen during the breakdown of organic matter, resulting in anaerobic conditions. Throughout this process, soil oxides including Mn5+, Fe3+, and SO42− deplete oxygen, hence diminishing the oxidation-reduction potential [28]. The resultant chemicals, including manganese, iron, sulphide, and organic acids, can impede nutrient absorption in paddy rice [29].

2.2.4. Hydrogen Ion Concentration

The pH, reflecting hydrogen ion concentration, serves as a rapid indicator of irrigation water appropriateness. Irrigation water generally exhibits a pH range of 6.5 to 8.4. Variations from this range may permit irrigation but can lead to nutritional imbalances or the introduction of detrimental ions [30]. Low pH values expedite corrosion in irrigation equipment, whereas very alkaline water diminishes the efficacy of trickle irrigation systems [31].

2.2.5. Trace Elements

Although trace elements are vital for crop development, elevated heavy metal levels in irrigation water can result in substantial harm. Copper (Cu) can induce leaf chlorosis and inhibit root development, although arsenic (As) and zinc (Zn) exhibit analogous effects. Aluminium (Al) in acidic soils may diminish productivity [32]. Toxic substances including cadmium (Cd), lead (Pb), and cyanide (CN) are rigorously controlled because of their propensity to bioaccumulate in crops, endangering human health [33]. The FAO's recommendations for irrigation water quality stipulate maximum allowable quantities of trace elements [26].

2.3. Legal and Regulatory Framework Governing Wastewater Use

A collection of regulations concerning the reuse of treated water in agriculture, promulgated by the FAO and World Health Organisation, emphasises the importance of considering microbial pathogens in the application of treated water for agricultural purposes. Furthermore, it underscores the necessity of ensuring that the quality of treated water adheres to international specifications and standards to mitigate health risks associated with its use for crop irrigation [26]. It is imperative to address concerns such as unauthorised usage and enforcement. Enhancing public awareness, augmenting regulatory capacity, establishing an adaptive framework, and incorporating worldwide best practices can bolster the efficacy of the current legislative structure. This will enhance sustainable water resource management.

2.4. Examination of the Potential Use of Treated Wastewater in Irrigation

The examination of three properties of treated wastewater for irrigation was conducted in accordance with the Jordanian Standards (893:2006), based on the following assumptions: The volume of treated wastewater meeting the requirements of the Jordan Valley enables the irrigation of all crops within the research area.

The quality of treated wastewater is anticipated to alter as outlined below:

- Enhanced from moderate restriction (present water quality) to negligible or little limitation.
- Progress from moderate to severe limitation.

The quality of treated wastewater (Table 2) was categorized in accordance with Jordanian

Standards for the utilisation of treated wastewater in irrigation as follows:

Reject minor limitations: Water is applicable for all crops, encompassing veggies and fruit trees. Agricultural land is defined as land designated as highly or moderately appropriate (S1 or S2) for at least one selected land utilisation type, including vegetables and fruit trees, and can be utilised to substitute the water for the currently irrigated area.

Moderate limitation and Current water quality: Treated wastewater can only be utilised for feed crops, whereas irrigation of fruit trees and vegetables is prohibited.

Agricultural land is defined as land classed as highly or moderately suitable for forage or rain-fed crops. Severe restriction: This water is prohibited for irrigation use. The analyses encompass regions designated as highly or moderately suitable exclusively for rain-fed crops. Furthermore, the presently watered areas utilising groundwater for irrigation are prohibited from being irrigated with this form of treated effluent.

Table 2: The Potential Irrigation Problems and Degree of Restriction on Use [6, 7].

Potential Irrigation Problems	Degree of Restriction on Use			
	No restriction	Slight	Moderate	Severe
EC (dS/m)	0.7	0.7-3	0.7-3	3
BOD5 (mg/l)	50	50-150	150-250	>250
COD (mg/l)	<200	200-500	500-700	>700
TSS (mg/l)	50	50-200	200-250	>250
FOG (fats, oil greases) (mg/l)	<8	8-12	8-12	>12
NH4+ (mg/l)	0	0-15	15 - 50	>50
Total Nitrogen (mg/l)	<50	50-100	50-100	>100
PO4- (mg/l)	0	0-15	0-15	>15
Cl- (mg/l)	0	0- 350	0-350	>350
HCO3- (mg/l)	0	0-520	0-520	>520
Total Coliforms (MPN/100 ml)	0	<1000	>1000	>1000

2.5. Sample Collection

In 2024, treated wastewater samples were taken from the primary Khirbet al-Samra in the focal region of central Jordan. The samples were collected in clean 1 L plastic bottles that had been meticulously rinsed with the corresponding wastewater samples prior to labelling. A pH meter was employed for in situ measurement. The samples were conveyed to the laboratory in an ice chest and refrigerated prior to examination. This collects wastewater from densely populated areas in the Amman and Zarqa regions. This is Jordan's largest wastewater treatment facility, employing advanced technology to remove organic matter and other pollutants from wastewater. The facility executes several procedures, including aeration, preliminary screening, coagulation, sedimentation, disinfection, and filtration, to eliminate dangerous substances and achieve the requisite quality standards [36].

2.6. Sample Preparation

The sample consisted of 17 specimens that were dried for thirty minutes in an oven maintained at 55 degrees Celsius. Particles less than 63 µm (0.05 mm) were selected for examination because of their ideal size in arid and semi-arid locations. A beaker with 100 ml of 1N HCl was utilised to treat a geological sample weighing roughly 2.5 grammes. The mixture was permitted to react for around twenty minutes while being stirred with a glass rod. After 20 minutes, strain the mixture and transfer the clear filtrate to a new beaker. Twenty millilitres of the test solution were transferred to a conical flask for the titration. NaOH was subsequently dispensed from a burette into the container, accompanied by 4 or 5 drops of bromophenol blue indicator.

2.7. Chemical and reagents

The chemicals utilised in the testing possessed analytical grade purity. Sodium acetate, acetone, and nitric acid (69% purity) were procured from GCC, UK. Fluka, Switzerland provided potassium dichromate, an o-phenanthroline indicator, and phosphoric acid (H3PO4). Ferrous ammonium sulphate was procured from BDH in England. Ammonium acetate from Scharlau Chemie S.A., Spain, and isopropyl alcohol from Fisher Scientific, USA, were utilised. The studies utilised n-hexane sourced from Frutarom in the United Kingdom, along with a reference standard solution of PAHs.

3. RESULTS AND DISCUSSION

The Jordanian Standards (JS), (893:2006) delineate precise regulations for the quality of treated wastewater intended for agricultural purposes. This standard categorises wastewater according to its chemical makeup and potential effects on crops and soil. The classifications encompass no to minimal restrictions, moderate restrictions, and severe restrictions. Each category specifies the allowable concentrations of various pollutants, including salt, heavy metals, and pathogens, that may be present in treated wastewater.

3.1. Suitability of Land for Agricultural Use under the Moderate Restriction of Treated Wastewater Quality (Current Water Quality)

The Jordanian Standards for the Utilisation of Treated Wastewater in Irrigation (893:2006) permit the use of treated wastewater for irrigating all crops with minimal to no restrictions. Consequently, the land designated for retention as an irrigated agricultural zone comprises areas classified as highly or moderately suitable for at least one of the following land use types: drip-irrigated vegetables and trees, sprinkler-irrigated crops, surface irrigated crops, and furrow irrigated crops. The assessment of land suitability for agricultural use with no to slight water quality restrictions (Figure 1) revealed that 8.6% of the study area was designated as highly suitable (S1), while approximately 28% was categorised as moderately suitable (S2) for agricultural purposes under the same conditions. The marginal (S3) and unsuitable (NS) regions for agricultural use encompass approximately 58.6% of the research area. The primary land constraints were soil depth, slope gradient, water-holding capacity, and precipitation. This sort of treated wastewater can be utilised for the irrigation of all crops without restrictions, thereby enabling the substitution of the water currently employed for irrigating vegetables and fruit trees (about 34,500 hectares) with treated wastewater to mitigate groundwater depletion. Furthermore, about 8,680 and 22,400 hectares were designated as highly (S1) and moderately (S2) suitable for agricultural use beyond the existing irrigated zones; this land can facilitate the expansion of irrigated vegetables and fruit trees through the treatment of wastewater utilising this water quality.

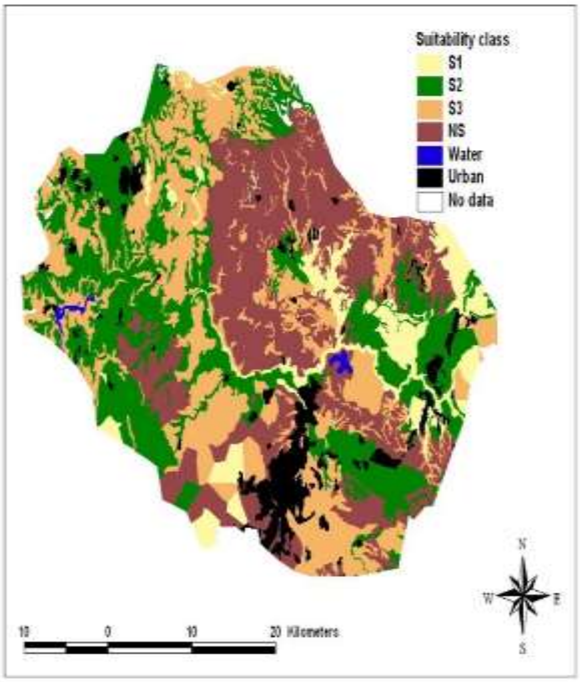

Figure 1: Suitability of Land for Agricultural Use under no to Slight Restriction of Water Quality [10].

Approximately 10,650 ha and 41,200 ha were designated as highly (S1) and moderately (S2) suitable for pasture and rain-fed crop use, respectively, under moderate water quality constraints. The marginal (S3) and unsuitable (NS) zones encompass around 38,640 and 40,870 hectares, respectively. A portion of this region is presently employed for irrigated agriculture, relying on groundwater for irrigation. The irrigated region, as indicated by the land cover map, is approximately 34,500 square kilometres. This land is prohibited from being irrigated with this specific sort of treated wastewater. The land area beyond the now irrigated fruit trees and vegetables, designated as highly (S1) and moderately (S2) suitable for agricultural usage, is around 7060 and 24000 hectares, respectively. Marginal (S3) and unsuitable (NS) zones for agricultural use encompass around 28,830 and 37,500 hectares, respectively. The distinction between negligible to minimal limitation and moderate restriction influences the type of crops that can be cultivated using treated wastewater. The agricultural land decreased from 51,900 hectares with no to minimal restrictions to 31,070 hectares with moderate restrictions, as only irrigated forage crops may be cultivated using this sort of treated effluent. Furthermore, at present, the irrigation of vegetables and fruit trees with this type of treated wastewater is prohibited.

3.2. Suitability of Land for Agricultural use under Severe Restriction of Water Quality

The region designated as partly suitable (S3) and unsuitable (NS) for rainfed crops has approximately 21,310 and 66,760 hectares, respectively, as seen in Figure 2. The area designated for agricultural use diminished from 51,900 hectares with no to modest restrictions to 31,070 hectares under moderate restrictions, and further to 9,340 hectares under severe restrictions. Despite the restricted availability of land for rainfed crops due to inadequate rainfall, certain soil-mapping units were designated as marginally (S3) or unsuitable (NS) for rainfed cultivation, yet classified as highly (S1) or moderately (S2) suitable for irrigated crops. This area can be irrigated with treated wastewater, provided that the water quality presents only slight or moderate restrictions. Therefore, to enhance the efficiency of land and water resource utilisation, the quality of treated wastewater must be elevated to comply with Jordanian Standards for use as an irrigation source for all cultivated crops.

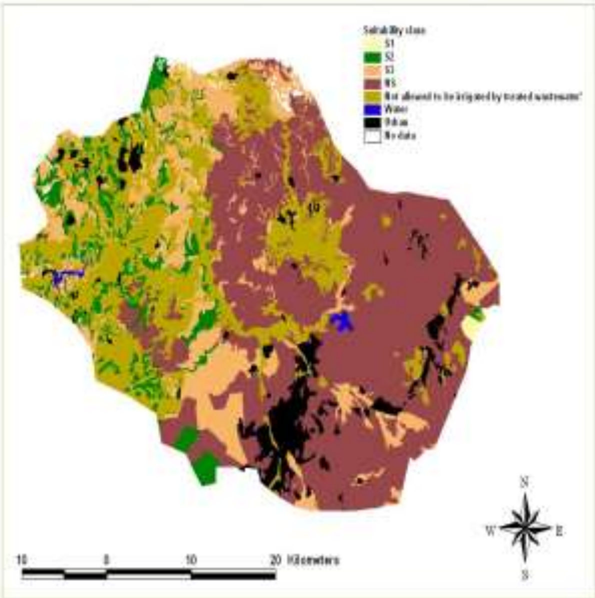

Figure 2: Suitability of Land for Agricultural use under Severe Restriction of Water Quality.

* Currently irrigated fruit trees and vegetables is not allowed to be irrigated by this type of treated wastewater quality [10].

3.3. Chemical Qualities of Treated Wastewater

Chemical Oxygen Demand is defined as the oxygen-equivalent of a sample's organic matter that is susceptible to oxidation by a strong oxidant. This is a technique for assessing the degree of organic matter pollution in water [37]. The chemical oxygen demand (COD) of raw wastewater released from the Al-Samra Wastewater Treatment Plant into the King Talal Dam is 37.4 mg/L (Table 3). Notwithstanding this reduced efficiency, the resultant COD values significantly beyond the permissible limits for wastewater release. The solubility of oxygen in water is inversely related to atmospheric pressure, salinity, and temperature. The DO concentration of the influent wastewater treatment achieved an enhancement of 5.7 mg/L, as shown in Table 3, suggesting that the WWTP is ineffective in augmenting DO levels. Nonetheless, as per the WHO [6] Only treated effluents from Al-Samra with a dissolved oxygen concentration of 0 mg/L do not meet the discharge criteria for surface water, as the standard is 1 mg/L. Low dissolved oxygen concentration in the pollutants signifies elevated microbial activity in the water due to the presence of biodegradable organic materials, such as cellulosic thickeners and styrene-acrylate binders. Excessive nutrient loading can diminish dissolved oxygen levels by promoting algal blooms, causing the mortality of aquatic creatures, and leading to asphyxia.

Biochemical Oxygen Demand (BOD) is crucial for determining the level of pollution in wastewater and evaluating the effectiveness of wastewater treatment methods. The concentration of Biological Oxygen Demand (BOD) in water significantly affects Dissolved Oxygen (DO). An increased BOD content correlates with a heightened level of oxygen depletion in aquatic environments. This diminishes the oxygen accessible to higher types of aquatic life, leading to the mortality of aquatic species [38]. The influent treatment achieved a 17.7% reduction in BOD at the Al-Samra Wastewater Treatment facility (Table 3). The effluents from all selected enterprises exhibited BOD values of 0.140 mg/L, failing to comply with WHO standards [6]. BOD norms of 60 mg/L. The heightened BOD levels in the effluent may stem from the presence of organic compounds, such as pure acrylic and styrene-acrylic binders, cellulose-based thickeners, and organic pigments, which are prone to microbial breakdown.

The BOD/COD ratio, known as the biodegradability index, is a crucial metric for evaluating the potential breakdown of organic matter in wastewater prior to treatment. A BOD/COD ratio greater than 0.6 indicates that the wastewater is comparatively biodegradable and appropriate for biological treatment methods [39]. Despite the treatment lowering the BOD/COD levels in the effluents, they persisted over 0.6 (Table 3). Increased BOD levels can result in effects akin to those induced by low dissolved oxygen, such as stress, asphyxiation, and mortality of aquatic animals. The discharge of wastewater with high BOD levels into aquatic ecosystems can markedly reduce dissolved oxygen, resulting in the asphyxiation and mortality of aquatic creatures in the impacted water bodies. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are often employed metrics for assessing the degree of organic contamination in water and wastewater systems [40].

Table 3: Chemical Qualities of Treated Wastewater of Al-Samra.

Category	Parameter	Value	Unit
Physical-Chemical	pH	6.85	-
	Temperature	26.7	°C
	Turbidity	3.0	NTU
	Total Suspended Solids (TSS)	22 (304*)	mg/L
	Dissolved Solids (DS)	32.0	g/L
	Volatile Solids (VS)	63.0	g/L
Organic Matter	COD	37.4	mg/L
	Volatile Suspended Solids (VSS)	82.9% of TSS	-
Nutrients	Total Alkalinity (TA)	3600	mg/L
	Volatile Acidity (VA)	125	mg/L
	VA/TA Ratio	0.03	-
	Total Kjeldahl Nitrogen (TKN)	4.0	mg/L
	Ammonia-Nitrogen (NH_3-N)	0.9	mg/L
	Nitrate-Nitrogen (NO_3-N)	18.3	mg/L
	Nitrite-Nitrogen (NO_2-N)	0.1	mg/L
	Total Phosphorus (P)	6.8	mg/L
	Dissolved Phosphorus	6.6	mg/L
Gases & Salts	Dissolved Oxygen (DO)	5.7	mg/L
	Sulfide	3.6	mg/L
	Sulfate (SO_4^{2-})	1487	mg/L
Microbial	Fecal Coliform	2.0	CFU/100 mL
Other	Oil & Grease	7.0	mg/L
	Free Chlorine	0.2	mg/L
	Total Chlorine	1.2	mg/L

Oil and grease are viscous, gelatinous lubricants distinguished by their high density and capability to remain buoyant on water owing to their low density. Increased levels of oil and grease (O and G) in aquatic ecosystems can severely hinder productivity. The World Health Organisation (WHO) does not have explicit guidelines for O and G; nonetheless, its wastewater discharge limitations of 0.1 mg/L and 2.5 mg/L show that all analysed wastewater samples significantly exceeded these regulatory levels, categorising them as hazardous for disposal. Excessive oil and grease in released effluents lead to the displacement and killing of aquatic creatures. The deposition of oil and grease on water surfaces hinders sunlight penetration, interrupting the photosynthesis of aquatic plants and thus reducing oxygen levels in aquatic systems [41].

Nitrates are produced by the aerobic decomposition of organic nitrogenous substances, whereas phosphates are essential nutrients for plant development. Nitrates and phosphates significantly contribute to water contamination as essential nutrients for algae proliferation. Organic nitrogen is turned into ammonia, which is then oxidised to produce nitrate, while organic phosphorus is changed into inorganic phosphate, promoting algal growth [29]. Only the effluent from company B complied with the regulation discharge criteria of 45 mg/L as stipulated by the WHO [6].

The effluent from the companies (P-Total: 6.8 mg/L, P-Dissolved:

6.6 mg/L, NO3-N: 18.3 mg/L, NO2-N: 0.1 mg/L) complied with the WHO nitrate disposal standards. The presence of nitrogenous chemicals in the effluent, including nitrocellulose thickener and resin, may explain the elevated nitrate levels. The discharge of these effluents can elevate nutrient loading in the receiving watershed, resulting in eutrophication.

Sulphate is an essential nutrient for tissue development in both flora and fauna. Sulphates play a crucial role in the global sulphur cycle owing to their capacity for reduction and oxidation through chemical and microbiological processes. Microorganisms diminish sulphates, establishing a link between sulphur and carbon biogeochemical pathways, which is essential for the breakdown of marine benthic sediments under anoxic conditions

[34]. Nonetheless, the treatment of raw wastewater decreased sulphate concentrations by 3.6 mg/L. The release of high-sulfate effluents might enhance the leaching of metals from streambed sediments, resulting in elevated flow alkalinity, which may harm aquatic organisms with insufficient tolerance for elevated pH values [42].

The WHO Standard [6] stipulates that chloride concentrations in wastewater must not exceed 350 mg/L to maintain environmental protection. Subsequently, all examined effluent samples adhered to the allowable regulatory thresholds post-treatment. Elevated chloride concentrations in aquatic ecosystems can destabilise ecological food chains, threatening the survival, growth, and reproductive viability of numerous species [41].

Total Suspended Solids (TSS) denote the concentration of particle matter suspended in water and are frequently employed to evaluate pollution levels in wastewater. Furthermore, TSS functions as a dependable measure of water turbidity, indicating the clarity and quality of the water [43]. The untreated wastewater from Al-Samra Wastewater Treatment exhibited a TSS concentration of 304.0 mg/L (Table 3). The dispersed particles included in the effluent conform to the standards delineated in the scientific literature for comparable factories producing paint and textiles [44].

Table 4: Sludge Treatment Process Parameters and Alerts.

Process Unit	Parameter	Status	Observed Value	Notes
Thickening Tank Overflow	$BOD_5 > COD$	Impossible	-	BOD_5 cannot exceed COD (biodegradable fraction ≤ total organic matter).
	$COD/BOD_5 < 3$	Unusual	-	Typical ratio for wastewater: $COD/BOD_5 \geq 2.5–3$.
	Free Cl_2 > Total Cl_2	Impossible	0.140 mg/L	Free chlorine is a subset of total chlorine; cannot exceed it.
	TSS > 300–500 mg/L	Unusual	304 mg/L	Borderline high TSS; may indicate poor settling.
Primary Sludge	pH < 6.5	Unusual	6.89	Close to threshold; monitor for acidification risks.
	TSS > 15 g/L	Unusual	-	High TSS may indicate poor primary settling efficiency.
Thickened Sludge	VSS > TSS	Impossible	-	VSS (volatile solids) cannot exceed TSS (total solids).
	pH < 6	Unusual	-	pH must be >6.0 for stability (typical range: 6.5–8.5).
	TSS < 50 g/L	Unusual	-	Low TSS indicates unsatisfactory thickening efficiency.
Digested Sludge	VFA/Alkalinity > 0.2	Unusual	0.04	Low ratio (ideal: 0.1–0.25); indicates stable anaerobic digestion.
	VFA > 800 mg/L	Unusual	130 mg/L	Low VFA suggests incomplete acidogenesis.
	NH_4^+-N > 1.5 g/L	Unusual	0.00 mg/L	No ammonia detected; check nitrogen balance in digestion.
Biogas	H_2 > 300 ppm	Unusual	-	High H_2 indicates process instability (e.g., acetogenesis inhibition).
	H_2S > 1%	Unusual	-	Toxic and corrosive; typical range: 0.2–0.6%.
	O_2 > 1%	Impossible	-	Biogas should be anaerobic; oxygen indicates air ingress.
Softened Water	Total Hardness (TH) > 10 mg/L	Unusual	9 mg/L	Slightly below threshold; acceptable for softened water.

Furthermore, the regulatory framework governing treated wastewater encompasses not only safety assurance but also the promotion of innovation and the encouragement of investment in wastewater treatment technologies. As the global population expands, the demand for food will inevitably rise, necessitating the acquisition of additional arable land to satisfy this growing need. It has been noted that the arable land in the study area has diminished; if the quality of water for agriculture declines, the land available for irrigated crops decreases from 51,900 hectares without restrictions to 31,070 hectares under moderate restrictions and 9,340 hectares under severe restrictions (Figure 3).

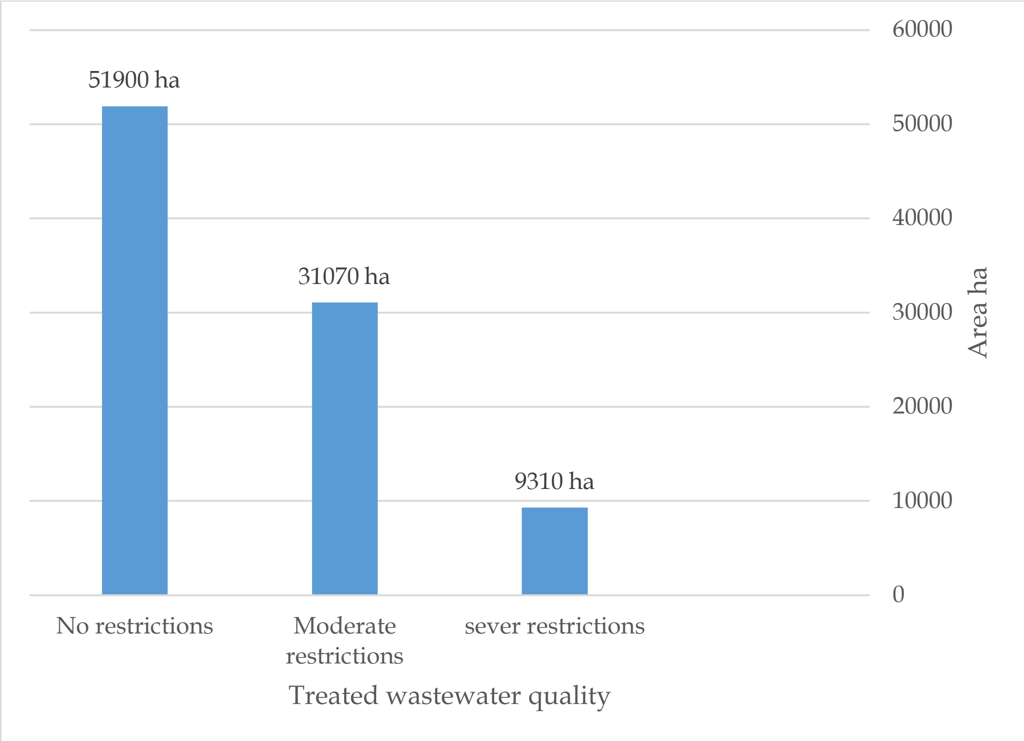

Figure 3: Available Agricultural Land (ha) in the Study Area as Affected by Different Qualities of Treated Wastewater.

This consequently exerts more strain on freshwater resources, necessitating the exploration of other sources, such as treated wastewater, to sustainably fulfil agricultural requirements [45]. Besides the economic ramifications, substantial environmental factors must be considered regarding the utilisation of treated wastewater for irrigation. The meticulous management of treated wastewater can aid in the preservation of natural water bodies, diminish the excessive extraction of groundwater, and alleviate the effects of agricultural runoff on ecosystems [46].

To augment agricultural output while simultaneously safeguarding the environment, it is essential to assess the quality of water utilised for crop irrigation [47]. A primary objective of this research is to apprise decision-makers regarding anticipated scenarios for treated water quality and its impact on crop types and the extent of arable land, as well as the significance of scientific inquiry pertaining to water utilisation in accordance with laws and regulations [48].

4. CONCLUSIONS

When utilising treated water in agriculture, it is imperative to consider the standards and specifications for water quality designated for irrigation to safeguard the health and safety of consumers of irrigated crops. The agricultural areas are significantly influenced by the quality of treated water, contingent upon its chemical qualities. Considering the constraints of limited rainfall and finite freshwater sources, it is imperative to enhance the quality of treated water to facilitate its utilisation for the majority of agricultural crops and available land, hence ensuring food security for population development.

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