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Evaluation of the Impact of Recycled Distillery Effluent on the Cultivation of Wheat and Sorghum

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Abstract: With increasing global water scarcity, the reuse of treated wastewater for agricultural irrigation offers a promising solution, particularly in arid regions. This study evaluates the impact of distillery wastewater from Kinmen Kaoliang Liquor Inc. (KKL) on the growth of wheat and sorghum in the Kinmen region. The field experiment applied varying proportions of KKL wastewater to assess its effects on soil properties, nutrient distribution, and crop performance. The results showed that wastewater irrigation increased soil concentrations of key nutrients, such as potassium (K), sodium (Na), magnesium (Mg), and phosphorus (P), but also raised the electrical conductivity (EC) and sodium adsorption ratio (SAR) beyond acceptable irrigation standards. K, Mg, Ca, and P primarily accumulated in the stems and grains, while Na was concentrated in the roots. However, higher wastewater concentrations negatively affected soil permeability due to Na accumulation, and elevated salinity levels led to reduced plant biomass. This study concludes that although wastewater irrigation improves nutrient availability, careful management is essential to mitigate salinity risks and ensure sustainable agricultural practices. These findings offer valuable insights into the potential of wastewater reuse in water-scarce regions and provide practical recommendations for managing associated risks.

Keywords: wastewater irrigation; soil salinity; nutrient accumulation; crop growth; agricultural sustainability

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1. Introduction

Facing the intensifying global extreme weather conditions, uneven rainfall distribution, and the growing demand for food and clean water driven by population growth, the issue of water scarcity is becoming increasingly urgent [1]. Agriculture, as the largest consumer of water globally, naturally faces severe challenges due to water shortages, especially in Asia and Africa [2]. The chemical composition of distillery wastewater is complex and variable, containing a large amount of both inorganic and organic compounds, posing significant challenges for treatment [3]. Howell et al. [4] found that distillery wastewater contains high levels of sodium (Na) and potassium (K), which may negatively impact soil structure. However, it also contains essential nutrients for plants, such as calcium, magnesium, phosphorus, and nitrogen, which could reduce the need for fertilizers and, consequently, lower costs. The application of treated wastewater in irrigation not only reduces the need for fertilizers but also mitigates wastewater pollution, leading to increased attention towards its use in agriculture in recent years [5]. Numerous past studies have demonstrated the potential of treated wastewater, which is rich in organic matter and nutrients, for agricultural irrigation [1,6–8]. In water-scarce regions such as parts of South Africa, Australia, and the United States, distillery wastewater is often reused for irrigation on pastures or crops [9,10]. Utilizing distillery wastewater as an alternative to water extracted from natural resources is likely to become a viable practice in the future. Repurposing distillery wastewater in this way would be particularly beneficial in areas facing water scarcity [4].

The quality of treated wastewater varies depending on its source. Common sources of treated wastewater used in previous studies include municipal sewage collected through urban drainage systems, industrial effluents from factories, as well as agricultural drainage and wastewater from distilleries. Due to varying land uses across different sites, the sources of treated wastewater may simultaneously contain multiple types. In these studies, the treated wastewater underwent different levels of treatment and was used as irrigation water for various crops ranging from cereals, grains, and tubers to vegetables and fruits, with evaluations conducted on its effects on crop growth, soil physicochemical properties, and element accumulation. Untreated raw distillery wastewater is acidic [11] and is commonly treated with large amounts of sodium hydroxide, either as a neutralizing agent or cleaning reagent, which leads to high sodium concentrations in the wastewater [12]. Treated distillery wastewater primarily consists of dissolved solids, minerals, and salts, including Na^+, K^+, Ca^{2+}, Cl^-, Mg^{2+}, Fe^{3+}, $HCO_3{}^-$, and $CO_3{}^{2-}$ [13]. These trace elements contribute to salinity, raising the electrical conductivity (EC) of the wastewater, while Na^+, Ca^{2+}, and Mg^{2+} increase the sodium adsorption ratio (SAR) [14]. The residual components in treated distillery wastewater are considered nutrient resources for plants and soil [15], but excessive application can lead to nitrate leaching and groundwater contamination [16]. The effectiveness of treated wastewater in providing nutrients for crop cultivation has been well documented. Singh [5] pointed out that using treated wastewater for irrigation can directly supply soil nutrients, serving as a substitute for fertilizers, thereby reducing fertilizer application rates and enhancing crop yields. Samarah et al. [17] found that when treated municipal wastewater was used to grow barley, an increase in the proportion of treated wastewater led to a rise in total nitrogen in the irrigation water, which in turn improved yield, dry weight, plant height, and water use efficiency. Alkhamisi et al. [18] utilized treated municipal wastewater to irrigate maize, wheat, and cowpea, and discovered that the supply of potassium, calcium, magnesium, and phosphorus from the treated wastewater was about 1.3 times that of groundwater, with crops showing higher yields and water use efficiency. Alkhamisi et al. [19] used tertiary-treated wastewater to irrigate forage crops and found that the treated wastewater provided up to 80 times more nitrogen, seven times more potassium, and four times more calcium compared to groundwater, resulting in superior crop performance in terms of dry weight, plant height, leaf area, protein content, and water use efficiency. Kiziloglu et al. [20] used treated municipal wastewater at different treatment stages to irrigate cauliflower and red cabbage, and found that wastewater from any treatment stage provided higher levels of nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, with a consistent trend of higher nutrient accumulation in the plants correlating with increased irrigation supply, and untreated wastewater having the highest nutrient concentrations accompanied by the highest yields.

On the other hand, the high salinity and varying inorganic salt contents of treated wastewater may also have adverse effects on crops and the environment. Excessive salinity can hinder plants' ability to absorb water due to osmotic stress [21,22]. The accumulation of salts in the soil from irrigation water may alter soil physical and chemical properties. While calcium and magnesium ions promote soil particle aggregation, sodium ions cause soil particle dispersion, leading to the formation of dense soil layers and reduced soil permeability [23]. In addition to serving as plant nutrients, the organic matter in treated wastewater also helps improve soil texture and increase permeability [24]. However, high salinity in water is often accompanied by elevated levels of sodium and chloride ions, with excessive sodium accumulation in plants potentially causing difficulties in water absorption, reduced nutrient uptake and photosynthetic efficiency, cell damage, and consequently, reduced germination rates, biomass, and yield [22]. Different crops exhibit varying levels of tolerance to salinity, and their growth responses to salt accumulation also differ significantly [25]. Wheat and sorghum are generally classified as moderately tolerant species, withstanding irrigation water electrical conductivity (EC) levels of up to 2400 to 3000 μS/cm [26,27].

Wastewater irrigation serves as an alternative resource to alleviate the pressure on freshwater usage. However, it is crucial to ensure that the quality of the wastewater does not pose risks to human health or the environment. As a result, international organizations and individual countries have developed regulations and guidelines for wastewater reuse. Notable examples include the Guidelines for the Safe Use of Wastewater in Agriculture by the Food and Agriculture Organization (FAO) and the Water Reuse Guidelines by the Environmental Protection Agency (EPA) [28]. Countries with advanced wastewater management systems have also implemented regulations for wastewater reuse in irrigation. For instance, China has established the GB20922-2007 standards [29]; Colorado, USA, has enacted reclaimed water regulations; Spain has introduced water reuse laws; and Italy's National Interministerial Committee for the Protection of Water from Pollution has developed relevant guidelines [30]. In Taiwan, irrigation water quality standards are based on the guidelines issued by the Ministry of Agriculture. In summary, the quality characteristics of treated wastewater often include high levels of organic matter and nutrients, which can benefit crop growth. However, treated wastewater may also contain high salinity, heavy metals, organic pollutants, or pathogenic microorganisms, potentially leading to long-term environmental and health risks [31]. Therefore, the use of treated wastewater in agriculture requires careful evaluation and management [32].

This study conducted a small-scale field experiment in which distillery wastewater from the Kinmen Kaoliang Liquor Inc. (KKL) was reused to irrigate the most widely cultivated sorghum and wheat varieties in the Kinmen area. The experiment involved analyzing the quality of the irrigation water, soil properties, and the distribution of potassium, sodium, calcium, magnesium, and phosphorus elements in the plant tissues to investigate the potential environmental and crop impacts of using treated wastewater for agricultural irrigation. The purpose of this study is to quantify the effects of various dilution ratios of Kinmen distillery wastewater on crop yield and to evaluate its impact on crop physiology and the environment. The wastewater has been treated to meet Taiwan's regulatory standards. If this wastewater can be successfully reused for agricultural irrigation, it would enhance water resource recycling and serve as a reference for future wastewater irrigation strategies in the Kinmen region.

2. Materials and Methods

2.1. Study Site

The experimental field is located in Jinhu Township, Kinmen County (24°26′48″ N, 118°27′21″ E), within the experimental plots of the Kinmen County Agricultural Research Institute. The soil texture is sandy loam, characterized by poor fertility, low organic matter content, and limited water and nutrient retention capacity (Kinmen County Agricultural Research Institute, 2008). According to the Central Weather Bureau's measurements at the Kinmen station, during the wheat cultivation period in this study, the area received approximately 180 mm of rainfall, with an evaporation rate of 245 mm; during the sorghum cultivation period, rainfall was about 23 mm, with an evaporation rate of 260 mm. The wheat cultivation period was from November 2022 to April 2023, with an average daily sunlight duration of 4.4 h and an average nighttime duration of 13 h. The sorghum cultivation period was from September 2023 to January 2024, with an average daily sunlight duration of 5.4 h and an average nighttime duration of 12 h.

Due to the hydrogeological conditions in Kinmen, the region's agriculture is predominantly focused on dryland crops such as sorghum and wheat. According to the Ministry of Agriculture's Agricultural Statistics Yearbook, from 2018 to 2022, the total agricultural planting area in Kinmen was approximately 3530 ha, with sorghum covering 1696 ha (47.9%) and wheat covering 1777 ha (50.5%). Together, these two crops accounted for over

98% of the agricultural land in Kinmen, making them the primary agricultural products of the region.

The KKL is a major pillar supporting the economic and livelihood development of Kinmen. The distillery consumes a significant number of freshwater resources daily for the production of sorghum-based liquor. According to statistics, in 2023, the average daily water consumption of the Kinmen distillery reached 1656 m^3, with an effluent discharge of 291 m^3. If the wastewater generated during the liquor production process could be reclaimed and utilized, it would help alleviate, to some extent, the water scarcity issues in Kinmen.

2.2. Experimental Design

The experimental crops included the most widely cultivated wheat and sorghum varieties in the Kinmen region. For wheat, the variety used was Taichung Selection No. 2 (*Triticum aestivum* L. *em Thell*), which has a plant height of approximately 90 cm, a growth period of around 125 days, and exhibits tolerance to high temperatures and intense sunlight. It is resistant to lodging, heavy fertilization, and shows some resistance to rust and powdery mildew, with an average yield of about 3700 kg/ha [33]. According to the Ministry of Agriculture's Agricultural Statistics Yearbook, the actual average yield of wheat in Kinmen is approximately 2230 kg/ha, with a crop water requirement of about 387 mm [34]. For sorghum, the hybrid variety Taichung No. 5 (*Sorghum bicolor* L. *Moench*) was selected. This variety has a plant height of approximately 130 cm, a growth period of 110 days, and is known for its tolerance to poor soils and resistance to pests and diseases, with an average yield of about 5000 kg/ha [35]. The actual average yield of sorghum in Kinmen, according to the Agricultural Statistics Yearbook, is approximately 1253 kg/ha, with a crop water requirement of about 405 mm [34].

The total area of the experimental field was approximately 1000 m^2, divided into five treatments (Control, 20% KKL, 40% KKL, 60% KKL, 80% KKL), with each treatment consisting of three replicates, totaling 15 subplots. Each subplot measured 4×5 m^2, with a 3-m gap between plots to minimize interference between different treatments. Irrigation was conducted using five water storage tanks connected to perforated pipes. The control treatment was irrigated with untreated water from the Houlong River (HR). The experimental treatments were irrigated with a mixture of wastewater from the KKL and HR water, combined in the following proportions for the five storage tanks: 100% HR water (Control), 80% HR water + 20% KKL water (20% KKL), 60% HR water + 40% KKL water (40% KKL), 40% HR water + 60% KKL water (60% KKL), and 20% HR water + 80% KKL water (80% KKL).

In water-scarce regions, treated wastewater is diluted before being used for irrigation. However, if the diluted wastewater has a pH below 6, it can cause nutrient toxicity; if its EC is below 2 dS/m, it will not pose a salinity hazard; and if the SAR remains below 10, it will not cause alkalinity problems. In addition to these three indicators, chemical oxygen demand (COD), Cl^-, K^+, and Na^+ are also key parameters of concern [36]. The distillery wastewater used in this study from KKL has a pH of 7.7, an EC of 3140 dS/m, an SAR of 28.4 $(meq/L)^1/^2$, a K^+ concentration of 212.5 mg/L, and a Na^+ concentration of 1039.7 mg/L. Overall, this wastewater is unsuitable for irrigation and must be diluted to mitigate potential hazards [37].

The wheat was sown on 30 November 2022 and harvested on 11 April 2023. During the growth period, a basal fertilizer was applied once before sowing, and irrigation with the experimental water mixtures was conducted twice on 14 February and 20 March 2023. Irrigation water samples were collected twice, on 14 February and 20 March 2023, soil samples were collected twice, before irrigation on 14 February and at harvest on 11 April 2023, and plant samples were collected three times, before irrigation on 14 February, before irrigation on 20 March, and at harvest on 11 April 2023. The sorghum was sown on 26 September 2023 and harvested on 29 January 2024. Basal and top-dressing fertilizers were applied twice, before sowing and on 14 November 2023, respectively.

Irrigation with the experimental water mixtures was conducted four times on 6 and 20 December 2023, and 3 and 17 January 2024. Irrigation water samples were collected twice, on 6 December 2023 and 3 January 2024. Soil samples were collected twice, on 14 November and at harvest on 29 January 2024, and plant samples were collected four times, on 14 November, before irrigation on 6 December 2023, before irrigation on 3 January, and at harvest on 29 January 2024. Each irrigation event involved a total water application of 2000 L per experimental treatment (totaling 4000 L for the entire wheat experiment and 8000 L for the entire sorghum experiment). Fertilizer application was standardized at 40 kg of organic compound fertilizer (N–P_2O_5–K_2O–CaO–S–organic matter: 20%–5%–10%–6.5%–4.5%–3%) (Taiwan Fertilizer Co. Ltd., Taipei, Taiwan) and 300 kg of basal fertilizer (N–P2O_5–K_2O–organic matter: 5–2%–1.5%–75%) (Taiwan Fertilizer Co., Ltd., Taipei, Taiwan) applied across the entire experimental field. Regarding the plant sample, during the wheat cultivation period, three times of sample collection were conducted, with approximately 375 wheat plants sampled each time. The average dry weight for every 20–30 wheat plants was 36.6 g. During the sorghum cultivation period, four times of sample collection were conducted, totaling 60 sorghum plants (15 plants per sample). At harvest, the average dry weight per sorghum plant was 85.2 g.

2.3. Analytical Methods for Water, Soil, and Plant

The analysis of irrigation water included measurements of pH, electrical conductivity (EC), and the concentrations of potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), and phosphorus (P), as well as the sodium adsorption ratio (SAR). The pH and EC of the irrigation water were measured using a pH and EC meter (Thermo Scientific Orion Star^{TM} A325 pH/conductivity portable multiparameter meter (Thermo Fisher Scientific Inc., Waltham, MA, USA). For the analysis of K, Na, Ca, Mg, and P concentrations, 45 mL of water samples preserved with nitric acid (adjusted to pH ≤ 2) were taken, followed by the addition of 4 mL concentrated nitric acid (Merck KGaA, Darmstadt, Germany) and 1 mL concentrated hydrochloric acid (Merck KGaA, Darmstadt, Germany). The samples were then digested using a microwave digestion system CEM, MARS 6 (Toyo Kohan Co., Ltd., Tokyo, Japan), and the concentrations of K, Na, Ca, Mg, and P in the irrigation water were determined using the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (Agilent Technologies, Inc., Santa Clara, CA, USA) procedure described by the National Environmental Research Academy (NIEA W311.54C) [38].

Soil analysis included measurements of pH, EC, and the concentrations of K, Na, Ca, Mg, and P, along with the assessment of available P and available K in the soil. Soil samples were collected from the 0 to 15 cm topsoil layer before and after irrigation, dried in an oven at 30 °C for 72 h, and ground. Soil pH was determined in 1:1 soil-to-water extracts, and Soil EC was measured in 1:5 soil-to-water extracts following procedures (TARI S501.1B) and (TARI S101.1B), respectively, by the Taiwan Agricultural Research Institute, Ministry of Agriculture [39]. For the determination of K, Na, Ca, Mg, and P concentrations, 0.5 g of air-dried soil passing through a No. 100 sieve was digested using 6 mL of concentrated hydrochloric acid and 2 mL of concentrated nitric acid in a microwave digestion system, CEM-MARS6 (Toyo Kohan Co., Ltd., Tokyo, Japan) using the NERA procedure (NIEA S301.61B) [40]. The elemental concentrations were then measured using ICP-OES (Agilent Technologies, Inc., Santa Clara, CA, USA) according to the NERA procedure (NIEA M104.02C) [41]. Available P and K were measured by extracting 5 g of air-dried soil passing through a No. 10 sieve with 50 mL of Mehlich 3 solution (Merck KGaA, Darmstadt, Germany). The mixture was shaken at 140 rpm for 5 min in a reciprocal shaker, filtered, and the concentrations of available P and K in the soil were determined using ICP-OES (Agilent Technologies, Inc., Santa Clara, CA, USA).

Plant tissue analysis included the determination of the concentrations of K, Na, Ca, Mg, and P in different parts of the plant (roots, stems, leaves, and grains), as well as the calculation of translocation factors for these elements. Whole plant samples were collected, washed, and dried in an oven at 60 °C for 72 h. The samples were then separated into roots, stems, leaves, and grains, ground, and 0.5 g of each part was taken for analysis. The samples were digested with 6 mL of concentrated hydrochloric acid (Merck KGaA, Darmstadt, Germany) and 2 mL of concentrated nitric acid (Merck KGaA, Darmstadt, Germany) using a microwave digestion system, and the elemental concentrations in each plant part were measured using ICP-OES (Agilent Technologies, Inc., Santa Clara, CA, USA). The translocation factor is calculated as the ratio of element concentrations between different plant parts, indicating the element transport trends within the plant. Typically, the concentration ratio between above-ground parts and roots is used. In this study, the concentration of elements in the stems, leaves, and grains was weighted by dry weight and divided by the concentration in the roots to calculate the translocation factor.

2.4. Statistical Analysis

The soil and plant tissue sample analysis results were grouped according to the irrigation water treatments and analyzed using the statistical software SAS (SAS Enterprise Guide 8.3) (SAS Institute Inc., Cary, NC, USA) and SPSS (IBM SPSS Statistics 26) (International Business Machines Corporation, Endicott, NY, USA). Initially, Levene's test for homogeneity of variances was conducted. If the test was not significant (indicating homogeneity), a one-way analysis of variance (ANOVA) was performed. If significant differences were found among groups, a post hoc test using the Least Significant Difference (LSD) method was applied to compare the effects of different wastewater irrigation ratios on soil properties and element distribution in plant tissues. If Levene's test indicated significant heterogeneity (non-homogeneous variances), Welch's ANOVA, which accounts for variance heterogeneity, was used to assess whether significant differences existed among the treatments. If significant differences were found, a post hoc test using the Dunnett T3 method was applied.

3. Results

3.1. Water Properties

The wastewater used in this study was the effluent from the Kinmen Distillery's Jinning plant. The effluent characteristics were monitored from August to November 2021 and from March to May 2022. According to data provided by the Agricultural Engineering Research Center, regulated parameters include pH and eight major heavy metals. The results showed that the effluent contained almost no detectable heavy metals, and the pH values were within the regulatory standards. However, other parameters exceeded Taiwan's irrigation water standards. The average electrical conductivity (EC) was 3393.3 μS/cm in 2021 and 3263 μS/cm in 2022, significantly higher than the national standard of 750 μS/cm. Similarly, other indicators were elevated, with the average chloride levels recorded at 248.7 mg/L and 251 mg/L in 2021 and 2022, respectively (standard: 175 mg/L), ammonium nitrogen (NH_3-N) at 22 mg/L and 9.8 mg/L in 2021 and 2022, respectively (standard: 3 mg/L), sodium adsorption ratio (SAR) at 11.3 and 6.9 $(meq/L)^{1/2}$ in 2021 and 2022, respectively (standard: 6.0 $(meq/L)^{1/2}$), and residual sodium carbonate (RSC) at 12.2 and 6.7 meq/L in 2021 and 2022, respectively (standard: 2.5 meq/L). The 2022 Kinmen Distillery Sustainability Report noted that the average biological oxygen demand (BOD) of the effluent in 2021 was 10.1 mg/L, while the average chemical oxygen demand (COD) reached 52.3 mg/L and 62.2 mg/L in 2021 and 2022, respectively. Despite the effluent's high SAR, salinity, residual sodium carbonate, and ammonium nitrogen levels, it also contained high concentrations of essential macronutrients such as calcium, magnesium, and sodium, which could support crop growth [42].

Taiwan irrigation water quality standards include control items and quality items. The control items include heavy metals (Cr, Ni, Cu, Zn, Cd, Pb, As, Hg) and pH; the quality items include EC, SS, NH_3-N, SAR, RSC, Cl^-, SO_4^{2-}, DO, anionic surfactants, oil, and grease. The results of the irrigation water quality analysis for the two experiments are presented in Table 1. The pH ranged between 6.55 and 8.13, and the EC values increased with the proportion of wastewater used. Except for the control treatment, all KKL treatments exceeded the irrigation water quality standard (EC > 750 µS/cm). The SAR ranged from a low of 2.55 $(meq/L)^{1/2}$ in the control treatment for sorghum experiment to a high of 12.56 $(meq/L)^{1/2}$ in the 80% KKL treatment for wheat experiment. Additionally, all treatments with more than 40% KKL exceeded the irrigation water quality standard for SAR (>6 $(meq/L)^{1/2}$). Since the original KKL effluent contains high concentrations of K, Na, Mg and P, the concentrations of K, Na, Mg, and P increased with the proportion of wastewater. However, the Ca concentration did not show a significant trend with the increasing proportion of wastewater.

Table 1. Chemical analysis of different treatment waters for wheat and sorghum experiments.

		Control	KKL Treatments				Original KKL Effluent	Standards [1]
			20%	40%	60%	80%		
Wheat	pH	6.55	7.40	7.77	8.13	7.99	7.87	6~9
	EC (µS/cm)	597.6	1084.6	2073.5	2779.0	3397.0	3625.0	<750
	K (mg/L)	20.53	57.68	137.80	197.05	254.58	283.58	-
	Na (mg/L)	71.40	150.40	327.35	455.60	579.90	591.08	-
	Ca (mg/L)	24.70	24.78	26.20	26.63	29.53	27.65	-
	Mg (mg/L)	5.75	18.20	44.28	62.88	80.95	92.10	-
	P (mg/L)	3.78	20.50	56.40	83.28	111.03	126.03	-
	Cr (mg/L)	ND	ND	ND	ND	ND	ND	<0.1
	Ni (mg/L)	ND	ND	ND	ND	ND	ND	<0.2
	Cu (mg/L)	ND	ND	ND	ND	ND	ND	<0.2
	Zn (mg/L)	0.13	0.1	0.15	0.18	0.3	0.15	<2
	Cd (mg/L)	ND	ND	ND	ND	ND	ND	<0.01
	Pb (mg/L)	ND	ND	ND	ND	ND	ND	<0.1
	As (mg/L)	ND	ND	ND	ND	ND	ND	<0.05
	Hg (mg/L)	ND	ND	ND	ND	ND	ND	<0.002
	NH_3-N (mg/L)	1.7	1.75	1.9	1.4	1.75	1.95	<3
	Cl^- (mg/L)	93.14	113.78	141.82	162.49	190.23	190.60	<175
	SO_4^{2-} (mg/L)	37.49	38.71	31.59	28.15	25.20	23.23	<200
	SAR $(meq/L)^{1/2}$	3.38	5.62	9.09	11.04	12.5	12.20	<6.0
Sorghum	pH	6.58	7.40	7.74	7.85	7.92	8.02	6~9
	EC (µS/cm)	694.0	1212.5	1809.0	2393.5	2725.5	3727.0	<750
	K (mg/L)	23.74	58.70	101.99	143.66	169.18	241.94	-
	Na (mg/L)	65.02	147.83	246.60	339.60	392.49	543.16	-
	Ca (mg/L)	38.41	39.12	39.07	38.12	44.94	30.51	-
	Mg (mg/L)	7.36	21.25	38.61	54.72	66.16	93.26	-
	P (mg/L)	2.44	20.37	41.95	62.67	81.69	109.90	-
	Cr (mg/L)	ND	ND	ND	ND	ND	ND	<0.1
	Ni (mg/L)	ND	ND	ND	ND	ND	ND	<0.2
	Cu (mg/L)	ND	ND	ND	ND	ND	ND	<0.2
	Zn (mg/L)	0	0.12	0.15	0.15	0.31	0.06	<2
	Cd (mg/L)	ND	ND	ND	ND	ND	ND	<0.01
	Pb (mg/L)	ND	ND	ND	ND	ND	ND	<0.1
	As (mg/L)	0.01	0.02	0.01	0.02	0.02	0.01	<0.05
	Hg (mg/L)	ND	ND	ND	ND	ND	ND	<0.002
	NH_3-N (mg/L)	1.45	4	3.5	4.55	5.15	5.7	<3
	Cl^- (mg/L)	93.14	113.78	141.82	162.49	190.23	190.60	<175
	SO_4^{2-} (mg/L)	78.99	65.91	43.36	30.70	23.71	ND	<200
	SAR $(meq/L)^{1/2}$	2.55	4.75	6.72	8.27	8.73	11.06	<6.0

Note: [1] Irrigation Water Standards, Ministry of Agriculture [43].

3.2. Soil Properties

The soil test results before and after the wheat experiment are shown in Table 2, while those for the sorghum experiment are shown in Table 3. It can be observed that the differences in soil properties between the treatments increased after irrigation. Except for soil pH, the soil EC, and the concentrations of K (K), Na (Na), Ca (Ca), Mg (Mg), P (P), available P, and available K all showed an upward trend with the increasing proportion of wastewater, indicating that wastewater irrigation effectively increased soil nutrient concentrations.

Table 2. Chemical properties of the surface soil before planting and after harvest with different treatment waters for wheat experiment.

Date		Control	KKL Treatments				*p*-Value [1]
			20%	40%	60%	80%	
Before planting (2/14)	pH	4.44 ± 0.32c	4.73 ± 0.45ab	4.60 ± 0.20bc	4.95 ± 0.13a	4.74 ± 0.29ab	0.551
	EC (1:5) (μS/cm)	193.43 ± 41.18c	328.63 ± 193.78ab	289.77 ± 129.39bc	252.03 ± 72.90bc	393.33 ± 92.75a	0.541
	K (mg/kg)	1589.33 ± 190.72a	1465.00 ± 225.71a	1082.67 ± 396.69b	1040.67 ± 166.64b	1497.00 ± 178.19a	0.153
	Na (mg/kg)	171.33 ± 35.31b	212.33 ± 72.34b	215.33 ± 72.44b	270.67 ± 61.76a	309.33 ± 35.16a	0.215
	Ca (mg/kg)	810.67 ± 127.42b	1216.67 ± 468.39a	1051.67 ± 145.21a	1192.00 ± 160.81a	1187.33 ± 69.59a	0.450
	Mg (mg/kg)	455.00 ± 47.84ab	482.00 ± 112.02a	381.67 ± 100.45b	480.00 ± 104.55a	523.67 ± 105.75a	0.681
	P (mg/kg)	730.67 ± 149.24b	828.33 ± 214.84ab	764.67 ± 14.38b	911.33 ± 42.87a	789.67 ± 43.05b	0.631
	Available P (mg/kg)	108.07 ± 47.50b	133.70 ± 51.37ab	124.20 ± 15.00ab	126.00 ± 11.39ab	142.50 ± 0.45a	0.864
	Available K (mg/kg)	108.13 ± 14.61b	148.40 ± 61.21ab	174.33 ± 88.89a	110.47 ± 25.95b	164.93 ± 59.04a	0.681
After harvest (4/11)	pH	5.04 ± 0.06a	4.73 ± 0.24b	4.49 ± 0.12c	5.05 ± 0.29a	4.76 ± 0.10b	0.053
	EC (1:5) (μS/cm)	120.68 ± 34.13c	154.73 ± 52.16c	322.23 ± 72.57b	339.80 ± 84.43b	409.43 ± 114.17a	0.015
	K (mg/kg)	1046.67 ± 36.54cd	977.00 ± 51.98d	1166.00 ± 281.64c	1459.00 ± 271.68b	1796.67 ± 231.62a	0.014
	Na (mg/kg)	107.00 ± 31.79c	105.67 ± 7.13c	266.00 ± 97.16b	291.00 ± 86.10b	378.33 ± 132.15a	0.033
	Ca (mg/kg)	658.00 ± 137.57c	680.33 ± 97.72c	953.67 ± 304.37b	1207.67 ± 37.75a	1305.67 ± 444.09a	0.090
	Mg (mg/kg)	286.00 ± 9.63c	311.33 ± 18.19c	429.67 ± 104.93b	629.00 ± 80.65a	692.33 ± 165.08a	0.005
	P (mg/kg)	481.33 ± 101.73e	593.33 ± 80.71d	794.00 ± 210.32c	1141.00 ± 22.76a	991.33 ± 58.98b	0.001
	Available P (mg/kg)	130.90 ± 22.09c	137.07 ± 17.03c	143.77 ± 35.42c	258.07 ± 51.04a	177.40 ± 35.86b	0.022
	Available K (mg/kg)	93.53 ± 15.84b	85.40 ± 26.91b	106.57 ± 22.27b	218.77 ± 36.13a	200.33 ± 69.34a	0.015

Notes: Values are the means ± standard deviation ($n = 3$). [1] ANOVA *p*-value. The different letter in each row is significantly different at $p < 0.05$, according to post-hoc test by Least Significant Difference (LSD) method.

Table 3. Chemical properties of the surface soil before planting and after harvest with different treatment waters for sorghum experiment.

Date		Control	KKL Treatments				p-Value [1]
			20%	40%	60%	80%	
Before planting (11/14)	pH	5.60 ± 0.06b	5.86 ± 0.05a	5.90 ± 0.09a	5.84 ± 0.04a	5.64 ± 0.14b	0.016
	EC (1:5) (μS/cm)	309.63 ± 63.13a	363.33 ± 43.56a	336.50 ± 91.82a	489.77 ± 56.06a	833.50 ± 367.01a	0.179 *
	K (mg/kg)	1854.33 ± 353.39b	1766.67 ± 62.99b	1913.67 ± 337.66b	2096.33 ± 148.72b	2573.33 ± 853.89a	0.435
	Na (mg/kg)	205.67 ± 74.92c	212.00 ± 46.50c	239.67 ± 50.62c	295.33 ± 24.25b	445.67 ± 41.59a	0.004
	Ca (mg/kg)	1663.67 ± 286.05c	1972.00 ± 112.82bc	2185.67 ± 429.46b	2059.67 ± 193.28b	2626.00 ± 418.38a	0.109
	Mg (mg/kg)	593.33 ± 131.60c	622.00 ± 47.10c	707.33 ± 71.21b	711.33 ± 61.33b	796.33 ± 56.10a	0.162
	P (mg/kg)	945.67 ± 133.56d	1152.33 ± 70.41c	1279.33 ± 139.99bc	1329.00 ± 133.84ab	1431.00 ± 178.00a	0.040
	Available P (mg/kg)	173.93 ± 5.83c	202.17 ± 24.52b	219.13 ± 16.12a	218.33 ± 15.78ab	205.90 ± 14.92ab	0.113
	Available K (mg/kg)	239.50 ± 53.20c	291.30 ± 23.76bc	335.80 ± 109.66b	355.07 ± 25.27b	442.07 ± 143.86a	0.260
After harvest (1/29)	pH	5.64 ± 0.25c	5.97 ± 0.18b	6.12 ± 0.08a	5.99 ± 0.10ab	6.02 ± 0.20ab	0.157
	EC (1:5) (μS/cm)	389.17 ± 235.19b	407.33 ± 162.45b	607.60 ± 80.69a	639.57 ± 133.35a	699.47 ± 265.59a	0.396
	K (mg/kg)	1979.67 ± 653.91b	1920.67 ± 428.41b	2084.67 ± 259.56b	2205.67 ± 218.48ab	2543.33 ± 438.29a	0.632
	Na (mg/kg)	252.67 ± 87.45e	318.33 ± 104.47d	436.33 ± 38.42c	518.00 ± 14.72b	630.00 ± 87.18a	0.003
	Ca (mg/kg)	1755.33 ± 428.50c	2187.33 ± 431.27b	2373.00 ± 425.38b	2497.00 ± 224.00ab	2710.67 ± 272.78a	0.181
	Mg (mg/kg)	616.00 ± 168.92d	695.33 ± 159.80cd	787.00 ± 100.57bc	852.00 ± 86.40ab	951.00 ± 40.36a	0.126
	P (mg/kg)	995.33 ± 17.82d	1272.67 ± 183.16c	1346.00 ± 127.67c	1511.67 ± 166.97b	1640.33 ± 82.14a	0.006
	Available P (mg/kg)	191.07 ± 28.50c	239.57 ± 2.69c	298.03 ± 4.73a	285.50 ± 3.83b	300.30 ± 3.29a	<0.0001 *
	Available K (mg/kg)	220.47 ± 122.85c	305.23 ± 99.84b	444.73 ± 65.27a	397.83 ± 52.51a	433.37 ± 97.18a	0.143

Notes: Values are the means ± standard deviation (n = 3). [1] ANOVA p-value. * Welch's ANOVA p-value. The different letter in each row is significantly different at $p < 0.05$ according to post-hoc test by Least Significant Difference (LSD) method.

Figure 1 illustrates the rate of change in soil element concentrations before and after the two experiments. The trends of change differed between the two experiments. In the wheat experiment, the element concentrations in the control treatment and the 20% KKL treatment decreased after irrigation, with significant accumulation only starting at concentrations greater than 40% KKL. In contrast, in the sorghum experiment, elemental accumulation was observed across all experimental treatments regardless of the proportion of wastewater used. Specifically, in the wheat experiment, K decreased the most in the control treatment by as much as −34.1%, while it increased the most by 40.2% in the 60% KKL treatment; Na decreased the most in the 20% KKL treatment by −50.2%, while it increased the most by 23.5% in the 40% KKL treatment; Ca decreased the most in the 20% KKL treatment by −44.1%, while it increased the most by 10.0% in the 80% KKL treatment; Mg decreased the most in the control treatment by −37.1%, while it increased the most by 32.2% in the 80% KKL treatment; and P decreased the most in the control treatment by −34.1%, while it increased the most by 25.5% in the 80% KKL treatment. In the sorghum experiment, K increased the most in the 20% KKL treatment by 13.7%; Na increased the most in the 40% KKL treatment by 70.8%; Ca increased the most in the 20% KKL treatment by 18.0%; Mg increased the most in the 80% KKL treatment by 20.2%; and P increased the most in the 80% KKL treatment by 26.9%.

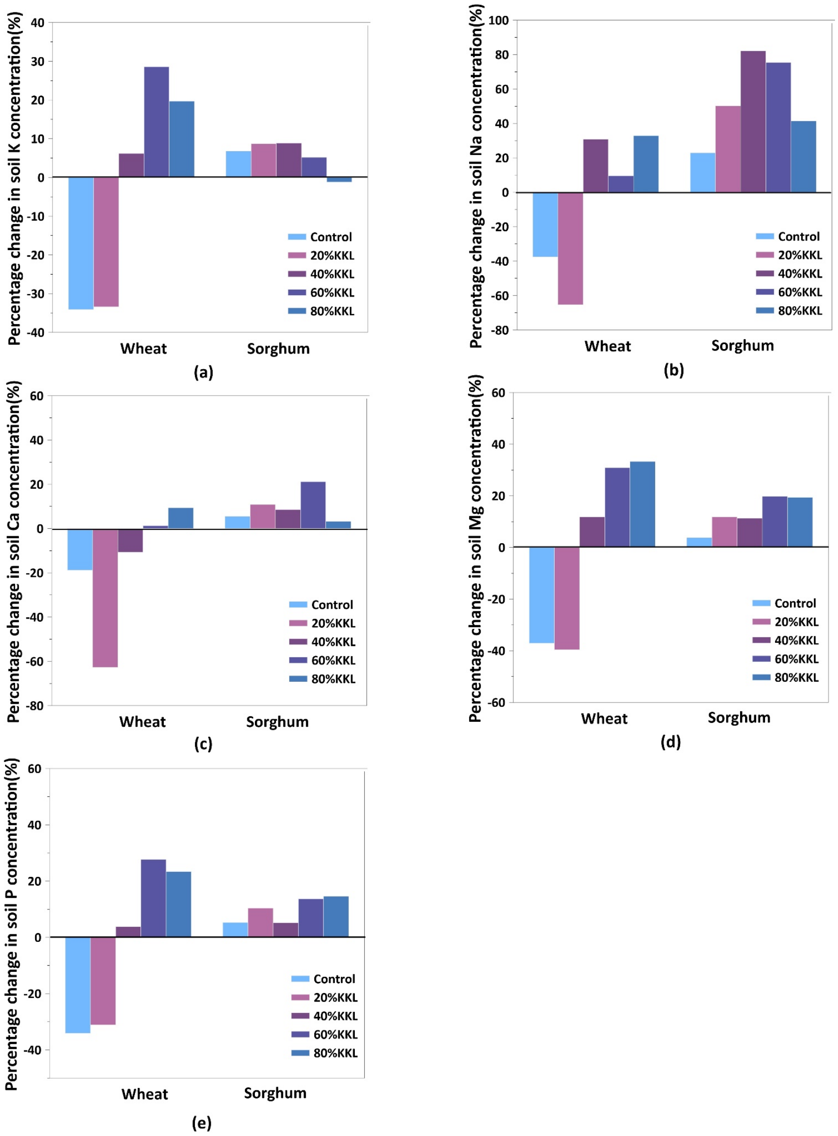

Figure 1. Changes in soil property after irrigation.

3.3. Plant Properties

Table 4 presents the concentration analysis results of K (K), Na (Na), Ca (Ca), Mg (Mg), and P (P) in various plant parts at the time of wheat and sorghum harvest. K was found at the highest concentration in the stems of both wheat and sorghum; Na was most concentrated in the stems of wheat and in the roots of sorghum; Ca was highest in the leaves of both wheat and sorghum; Mg was most concentrated in the leaves of wheat and the stems of sorghum; and P was found in the highest concentration in the grains of both wheat and sorghum. Additionally, the accumulated concentrations of elements in different plant parts increased with higher proportions of wastewater in the irrigation, although for certain elements in specific plant parts, the differences in accumulated concentrations among different wastewater treatments did not reach statistical significance.

Table 4. K, Na, Ca, Mg, P concentration in different parts of wheat and sorghum plants at harvest.

	Wheat					Sorghum				
	Control	**20%**	**40%**	**60%**	**80%**	**Control**	**20%**	**40%**	**60%**	**80%**
K (g/kg)										
Root	7.19	4.23	4.66	6.90	8.86	10.12	8.31	11.17	9.75	10.03
Stem	23.68	23.42	26.30	31.11	36.24	13.86	13.57	13.05	15.60	17.78
Leaf	9.22	9.84	9.85	11.05	11.07	12.55	14.34	13.84	15.21	14.78
Grain	5.44	4.54	5.69	7.37	10.87	5.20	6.51	6.13	6.21	6.30
Na (g/kg)										
Root	1.40	1.04	1.18	2.97	2.21	0.77	0.85	1.62	1.95	2.11
Stem	0.97	2.50	3.06	4.70	5.52	0.35	0.40	0.61	0.92	1.10
Leaf	0.40	0.75	0.91	1.44	1.47	0.12	0.13	0.23	0.38	0.29
Grain	0.18	0.25	0.45	0.83	1.72	0.50	0.61	0.73	0.98	1.02
Ca (g/kg)										
Root	1.41	1.59	1.26	1.37	1.71	1.35	1.28	1.19	0.86	1.05
Stem	2.27	3.61	3.17	3.99	3.62	3.88	2.96	2.78	2.73	2.16
Leaf	6.53	8.81	7.29	9.06	9.42	8.11	7.29	6.89	6.56	6.16
Grain	0.97	1.18	1.56	2.06	2.58	2.15	1.82	2.12	2.25	1.66
Mg (g/kg)										
Root	0.38	0.45	0.42	0.45	0.54	1.18	1.13	1.21	1.03	1.14
Stem	0.63	0.79	0.71	0.83	0.84	3.33	3.04	3.55	3.11	2.64
Leaf	1.46	1.93	1.75	1.80	2.04	2.21	2.50	2.86	2.65	2.83
Grain	1.26	1.30	1.44	1.50	1.78	2.16	2.32	2.58	2.74	2.31
P (g/kg)										
Root	0.48	0.59	0.50	0.59	0.83	1.48	1.57	1.76	1.59	1.55
Stem	0.29	0.40	0.35	0.46	0.96	2.39	2.76	2.92	2.83	2.55
Leaf	1.41	2.02	1.63	1.73	2.52	2.83	3.13	2.77	3.04	2.97
Grain	2.51	2.58	2.49	2.90	3.46	4.08	4.20	4.63	4.90	4.53

Note: Values are the means of three replicate subplots.

Figures 2 and 3 display the total distribution ratios of each element across different parts of wheat and sorghum at various stages. The plant parts with the highest total distribution of each element at harvest were consistent between wheat and sorghum: K, Ca, Mg, and P were predominantly distributed in the stems, while Na was primarily distributed in the roots. The impact of different wastewater proportions on the distribution of elements across plant parts was not significant, with most elements showing a decline in their proportion in roots and leaves as the growth period progressed.

Table 5 shows the translocation factor results for wheat and sorghum at harvest. Overall, there were no significant differences in the translocation factors of each element for sorghum under different wastewater irrigation treatments. Among the different elements, the translocation factors for K, Ca, Mg, and P were relatively high, indicating a strong tendency for these essential nutrients to be transported from the roots to the aboveground parts of the plant. In contrast, the translocation factor for Na was lower, suggesting that its movement was largely restricted to the roots.

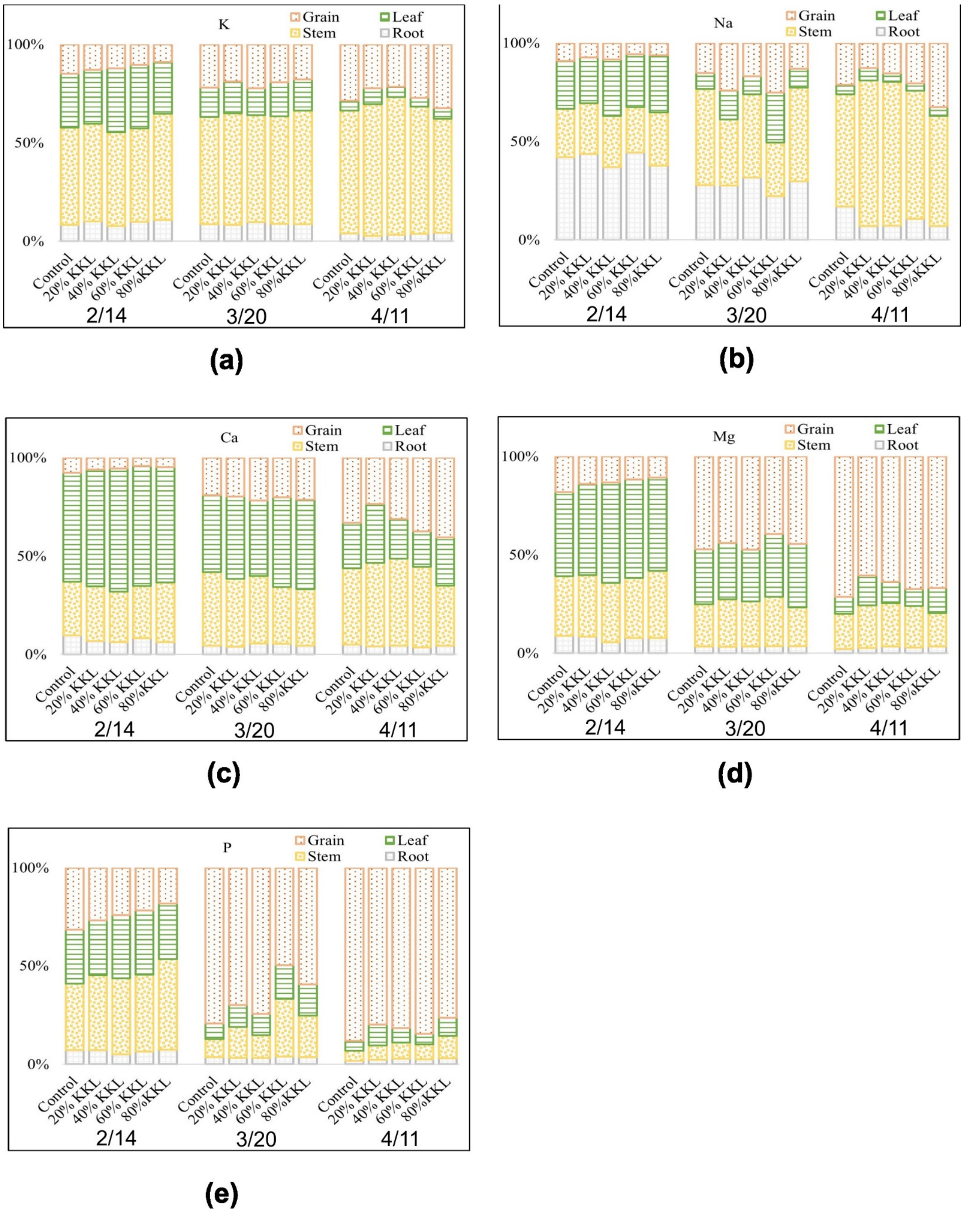

Figure 2. Elements distribution in different parts of wheat.

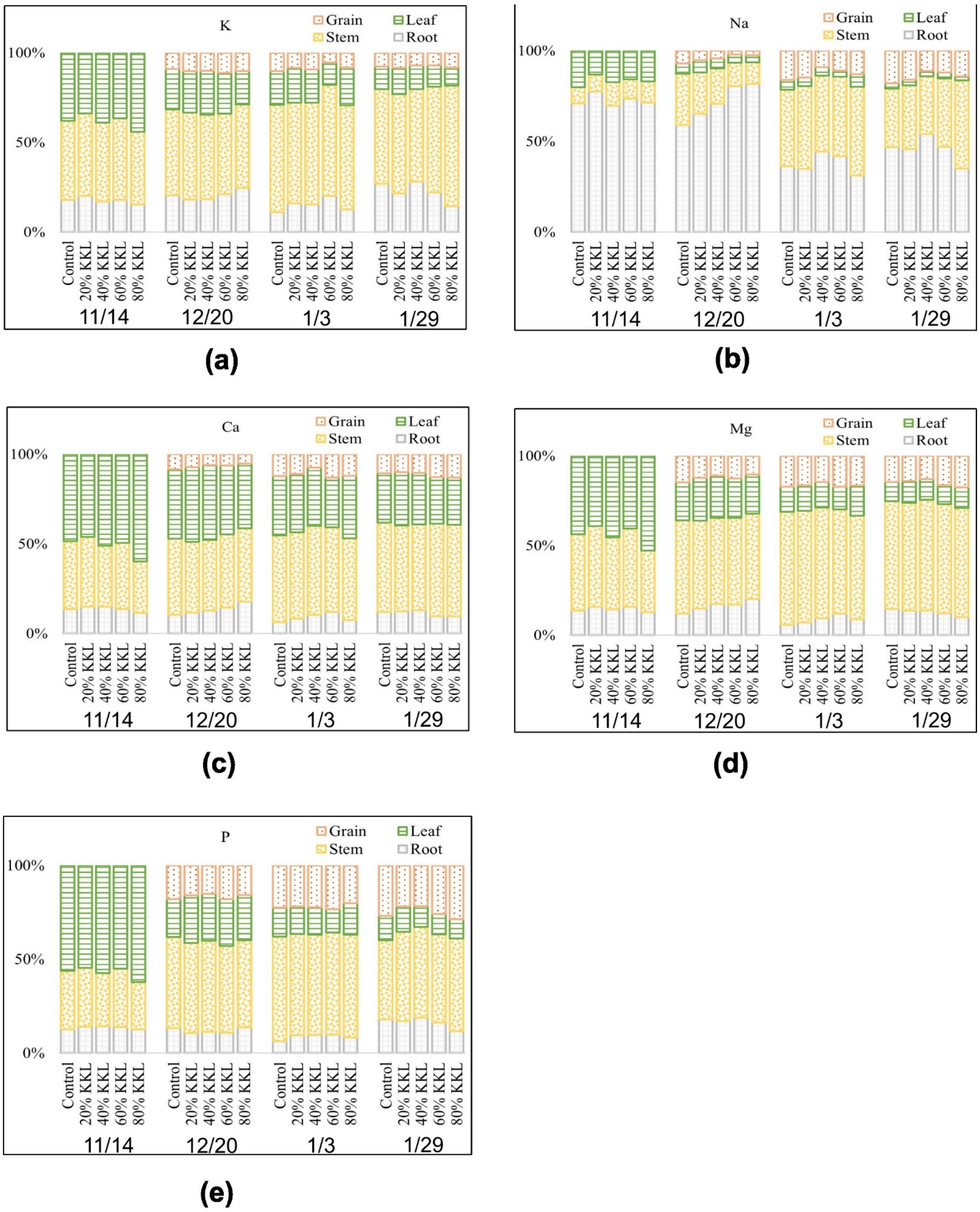

Figure 3. Elements distribution in different parts of sorghum.

Table 5. Translocation factors of wheat and sorghum plants at harvest.

	Wheat					Sorghum				
	Control	**20%**	**40%**	**60%**	**80%**	**Control**	**20%**	**40%**	**60%**	**80%**
K	1.91	2.80	3.84	2.50	3.24	1.25	1.21	1.38	1.22	1.23
Na	0.72	1.56	1.83	0.96	1.48	0.12	0.09	0.12	0.11	0.09
Ca	1.30	1.80	2.09	2.33	2.08	1.70	1.80	1.66	1.71	1.76
Mg	2.89	2.64	2.81	2.90	2.88	1.84	1.64	1.75	1.44	1.51
P	3.91	2.96	3.33	3.39	4.38	1.86	1.89	1.65	1.68	1.56

Note: Values are the means of three replicate subplots.

4. Discussion

4.1. Effect of KKL Water Irrigation on Soil Properties

The KKL wastewater contains high concentrations of inorganic salts, resulting in significant salinity. According to USSL [23] and Al-Kubaisi and Al-Salih [44], the use of moderately saline water (such as in the control treatment) requires frequent leaching and the cultivation of moderately salt-tolerant crops. For highly saline irrigation water (e.g., 20% and 40% KKL treatments), more rigorous salt management, leaching, and the use of highly salt-tolerant crops are necessary, with an additional caution to avoid poorly drained soils. For extremely saline water (e.g., 60% and 80% KKL treatments), irrigation is generally not recommended unless very high leaching rates are applied, making it only marginally suitable for very salt-tolerant crops. In terms of sodium (Na) hazard, both experiments exceeded the medium Na hazard threshold outlined by USSL [23], indicating that the water is best used on well-drained soils rich in organic matter or calcium (Ca) to counteract the negative effects of Na.

A comparison of soil property changes between the wheat and sorghum experiments (Tables 2 and 3) revealed that soil element concentrations increased with higher wastewater proportions in both experiments, aligning with the finding of previous studies [20,45]. However, despite the use of the same experimental field, initial soil properties varied between the two crop cycles. For example, soil pH and available P and K concentrations were higher at the start of the sorghum experiment, likely due to greater fertilization during early stages. In terms of elemental accumulation patterns, the two experiments differed. For the wheat experiment, soil element concentrations decreased in the control and 20% KKL treatments, with increases only observed in treatments with higher wastewater proportions. For the sorghum experiment, element concentrations increased across all treatments, regardless of wastewater proportion. Although the water quality in both experiments was similar, the differences in irrigation frequency and total water volume may explain the variation in soil accumulation patterns. Sorghum received more frequent irrigation, potentially leading to higher accumulation, whereas higher rainfall during the wheat experiment likely resulted in increased leaching of nutrients from the soil surface.

4.2. Effect of KKL Water Irrigation on Nutrient Distribution in Plants

Among the elements analyzed, potassium (K) was the most abundant element in the plant tissues, which aligns with its crucial role in plant physiology. In both wheat and sorghum, K accumulation was primarily concentrated in the stems, consistent with previous studies [46,47]. In wheat, the K concentration in the stems and grains increased with higher wastewater proportions. Although sorghum stems did not show a significant increase compared to the control treatment, the 80% KKL treatment resulted in the highest accumulation. Previous research [47] indicates that K concentrations in wheat stems are approximately three times higher than in grains, and higher K supply promotes linear increases in K accumulation. This trend was also observed in this study, where both wheat and sorghum showed higher K concentrations in plant tissues with increasing wastewater use.

In contrast, sodium (Na) was predominantly concentrated in the roots and stems of both crops, with relatively lower levels in the leaves and grains. This aligns with the protective mechanisms that plants employ to prevent Na from being transported upward to the leaves, which helps maintain salt tolerance [22,48]. However, increasing Na concentrations with higher wastewater proportions could pose risks to crop health. Salt-sensitive varieties tend to accumulate higher Na-to-K ratios in their leaves, which is associated with reduced chlorophyll content, impaired photosynthesis, and lower yields [49,50].

Regarding calcium (Ca), this study found higher Ca concentrations in the leaves of both wheat and sorghum, with lower concentrations in the roots. These results align with Bavi et al. [51], who found that Ca tends to accumulate in the leaves under high-salinity conditions. However, other studies (Guo et al. [52]) suggest that Ca may accumulate more in the roots when salinity is low or when additional Ca is supplied. The interaction between Ca and other cations, such as K, Na, and Mg, can affect Ca uptake, with high K or Na concentrations reducing Ca absorption [53]. In this study, sorghum showed a decrease in Ca concentrations with increasing wastewater proportions, whereas wheat did not, potentially reflecting species-specific differences in ion uptake mechanisms.

Magnesium (Mg) showed varying distribution patterns between the two crops. In wheat, Mg accumulated at the highest levels in the leaves and grains, while in sorghum, the Mg concentrations was higher in the stems, leaves, and grains than in the roots. This pattern is consistent with previous studies [52], although some research suggests that Mg can accumulate more in the roots under certain conditions [54]. Similar to Ca, Mg uptake is also subject to antagonistic interactions with other cations, which may explain the decrease in Mg concentration in the stems and grains of sorghum at 80% KKL irrigation [55,56].

Phosphorus (P) concentrations in this study decreased in the leaves and increased in the grains as the crops matured, reflecting the translocation of P to the grains for storage to support the next generation [57]. This nutrient allocation is consistent with other studies showing that higher P levels in grains are associated with lower P concentrations in the leaves and stems [58].

Previous studies have shown that elevated Na concentrations in irrigation water can inhibit the uptake of essential nutrients such as K, Ca, Mg, and P by plants, even when other conditions remain constant [59,60]. Similarly, excessive K can interfere with the absorption of Ca and Mg in plant tissues [55]. In this study, a decline in Ca concentration was observed in sorghum, whereas the concentrations of other elements in both sorghum and wheat either remained stable or increased with higher wastewater proportions. This suggests that higher overall elemental content in the wastewater may have partially offset the reduced uptake of other nutrients, compensating for the inhibitory effects of elevated Na and K levels.

4.3. Effect of KKL Water Irrigation on Nutrient Accumulation in Plants

As the growth period progressed, nutrient distribution shifted from the roots and leaves to the stems and grains, reflecting changes in biomass distribution. At harvest, both wheat and sorghum exhibited similar patterns: K, Ca, Mg, and P were primarily concentrated in the stems, while Na was mostly retained in the roots. This pattern likely reflects the plants' strategy to direct nutrients to the stems and grains as they mature, while minimizing Na accumulation in sensitive tissues to avoid osmotic stress.

The total nutrient accumulation in plant tissues is influenced by both elemental concentrations and biomass. Although higher wastewater proportions increased the concentrations of K, Na, and Mg in plant tissues, the total biomass of the plants decreased, likely due to the negative impact of salinity on crop growth. Similar results have been reported by Ma et al. [61], who found that high Na concentrations in the soil reduced tiller production and overall dry weight in wheat. Likewise, Kafi et al. [62] observed that increasing irrigation water salinity led to reduced biomass in sorghum.

The nutrient distribution and concentration are particularly important for maintaining crop yield and quality. Previous studies [59,63–65] have shown that high Na accumulation in above-ground tissues with a lower Na-to-K ratio typically correlates with lower fresh and dry weights. In contrast, increasing K supply has been linked to higher nitrogen content and improved grain carbohydrate composition in sorghum [66]. Additionally, Hermans et al. [54] found that Mg deficiency reduced Mg content in sugar beets while increasing glucose and sucrose levels, further demonstrating the complex interplay between nutrient availability and crop quality.

5. Conclusions

This study explored the potential of using distillery wastewater from Kinmen Kaoliang Liquor (KKL) as an alternative water source for agricultural irrigation, focusing on its effects on soil properties, plant nutrient distribution, and crop performance in wheat and sorghum cultivation. The findings indicate that KKL wastewater contains high levels of potassium (K), sodium (Na), magnesium (Mg), and phosphorus (P), with minimal heavy metal content, offering both opportunities and challenges for agricultural use.

The reuse of wastewater improved soil nutrient availability, as higher proportions of KKL wastewater led to increased concentrations of K, Na, Ca, Mg, and P in the soil. However, the wastewater's high electrical conductivity (EC) and sodium adsorption ratio (SAR) exceeded Taiwan's irrigation water standards, posing salinity and sodium hazards. These findings underscore the need for careful management of wastewater dilution and irrigation schedules to mitigate risks associated with excessive salinity and sodium accumulation in soils.

In terms of plant nutrient uptake, K was the most abundant element in both wheat and sorghum, particularly concentrated in the stems, while Na was mainly retained in the roots, reflecting the plants' sodium exclusion mechanism. While the use of wastewater increased the concentrations of several elements across plant tissues, it also led to a decline in the biomass of both crops, likely due to the osmotic stress and reduced water uptake associated with high salinity. The study further showed that Na accumulation in plant tissues, particularly in sorghum, could impair nutrient uptake and reduce yield potential, highlighting the importance of crop selection and salt-tolerant varieties when using wastewater irrigation.

The study confirmed that elemental distribution within plant parts followed a consistent trend, with K, Ca, Mg, and P accumulating primarily in the stems and Na remaining largely confined to the roots. This pattern suggests a shift in nutrient allocation from roots and leaves to stems and grains as the crops matured, supporting grain development. However, the antagonistic interactions between Na, K, Ca, and Mg observed in the experiments highlight the complexity of nutrient uptake under saline conditions, with higher Na levels potentially limiting the absorption of other essential nutrients.

In summary, the results demonstrate that KKL wastewater offers valuable nutrients for crop growth and can contribute to water resource recycling, but its use requires strategic management to avoid adverse effects on soil health and crop performance. The insights gained from this research provide a foundation for developing sustainable wastewater irrigation strategies in water-scarce regions, such as Kinmen, by balancing nutrient benefits with salinity risks. Future studies should focus on long-term field trials and crop-specific salt tolerance to further optimize wastewater reuse practices for sustainable agriculture.

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