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Assessing the Effect of Irrigation Using Different Water Resources on Characteristics of Mild Cadmium-Contaminated Soil and Tomato Quality

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Abstract: As the world economy and society have developed quickly, the amount of farmland soil pollution has become alarming, which has seriously threatened global food security. It is necessary to take effective measures on the moderately contaminated soil to produce high-quality food and to protect food security worldwide by effective use of land resources. Our experimental design was to study the changes in soil physicochemical properties and tomato yield and quality indicators by irrigating tomatoes on cadmium-contaminated soil with two different water qualities (reclaimed water irrigation: RW; tap water irrigation: TW) through drip irrigation devices. Tomato quality indicators were determined using plant physiological assays, as well as vitamin C (VC), total acidity (TA), protein content (PC), and soluble sugar content (SS). We tested five different types of cadmium-contaminated soils (less than 0.60 mg/kg, 0.60–1.20 mg/kg, 1.20–1.80 mg/kg, 1.80–2.40 mg/kg, 2.40–3.00 mg/kg) against RW and TW, and performed high-throughput sequencing of the soils to obtain environmental results for soil microbial diversity. The results reveal that compared with the TW condition, soil nutritional status was increased with the irrigated RW. The yield of the tomatoes increased by 52.03–94.03% than TW. The results of the study showed significant and highly significant relationships between tomato quality indicators (TA, SS, yield) and soil physical and chemical properties indicators ($p < 0.01$, 0.05). For instance, the RW increased the SOM by 6.54–12.13%, the TP by 0.48–24.73%, the yield of the tomatoes by 52.03–94.03% than TW, while the cadmium content did not show significant differences ($p < 0.05$), and the cadmium content did not increase the soil's pollution level. Compared with TW treatment, RW treatment alleviated the inhibition of soil microbial diversity by cadmium and RW also increased its soil microbial diversity. The relative abundance of *Proteobacteria*, *Gemmatimonadetes*, and *Bacteroidetes* in the RW condition were higher than in the TW condition at different cadmium concentrations. In conclusion, RW improved the overall quality conditions of soil and the diversity of microbial communities, and did not aggravate the pollution degree of cadmium-contaminated soil, and affected the yield of tomatoes positively. RW can be an effective irrigation technique to reduce the use of clean water.

Keywords: cadmium contaminates soil; reclaimed water; tap water; soil characteristics; tomatoes quality parameters; soil microbial diversity

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Citation: Cui, J.; Li, P.; Qi, X.; Guo, W.; Rahman, S.U. Assessing the Effect of Irrigation Using Different Water Resources on Characteristics of Mild Cadmium-Contaminated Soil and Tomato Quality. *Agronomy* **2022**, *12*, 2721. https://doi.org/10.3390/agronomy12112721

Academic Editors: Antonella Lavini and Mohamed Houssemeddine Sellami

Received: 24 August 2022
Accepted: 1 November 2022
Published: 2 November 2022

1. Introduction

Tomato (*Solanum lycopersicum* L.) is a common and indispensable food for a healthy human diet in modern daily life and is also widely grown worldwide as one of the essential vegetables. The dwarf millennial red tomato *(Lycopersicon esculentum Mill.*) has been widely recognized for its unique characteristics (easy agronomic practices, long fruiting period, high economic efficiency, high consumption, etc.) and is responsible for the increase in planting scale and production growth in recent years [1,2]. Tomatoes have significant importance in the human dietary system because it contains all essential nutrients, such as protein, vitamin C, trace elements (iron, magnesium, etc.), organic acids, and soluble sugars [3,4]. Being a necessary dietary item, the quality of tomatoes plays a significant role in people's everyday diet. The *Lycopersicon esculentum Mill*. belongs to the Solanaceae family and has a well-developed root system with high biomass. Cadmium is a superlatively poisonous element that can easily penetrate the soil and is highly enriched in the crop, as cadmium in the soil is easily absorbed by the well-developed root system of tomato and accumulated cadmium contamination transfers to fruit. The study showed that the toxic analysis of crops under different cadmium concentration stresses revealed that tomato is a crop that is more sensitive to cadmium and susceptible to toxicity [5]. Cadmium accumulates in body organs and tissues when humans consume cadmium-contaminated plants, which causes serious health problems. It is necessary to study the quality of tomatoes grown on lightly to moderately cadmium-contaminated soils to observe the possible effects of cadmium on the quality of tomatoes. Combined with the related studies on PSC (pollution-safe cultivar) strategy [6,7], it was found that the reference studying the relationship between tomato and cadmium was less.

The People's Republic of China's Ministry of Ecology and Environment published the "Communiqué on the State of the Ecological Environment in China" in 2020 [8], and ranked inorganic cadmium as the most influential factor in agricultural land. Cadmium contamination not only damages the structural diversity of soil microbial communities [9], it can also be harmful to soil quality [10], and adversely affect the crop biomass and yield [11]. Soil microbial community composition can reflect soil fertility and soil quality, and when the bacterial community composition diversity increases, the overall soil conditions will improve [12]. Thus, the quality of cadmium-contaminated soil, and how this reflects agricultural production, is worth studying.

Reclaimed water came from urban wastewater after an appropriate regeneration process to achieve certain water quality requirements it can be used to beneficial use of water. Reclaimed water contains balanced amount of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and other macro-elements needed for optimum crop growth; it can also relatively reduce the use of chemical fertilizers, saving agricultural farming and daily production costs, improving the efficiency of resource utilization, and having a certain degree of economic benefits [13]. Reclaimed water irrigation can positively affect the structural diversity of soil microbial communities [14,15] by improving soil organic matter (SOM) [16]. Reclaimed water irrigation can also increase crop yields [17]. Therefore, irrigation with reclaimed water is a way and strategy to improve the sustainable use of water resources and alleviate water scarcity that can be promote [18,19].

In the present study, we examined the potential role of two different irrigated water sources (reclaimed water and tap water) on cadmium-contaminated soil characteristics, microbial community, and tomatoes grown in cadmium-contaminated soils. Moreover, we explored how to combine the safe use of reclaimed water in the cultivation of tomatoes on cadmium-contaminated soil in order to alleviate the water shortage and maximize the safe use of reclaimed water for safe agricultural production on cadmium-contaminated soil.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out in a greenhouse (35.27′ N, 113.93′ E, 73.2 m above sea level) of the Agricultural Water and Soil Environment Field Scientific Observation and Experiment Station in Xinxiang, Henan, Chinese Academy of Agricultural Sciences. The average annual temperature is 14.1 °C, the frost-free period is 210 d, and the sunshine time is 2398.8 h. The average precipitation of Xinxiang city is 588.8 mm with large inter-annual variation, while the precipitation during the wet years is three to four times that of dry years. Moreover, the precipitation within the year is uneven with maximum precipitation (70% of the annual precipitation) reported during the months of July to September. The annual average evaporation was recorded at 2000 mm by year. The relative humidity in the greenhouse averages 25.64–66.96% throughout the year, with an annual PCR of 305.63–947.65 MJ/m^2 and indoor temperatures of up to 55.74 °C and down to −6.47 °C throughout the year.

2.2. Experimental Design

The soil used in this study was collected from some sewage irrigation area in Henan province. This area has been irrigated with sewage for historical reasons, resulting in cadmium contamination of the soil. The soil samples were naturally air dried. The stones, plant fine roots, and biological residues visible to the naked eye were removed and then passed through a 5 mm sieve. According to the concentration of the first serious metal Cd within the soil, identical soil background is organized to confirm the consistency of soil physicochemical properties and soil microorganisms. We added Cd in the form of $CdCl_2.2H_2O$ in the air-dried soil in the form of water solution for a one-month passivation period to meet the configuration concentration. Soil cadmium content is configured according to soil environmental quality survey on soil pollution level classification [20]. The setting range of Cd concentration is Cd1—no pollution (less than 0.60 mg/kg), Cd2—slight pollution (0.60–1.20 mg/kg), Cd3—mild pollution (1.20–1.80 mg/kg), Cd4—moderate pollution (1.80–2.40 mg/kg), and Cd5—moderate pollution (2.40–3.00 mg/kg) [20]. According to laboratory determination, the final Cd1–Cd5 contents were 0.30 mg/kg, 0.69 mg/kg, 1.20 mg/kg, 2.07 mg/kg, and 2.74 mg/kg, respectively.

Ten treatments were marked with RCd1, RCd2, RCd3, RCd4, RCd5, TCd1, TCd2, TCd3, TCd4, and TCd5, as depicted in Table 1, with 5 replicates per treatment and 50 pots in total. We used pots made of polyvinyl chloride (PVC) with an upper diameter of 38 cm and a bottom diameter of 30 cm, while the height was 40 cm. Each pot contained 36 kg of soil, with *Lycopersicon esculentum Mill.* as a model plant.

Table 1. Design explanation of different treatments and irrigation water quality indicators.

Water Source for Irrigation	Irrigation Level Symbol	pH	EC/ $\mu s \cdot cm^{-1}$	TN/$mg \cdot L^{-1}$	TP/$mg \cdot L^{-1}$	COD/$mg \cdot L^{-1}$	Cd/$mg \cdot L^{-1}$	Treatment
Reclaimed water	R	7.33	1298	8.9	0.75	<15	<0.0001	RCd1 RCd2 RCd3 RCd4 RCd5
Tap water	T	8.08	249.67	0.6	0.2	<10	<0.001	TCd1 TCd2 TCd3 TCd4 TCd5

Note: Cd1 means no pollution (less than 0.60 mg/kg), Cd2 means slight pollution (0.60–1.20 mg/kg), Cd3 means mild pollution (1.20–1.80 mg/kg), Cd4 means moderate pollution (1.80–2.40 mg/kg), Cd5 means moderate pollution (2.40–3.00 mg/kg).

Tomato plants were irrigated with two sources of water (1) reclaimed water (RW) and (2) tap water (TW), where the reclaimed water was taken from the Luotuowan Urban Domestic Sewage Treatment Plant and the tap water was taken from Agricultural Water and Soil Environment Field Scientific Observation and Experiment Station in Xinxiang, Henan, Chinese Academy of Agricultural Sciences. The experiment was set up to irrigate tomatoes using a drip irrigation equipment. The upper and lower limits of irrigated water were adjusted to 90 and 60% of soil moisture contents, respectively. To measure water contents on regular basis, we installed HOBO (HOBO U30 station. On set Company, Bourne, MA, USA). When soil moisture content value from HOBO measurement was equal to or less than the soil moisture lower limit value, the irrigation water volume per pot was 1 L in everyone treatments. The total amount of both reclaimed and tap water irrigation in the whole tomato growth period was 34 L.

2.3. Measurement Items and Methods

2.3.1. Sample Collection

We collected rhizosphere soil from each replication according to the rhizosphere soil collection method [21]. This was replicated for each treatment, and then five replicate rhizosphere soil samples from each treatment were pooled into one sample, so a total of 10 samples were collected.

Each composite sample was divided into two parts and placed in clean self-sealing bags after being sieved through a 2 mm sieve; one part was stored at room temperature and air-dried to determine basic physical and chemical properties of the soil, and the other was used for subsequent assessment of microbial community diversity in triplicate.

During harvesting, the tomato fruits were labeled with the corresponding strain number and each replicate was weighed for tomato yield by 0.01 g precision electronic balance [22]. For fruit quality test in terms of vitamin C content, soluble sugar content, titratable acidity, sugar-acid ratio, and soluble protein content the tomato samples were collected from each replicate and processed for further analysis.

2.3.2. Soil Physicochemical Analysis

The soil physical and chemical properties were measured according to Bao Shidan's "Soil Agrochemical Analysis" [23]. Soil pH with a 5:1 water-soil ratio was measured by using pH meter (Ori-on-star A211, Waltham, MA, USA). Soil electrical conductivity (EC) was accessed by using portable conductivity meterDDB-303A (Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China). Soil macro and microelements such as available potassium contents (AK) were measured by NaOH fusion flame photometry, available phosphorus contents (AP) were measured by $NaHCO_3$ extraction-molybdenum antimony anti-colorimetric method, and total nitrogen (TN) and total phosphorus contents (TP) were measured by continuous flow analysis method (Auto Analyzer 3, BRAN LUEBBE, Germany, sensitivity 0.001 AUFS). Finally, soil organic matter (SOM) was measured by low temperature external thermal potassium dichromate oxidation-colorimetric method (sensitivity 0.001AUFS). The initial parameters of the test soil can be viewed in Table 2.

Table 2. Initial physical and chemical properties of the experiment soil.

Treatment	pH	EC Value $\mu s \cdot cm^{-1}$	Organic Matter Content/$g \cdot kg^{-1}$	Total N Content/$mg \cdot g^{-1}$	Total P Content/$mg \cdot g^{-1}$	Available P Content/$mg \cdot kg^{-1}$	Available K Content/$mg \cdot kg^{-1}$	Total Cd Content/$mg \cdot kg^{-1}$
Cd1	8.13	360.50	31.10	1.00	0.90	68.62	324.90	0.30
Cd2	8.20	338.40	24.60	0.79	0.73	63.95	276.60	0.69
Cd3	8.28	394.30	18.97	0.70	0.59	53.03	245.40	1.20
Cd4	8.20	505.80	25.74	0.67	0.58	62.54	251.60	2.07
Cd5	8.22	459.80	20.26	0.64	0.62	50.15	248.50	2.74

2.3.3. Plant Analysis

Tomato yield was accessed by counting the total numbers of fruits per plant. Tomato quality was determined according to Chen Gang's Experiments in Plant Physiology [24] by the following methods: vitamin C content was determined by the 2,6-dichloroindophenol titration method; soluble protein content was determined by the UV absorption method; soluble sugar content was determined by the anthrone colorimetric method; titratable acid content was determined by the alkaline titration method; and the sugar-acid ratio (%) was the ratio of soluble sugar content to organic acid content.

2.3.4. DNA Extraction

Soil DNA isolation was performed by using the power soil NAA isolation Kits (MoBio Laboratories, Carlsbad, CA, USA). Using a Nanodrop2000, the collected DNA was analyzed for DNA quality and concentration (ThermoFisher Scientific, Inc., Waltham, MA, USA). For upcoming studies, the quality-checked samples were kept in a −20 °C freezer.

2.3.5. PCR Amplification

The primers 338F (5′-ACTCCTACGGGAGGCAGCAG-3′) and 806R (5′-GGACTACHV GGGTWTCTAAT-3′) were used to amplify the bacterial 16S rRNA gene's V3–V4 region. An 8 bp barcode sequence was added to the 5′ end of each of the upstream and downstream primers to distinguish between different samples. PCR reaction system (total system of 25 µL): 12.5 µL 2xTaq Plus Master Mix II (Vazyme Biotech Co., Ltd., Nanjing, China), 3 µL BSA (2 ng/µ reaction parameters: 95 °C pre-denaturation for 5 min; denaturation at 95 °C for 45 s, annealing at 55 °C for 50 s, extension at 72 °C for 45 s, and extension at 72 °C for 28 cycles). Amplification was performed on an ABI 9700 PCR instrument (ThermoFisher Scientific, Inc., Waltham, MA, USA), and the PCR products were detected by 1% agarose gel electrophoresis to detect the size of the amplified target bands. The amplified bands were analyzed with an Agencourt AMPure XP (Beckman Coulter, Inc., Pasadena, CA, USA) nucleic acid purification kit.

2.3.6. Library Construction and MiSeq Sequencing

The PCR products were used to construct microbial diversity sequencing libraries using the NEB Next Ultra II DNA Library Prep Kit (New England Biolabs, Inc., Ipswich, MA, USA) library construction kit. Paired-end sequencing was performed using the Illumina Miseq PE300 (Illumina, Inc., Santiago, CA, USA) high-throughput sequencing platform at Beijing Allwegene Company Co (Beijing, China). The sequenced raw sequences were uploaded to NCBI's SRA database. Different samples use the same specification sequencing information, and the library types are: library strategy is amplicon, library source is other, library selection is PCR, and library layout is paired. The platform sequencing instrument is Illumina, the instrument model of which is Illumina MiSeq. The design description sequencing region is 16S V3–V4, and the filetype original file format is fastq.

2.4. Data Analysis

The downstream data were filtered and spliced by QIIME (v1.8.0) software (Gregory Caporaso, Flagsta, AR, USA) by splitting the samples according to Barcode sequences. The raw data were filtered using Pear (v0.9.6) software [25]. The data were filtered and spliced using Pear (v0.9.6) software, the scores below 20, containing ambiguous bases and primer mismatches, were removed. The minimum overlap was set to 10 bp and the mismatch rate was 0.1. After splicing, sequences less than 230 bp in length were removed using Vsearch (v2.7.1) software [26], and chimeric sequences were removed by comparing with Gold Database database using UCHIME method [27]. OTU clustering (Operational Taxonomic Units) was performed on the quality sequences using the Vsearch (v2.7.1) software uparse algorithm with a sequence similarity threshold of 97%. Comparison with the Silva138 database was performed using the BLAST algorithm with an e-value threshold set to 1e-5 to obtain the species classification information corresponding to each OTU. The α-diversity index analysis (including Shannon, Simpson, and Chao1 indices) was then performed using QIIME (v1.8.0) software. Chao1 is a species richness index, Simpson is one of the indices used to estimate microbial diversity in samples. Observed species is the number of OTUs actually observed as the sequencing depth increases. Goods coverage is a depth of observation. PD_whole_tree is a spectral diversity, which takes into account the species abundance and evolutionary distance. Shannon is one of the indices used to estimate microbial diversity in samples. Based on the species annotation and relative abundance results, histogram analysis of species composition was performed using R (v3.6.0) software (Robert Gentleman&Ross Ihaka, NJ, USA). The beta diversity distance matrix was calculated using QIIME (v1.8.0), the cluster heat map and PCoA analyses were performed using R (v3.6.0) software based on Weighted Unifrace distances. The metastats intergroup variance analysis was performed using Mothur (v.1.34.4) software (Ann Arbor, MI, USA). Tables and plots were drawn using Microsoft Excel 2016 and Origin 2021.

3. Results

3.1. Changes in Soil Physicochemical Properties under Drip Irrigation with Different Water Sources

According to the results in Table 3, our study showed that cadmium-contaminated soil irrigated with various water sources had same trend for soil pH, EC, and SOM. For instance, soil pH was higher in soils treated with reclaimed water than those irrigated with tap water. In addition to different irrigated water, cadmium concentration also affects the soil pH. For instance, soil pH for cadmium contaminated is 0.69 irrigated with reclaimed irrigation water was higher than that of cadmium contaminated is 0.69 irrigated with tapped irrigated water, but the difference was not significant ($p < 0.05$), while the soil pH for remaining cadmium concentrations treated with reclaimed irrigation water showed significant differences ($p < 0.05$) as compared to tap irrigated water with corresponding cadmium concentrations. Similarly, EC was higher for cadmium-contaminated soils irrigated with reclaimed water as compared to cadmium-contaminated soils irrigated with tap water, which was 65–199%, showing significant differences ($p < 0.05$). The SOM of cadmium-contaminated soils treated with RW was both higher than those soils irrigated with TW, the increased was 6.54–12.13%; however, the difference was not significant ($p < 0.05$). All treatments showed a decreasing trend in the SOM with the increase of soil cadmium concentration.

Table 3. Physical and chemical properties of soil used in treatment.

Treatment	pH	EC Value/µs·cm^{-1}	Organic Matter Content/g·kg^{-1}	Total N Content/mg·g^{-1}	Total P Content/mg·g^{-1}	Available P Content/mg·kg^{-1}	Available K Content/mg·kg^{-1}	Total Cd Content/mg·kg^{-1}
RCd1	8.6 ± 0.01 ab	490.33 ± 11.02 bc	34.49 ± 0.09 a	0.86 ± 0.01 a	0.95 ± 0.02 a	52.95 ± 0.47 a	259.37 ± 1.5 a	0.28 ± 0.02 e
RCd2	8.44 ± 0.07 c	574.00 ± 33.15 a	32.10 ± 2.36 ab	0.64 ± 0.01 b	0.72 ± 0.04 bc	43.79 ± 2.23 b	224.42 ± 2.19 b	1.00 ± 0.08 d
RCd3	8.60 ± 0.01 ab	510.00 ± 7.00 b	31.77 ± 1.36 abc	0.56 ± 0.02 bc	0.56 ± 0.02 def	37.87 ± 1.46 cd	215.27 ± 3.96 c	1.23 ± 0.06 c
RCd4	8.57 ± 0.02 b	485.00 ± 2.65 c	28.47 ± 0.56 cde	0.58 ± 0.03 bc	0.59 ± 0.02 d	36.79 ± 0.47 cd	214.56 ± 0.46 c	2.31 ± 0.13 b
RCd5	8.64 ± 0.02 a	450.33 ± 8.62 d	27.77 ± 0.54 de	0.57 ± 0.01 bc	0.53 ± 0.03 ef	35.88 ± 0.41 cd	204.00 ± 3.61 d	2.99 ± 0.01 a
TCd1	8.33 ± 0.01 e	216.33 ± 0.58 f	32.15 ± 0.50 ab	0.80 ± 0.01 a	0.76 ± 0.02 b	42.43 ± 1.48 b	254.37 ± 4.83 a	0.28 ± 0.02 e
TCd2	8.40 ± 0.04 cd	191.9 ± 1.91 g	30.13 ± 1.58 bcd	0.63 ± 0.01 b	0.7 ± 0.06 c	39.57 ± 4.28 bc	220.37 ± 1.39 bc	0.91 ± 0.09 d
TCd3	8.44 ± 0.01 c	231.67 ± 10.12 ef	28.33 ± 3.61 cde	0.60 ± 0.13 bc	0.51 ± 0.07 f	27.96 ± 1.44 e	173.23 ± 1.07 e	1.30 ± 0.11 c
TCd4	8.35 ± 0.04 de	240.33 ± 3.06 e	25.37 ± 3.18 e	0.55 ± 0.01 bc	0.58 ± 0.01 de	35.33 ± 5.59 cd	202.47 ± 8.3 d	2.26 ± 0.13 b
TCd5	8.34 ± 0.04 de	273.33 ± 10.21 d	24.89 ± 1.99 e	0.52 ± 0.05 c	0.52 ± 0.02 ef	33.83 ± 1.08 d	200.11 ± 3.86 d	2.89 ± 0.17 a

Note: The lowercase letters in the same column indicate significant differences among different treatments.

TN in cadmium-contaminated soils irrigated with reclaimed water and tap water did not show significant differences ($p < 0.05$). When cadmium concentration was 1.20 mg/kg, the TN of treatments those irrigated with reclaimed water was slightly lower than these tap irrigated water treatments, while the TN for other cadmium concentrations in reclaimed water was marginally higher than these tap irrigated water treatment.

The TP of treatments those irrigated with reclaimed water were all higher than those tap irrigated water treatments, with an increase of 0.48–24.73%. When the cadmium concentration was 0.30 mg/kg, the TP of treatments between reclaimed water irrigation and tap water irrigation treatments showed significant differences ($p < 0.05$), and at other cadmium concentrations, none of them showed significant differences ($p < 0.05$).

When the cadmium concentration was 0.30 mg/kg, the available phosphorus (AP) showed the same trend, where AP was higher for reclaimed irrigation water treated to cadmium-contaminated soil as compared to tap irrigated water to cadmium-contaminated soils. The available potassium (AK) showed a similar trend to AP in treatments, the contents of which were higher in those irrigated with reclaimed treatments than those irrigated with tap water, when the soil cadmium concentration was 1.20 and 2.07 mg/kg, showing significant differences ($p < 0.05$) between treatments. There is no significant difference ($p < 0.05$) between soils irrigated with reclaimed water and tap water. In particular, the cadmium-contaminated soil did not show significant differences due to RW compared to TW.

3.2. Effect of Different Treatments on Yield and Quality of Tomatoes

Results of our study showed in Table 4, the vitamin C (VC) of tomatoes in the cadmium-contaminated soils irrigate with reclaimed water was lower than that in the corresponding soils irrigated with tap water, and showed significant differences ($p < 0.05$). In our results, when the soil cadmium concentration was 0.30 mg/kg, there was no significant difference between the sugar-acid ratio content under RW and TW, and the remaining cadmium concentration showed significant difference ($p < 0.05$). Under different cadmium concentrations, compared to TW treatments, treatments irrigated with reclaimed water produced a higher yield. The range of increase in production was 52.03–94.46%.

Table 4. Effect of different treatment on tomato quality.

Treatment	Vitamin C Content/mg·kg^{-1}	Soluble Sugar Content/%	Titratable Acid Content/%	Soluble Protein Content/mg·kg^{-1}	Sugar-Acid Ratio/%	Yield/g
RCd1	311.72 ± 17.16 c	2.94 ± 0.1 d	0.75 ± 0.02 bc	16.58 ± 2.39 cd	3.92 ± 0.13 de	195.33 ± 69.67 ab
RCd2	320.01 ± 4.90 c	2.85 ± 0.39 d	0.91 ± 0.09 ab	15.75 ± 0.86 de	3.14 ± 0.36 e	186.53 ± 28.66 ab
RCd3	275.83 ± 17.28 d	2.52 ± 0.26 d	0.89 ± 0.1 ab	13.61 ± 0.65 e	2.83 ± 0.31 e	205.48 ± 2.28 ab
RCd4	254.81 ± 10.35 d	2.37 ± 0.28 d	0.61 ± 0.06 c	16.45 ± 2.86 cd	3.88 ± 0.53 de	214.45 ± 45.26 ab
RCd5	263.83 ± 13.91 d	2.51 ± 0.35 d	0.84 ± 0.15 ab	14.78 ± 0.48 e	3.07 ± 0.91 e	243.57 ± 6.45 a
TCd1	385.53 ± 21.43 a	4.06 ± 0.17 c	0.86 ± 0.11 ab	20.26 ± 1.22 b	4.82 ± 0.85 cd	116.02 ± 13.98 a
TCd2	354.20 ± 8.22 b	4.67 ± 0.19 b	0.85 ± 0.1 ab	18.61 ± 0.93 bc	5.55 ± 0.65 bc	95.92 ± 29.63 ab
TCd3	400.29 ± 22.21 a	4.4 ± 0.24 bc	0.96 ± 0.09 a	25.11 ± 1.56 a	4.64 ± 0.65 cd	135.16 ± 29.05 a
TCd4	393.92 ± 29.39 a	5.55 ± 0.26 a	0.75 ± 0.04 bc	20.19 ± 0.62 b	7.44 ± 0.68 a	125.86 ± 45.01 ab
TCd5	383.93 ± 2.12 a	5.61 ± 0.58 a	0.87 ± 0.02 ab	21.29 ± 1.56 b	6.43 ± 0.64 ab	128.24 ± 6.83 b

Note: The lowercase letters in the same column indicate significant differences among different treatments.

3.3. Interrelationship between Soil Physicochemical Properties and Tomato Quality Indicators after Irrigation

Correlation analysis of tomato quality: vitamin C (VC), total acid (TA), soluble protein (SP), soluble sugar content (SS), and sugar-acid ratio with soil physicochemical properties was constructed using Origin 2021 software, and a correlation heat map was obtained (Figure 1). It showed that the correlation coefficients of pH with VC, SS, SP, sugar-acid ratio, and yield of tomato were −0.843, −0.812, −0.636, −0.720, and 0.789, respectively, with highly significant negative correlations ($p < 0.01$) with VC, SS, SP and sugar-acid ratio and highly significant positive correlations ($p < 0.01$) with yield. The correlation coefficient with TA was −0.190, showing a negative correlation; conductivity showed the same phenomenon. The correlation coefficients of SOM with SS and sugar-acid ratio were −0.483 and −0.470, showing highly significant negative correlations ($p < 0.01$), and correlation coefficients with SP content was −0.366, showing significant negative correlations ($p < 0.05$). SP also showed significant negative correlations ($p < 0.05$) with AP and AK: the correlation coefficients were −0.450 and −0.390. TN was negatively correlated with SS, TA, sugar-acid ratio, and yield, and positively correlated with VC and SP, but did not show significant differences. TP was positively correlated with VC only and negatively correlated with other quality indicators, while soil cadmium content was negatively correlated with VC, TA, and SP, and positively correlated with SS, sugar-acid ratio, and yield, all of which did not show significant differences.

3.4. Analysis of the Diversity and Structure of the Soil Bacterial Community

Information on the community composition of rhizosphere soil microorganisms at the phylum taxonomic level and genus taxonomic level for each treatment is shown in Figure 1. A total of 6014 OUTs were obtained by clustering at 97% sequence similarity level, and the remaining 5958 valid sequences were obtained after sampling flat for each sample with different treatments. Species classification statistics were obtained for 41 phylums, 119 classes, 273 orders, 375 families, and 643 genera. Table 5 shows the results of soil microbial diversity index among different treatments, the Chao1 index, Shannon index, and PD whole tree of the treatments irrigated with reclaimed water at different cadmium concentrations were higher than those of the TW treatment (Table 5), but did not reach a significant level. The comparative research revealed that the irrigation treatment using reclaimed water enhanced the diversity and richness of rhizosphere soil bacteria, although not to a significant level. The Simpson index is a predicted microbial diversity index; when the cadmium concentration was 0.30 mg/kg, the TW treatment showed significant differences with other treatments, indicating that the microbial diversity of tap water irrigated uncontaminated soil with cadmium was less than the microbial diversity of other treatments. The observed species index, which was used to calculate the number of OTUs in the community with increasing sequencing depth, and the goods coverage index, which represented the depth of observation, were not significantly different from each other, reflecting that the sequencing results can represent the real situation and consistency of microorganisms in all samples, and can describe the microbial community of the samples more accurately. The information of microbial community in the samples can be described more accurately.

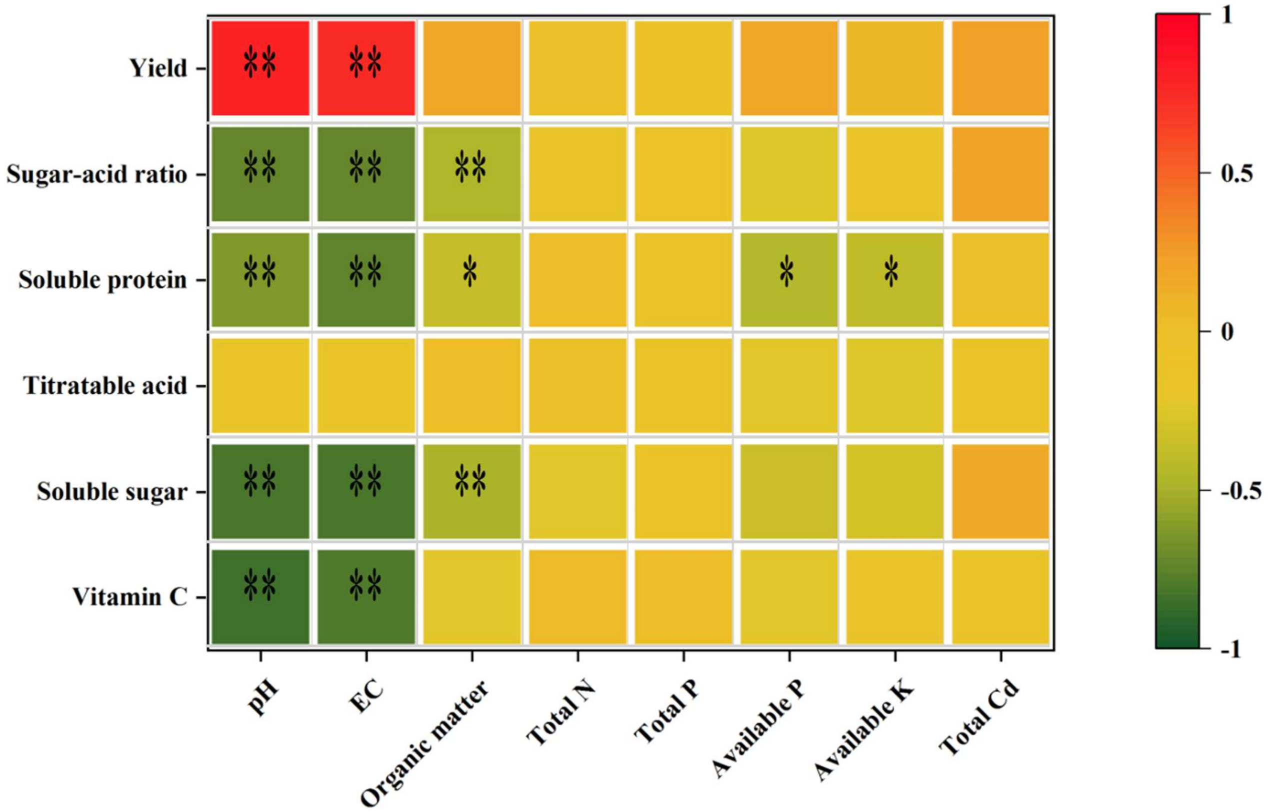

Figure 1. Correlation heatmap of tomato quality with soil physicochemical properties. "*" means the correlation is significant at 0.05 level. "**" means the correlation is significant at 0.01 level.

Table 5. Bacterial community diversity indices for different treatment.

Treatment	Chao1	Goods Coverage	Observed Species	PD Whole Tree	Shannon	Simpson
RCd1	3676.65 ab	0.96 a	2612.2 bc	225.37 bc	9.57 ab	1 a
RCd2	3949.29 a	0.96 a	2795.17 a	240.65 a	9.72 a	1 a
RCd3	3823.74 ab	0.96 a	2696.93 abc	235.94 ab	9.67 ab	1 a
RCd4	3837.97 ab	0.96 a	2714.6 abc	241.92 a	9.64 ab	1 a
RCd5	3897.8 a	0.96 a	2750.73 ab	241.59 a	9.72 a	1 a
TCd1	3598.63 b	0.96 a	2569.87 c	218.58 c	9.41 b	0.99 b
TCd2	3759.83 ab	0.96 a	2657.27 abc	223.65 bc	9.67 ab	1 a
TCd3	3794.19 ab	0.96 a	2675.57 abc	223.61 bc	9.67 ab	1 a
TCd4	3744.05 a	0.96 a	2718.23 abc	230.1 abc	9.56 ab	1 a
TCd5	3868.75 ab	0.96 a	2757.77 ab	230.52 abc	9.72 a	1 a

Note: The lowercase letters in the same column indicate significant differences among different treatments.

Information on the community composition of rhizosphere soil bacteria at the phylum taxonomic level and genus taxonomic level for each treatment is shown in Figure 2. At the phylum taxonomic level, the structural composition of the bacterial community was highly similar among the treatments, and the main dominant groups included *Acidobacteria* (13.6–32.6%), *Proteobacteria* (20–27.3%), *Actinobacteria* (11.6–26.8%), *Chloroflexi* (7.5–11.0%), *Gemmatimonadetes* (4.0–10.9%), and *Bacteroidetes* (4.3–9.9%), with the relative abundance of these six groups accounting for more than 80% of the rhizosphere soil bacterial community. Among them, *Acidobacteria* accounted for the highest percentage.

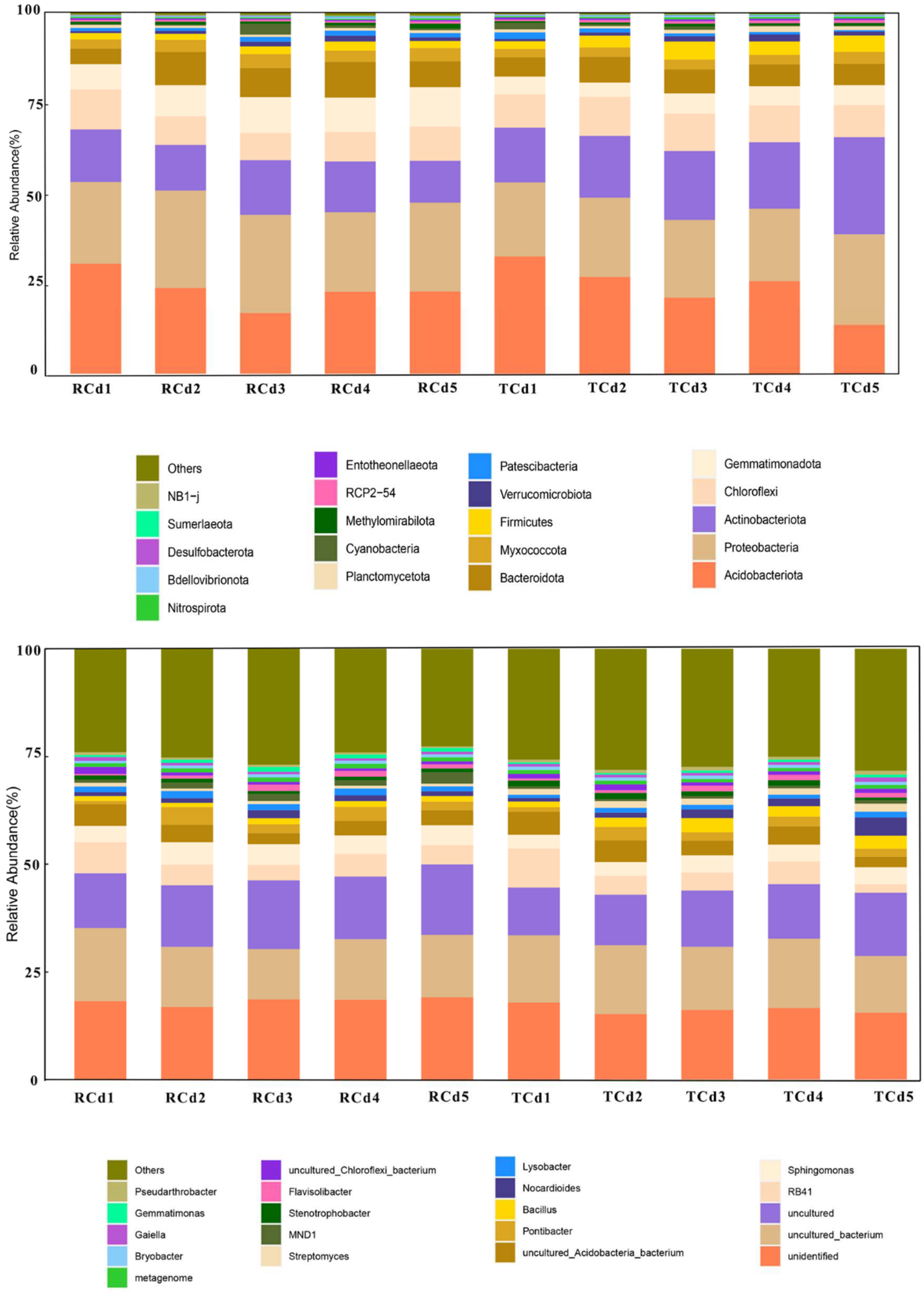

Figure 2. Histograms of the relative abundances of bacterial communities in the rhizosphere soil at the phylum (**top**) and genus (**bottom**) levels.

The bacterial population in tomato rhizosphere soil varied in composition, but the general pattern remained constant. While the relative abundance of *Acidobacteria* was higher in the RW treatment than in the TW treatment when the cadmium concentration was 2.74 mg/kg, it was lower in the RW treatment when the cadmium concentration was at other concentrations. When the cadmium concentration was 2.74 mg/kg, the relative abundance of *Proteobacteri* in the RW treatment was slightly lower than that in the TW treatment, and when the cadmium concentration was other concentrations, the relative abundance of *Proteobacteri* in the RW treatment was higher than that in the TW treatment.

At different cadmium concentrations, the relative abundance of *Actinobacteria* was lower in the irrigation treatment using reclaimed water than in the irrigation treatment using tap water. At different cadmium concentrations, the RW treatment had a higher relative abundance of *Gemmatimonadetes* than the TW treatment. When the cadmium concentration was 0.30 mg/kg, the relative abundance of *Bacteroidetes* was marginally greater than that of the TW treatment, and when the cadmium concentration was at other cadmium concentrations, it was lower than that of the TW treatment.

At the genus classification level, the dominant genera with Top 20 abundance accounted for about 70% of the relative proportion of genera, and the top three dominant genera among treatments were all unidentified genera and uncultured genera (42.9–50.0%), with the remaining genera *RB41* (2.0–9.1%), *Sphingomonas* (3.2–5.3%), *Pontibacter* (0.7–4.1%), *Bacillus* (0.9–3.3%), and *Nocardioides* (0.8–4.2%); the relative abundance of these dominant genera varied considerably among treatments.

3.5. Correlation Analysis between Soil Bacterial Community Clustering Characteristics and Environmental Factors

To examine the similarities and differences in the bacterial community composition of rhizosphere soils from various treatments, PCoA analysis based on Bray-Curtis distance was performed. The different shape legends in Figure 3 represent tomato rhizosphere soil samples from different treatments, and the PC1 and PC2 axes explained 26.93% and 17.46% of the results, respectively. The cumulative contribution of PC1 and PC2 axes reached 44.57%, indicating that different cadmium-contaminated soil covers could explain the different structural composition of microbial communities among the samples.

The results indicated that for different cadmium concentrations, the heterogeneity of the rhizosphere soil bacterial community was larger. When the cadmium concentration was 0.30 mg/kg, the samples within the RW group were closer together and had similar microbial communities, and the samples within the TW group were farther apart and had differences in microbial community similarity. As the cadmium concentration increased, the sample distance within the RW treatment group increased. The differences in microbial community similarity the magnitude of soil cadmium concentration had a significant difference in the community of soil bacteria in the rhizosphere.

There was no overlapping part of sample coverage area between RW and TW in the figure; the sample sites were further apart, showing that TW and RW had different structural compositions of microbial communities. This also indicates that the difference of irrigation water quality also affected the composition of rhizosphere soil bacterial communities.

The correlation between the community composition of the bacterial genus level and different environmental factors in the rhizosphere soil samples of different treatments was revealed by RDA (Figure 4). The explanation rate of axis I and II were 27.58% and 22.70%, respectively, and the total explanation rate was more than 50%. The study indicates that soil pH and EC exhibited highly significant correlations ($p < 0.05$) with changes in bacterial populations in rhizosphere soil samples ($p < 0.01$) with total nitrogen content and changes in bacterial communities in rhizosphere soil samples, indicating that environmental factors have a great influence on rhizosphere soil bacterial community.

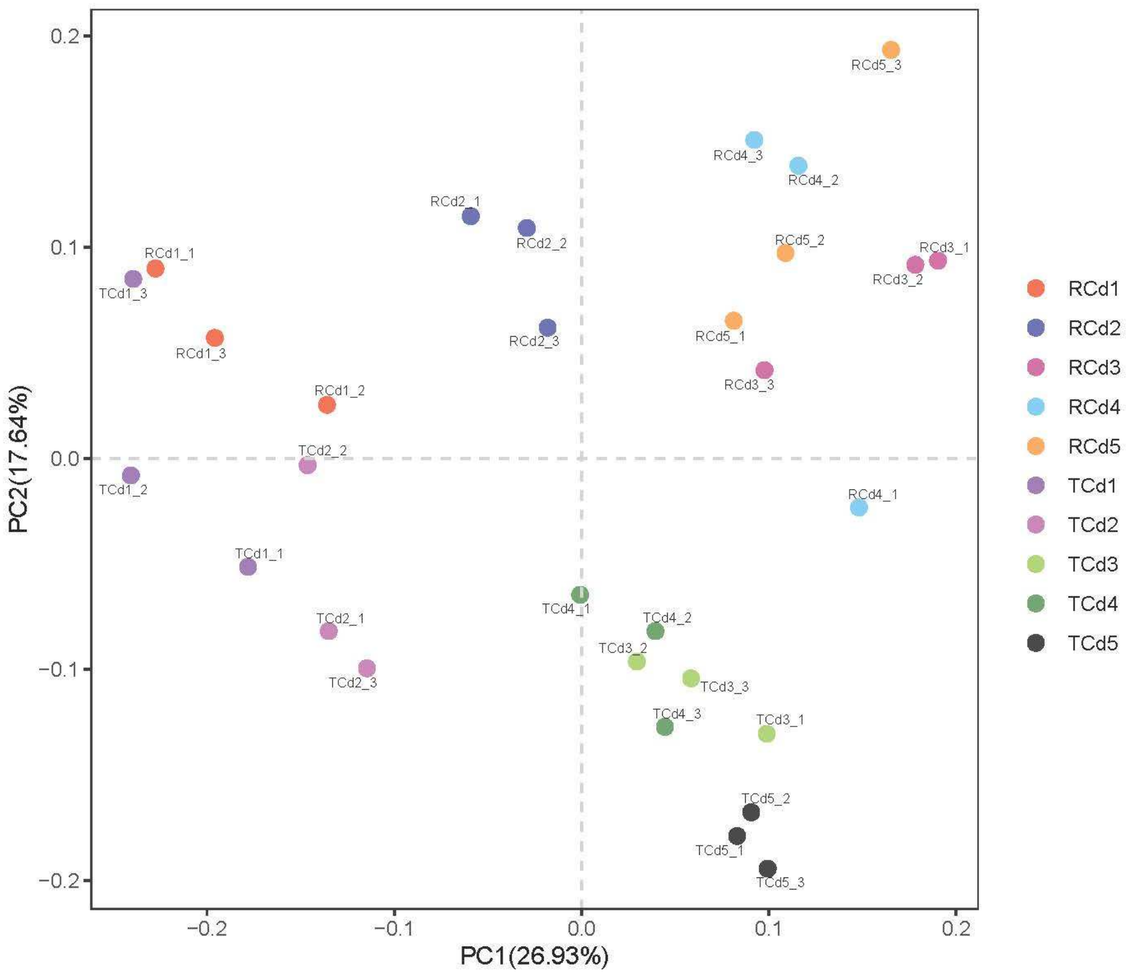

Figure 3. Principal component analysis (PCoA) of bacterial communities in the rhizosphere of different samples.

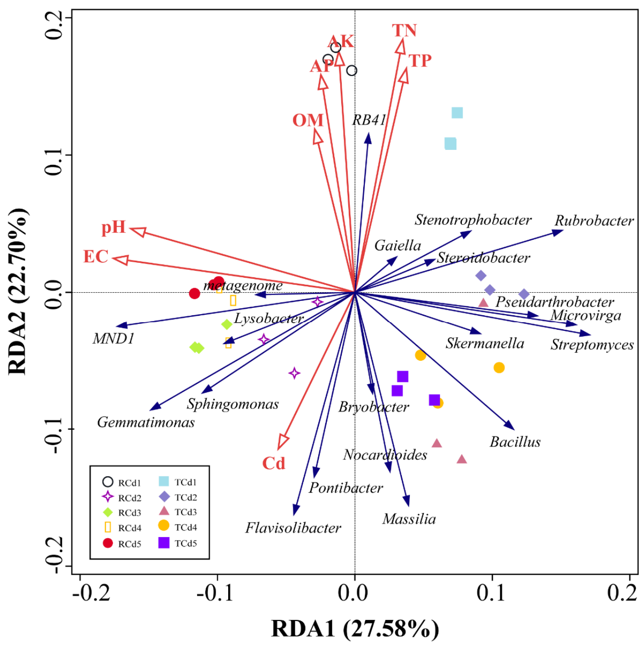

Figure 4. Redundancy analysis of bacterial communities and environmental factors in different samples.

OM showed an acute angle shape with AP, AK, TN, and TP, indicating a positive correlation between their environmental factors. EC showed an acute angle shape with pH, and an obtuse angle shape with OM, AP, AK, TN, and TP, indicating a positive correlation between two environmental factors EC and pH, and negative correlation with OM, AP, AK, TN, and TP environmental factors. Cd content showed an acute angle shape with EC and pH, and an obtuse angle shape with other environmental factors, indicating that Cd content was inversely correlated with other ecological factors and positively connected with EC and pH.

The effect of different environmental factors on the horizontal community composition of the rhizosphere soil bacterial genus was analyzed by correlation Heatmap plots (Figure 5).

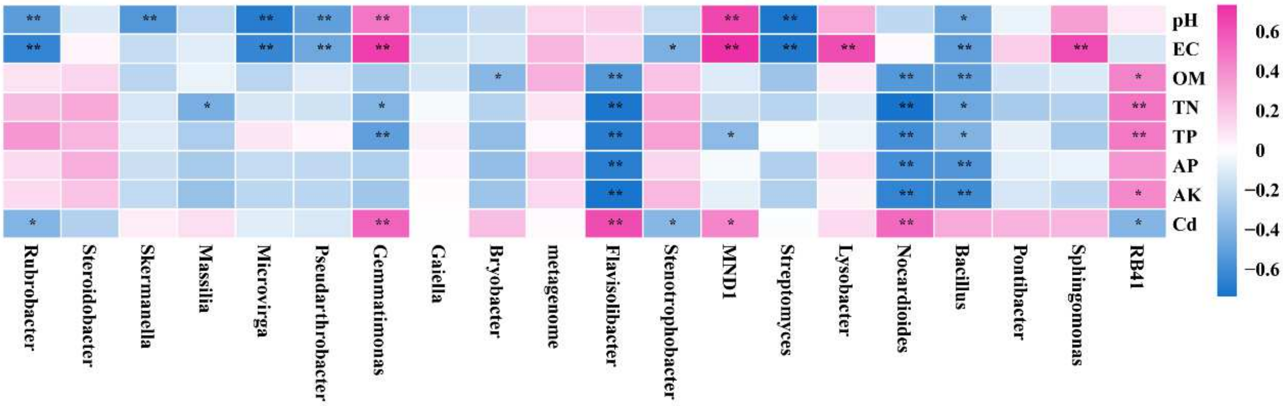

Figure 5. Spearman rank correlation Heatmap used to study the environmental factors and bacterial community compositions. * means 0. 01 < $p \leq 0.05$, ** means $p \leq 0.001$.

RB41 showed a highly significant positive correlation with TP and TN, a significant positive correlation with AK and OM, and a significant negative correlation with Cd. *Sphingomonas* was highly significantly and positively correlated with EC. *Bacillus* was highly significantly and negatively correlated with EC, OM, AP, and AK and highly significantly negatively correlated with pH, TN, and TP. *Nocardioides* was highly significantly negatively correlated with OM, TN, TP, AP, and AK, and was highly significantly positively correlated with Cd. *Streptomyces* showed a highly significant negative correlation with pH and EC. *MND1* showed highly significant positive correlations with pH and EC, significant negative correlations with TP, and significant positive correlations with Cd. *Stenotrophobacter* was significantly negatively correlated with EC and Cd. *Flavisolibacter* was highly significantly negatively correlated with OM, TN, TP, AP, and AK, and highly significantly positively correlated with Cd. *Gemmatimonas* showed highly significant positive correlations with pH, EC, and Cd, highly significant negative correlations with TP, and significant negative correlations with TN. *Pseudarthrobacter* was highly significantly negatively correlated with pH and EC. *Microvirga* was highly significantly negatively correlated with pH and EC. *Massilia* had a significant negative correlation with TN. *Skermanella* had a highly significant negative correlation with pH. *Rubrobacter* had a highly significant negative correlation with pH, EC, and Cd. The correlation coefficient between each genus and environmental factors can be viewed in detail in Table 6.

Table 6. Correlation coefficients of strains and environmental factors.

		pH	EC	OM	TN	TP	AP	AK	Cd
RB41	r			0.432	0.486	0.467		0.412	−0.538
	p			0.017	0.006	0.009		0.024	0.002
Sphingomonas	r		0.632						
	p		0.0001						
Bacillus	r	−0.461	−0.505	−0.040	−0.462	−0.403	−0.555	−0.604	
	p	0.010	0.004	0.004	0.010	0.027	0.001	0.0004	
Nocardioides	r			−0.543	0.740	−0.598	−0.600	−0.650	0.522
	p			0.002	0.00000293	0.0005	0.0004	0.0000988	0.003
Streptomyces	r	−0.723	−0.706						
	p	0.00000653	0.0000132						
MND1	r	0.648	0.732			−0.362			0.427
	p	0.0001	0.00000428			0.049			0.019
Stenotrophobacter	r		−0.414						−0.382
	p		0.023						0.037
Flavisolibacter	r			−0.541	−0.720	−0.688	−0.682	−0.732	0.626
	p			0.002	0.00000726	0.000027	0.0000337	0.00000424	0.0002
Gemmatimonas	r	0.478	0.679		−0.400	−0.505			0.543
	p	0.007	0.0000371		0.028	0.004			0.002
Pseudarthrobacter	r	−0.500	−0.464						
	p	0.004	0.010						
Microvirga	r	−0.687	−0.634						
	p	0.0000279	0.0002						
Massilia	r				−0.428				
	p				0.018				
Skermanella	r	−0.548							
	p	0.002							
Rubrobacter	r	−0.526	−0.647						−0.399
	p	0.003	0.0001						0.029

Note: r means high or low correlation coefficient, $p < 0.05$ implies a significant correlation between the two variables, and $p < 0.01$ implies a highly significant correlation between the two variables.

The correlations between bacterial communities and environmental factors were classified into different groups (Group1–Group3) based on Spearman's correlation coefficient and *p*-value. Among them, Group1 consists of genera with highly significant positive/negative correlation with environmental factors, namely *Nocardioides, Flavisolibacter*, and *Gemmatimonas*, Group2 consists of genera with significant positive/negative correlation with environmental factors, namely *RB41* and *MND1*, and Group3 consists of genera with highly significant positive/negative or significant positive/negative correlation with environmental factors, namely *Sphingomonas*, *Bacillus*, *Lysobacter*, *Streptomyces*, *Stenotrophobacter*, *Bryobacter*, *Pseudarthrobacter*, *Microvirga*, *Massilia*, *Skermanella*, and *Rubrobacter*. The results above show that the soil environment affects the rhizosphere soil bacterial community. This variation is related to the difference in irrigation water quality and the quality of soil contaminated with different concentrations of cadmium.

4. Discussion

4.1. Changes in Physicochemical Properties of Tomato Soils Contaminated with Different Cadmium Concentrations by Different Irrigation Water Sources

Soil physical and chemical properties are one of the indicators of soil fertility. The variation in the strength of soil fertility also affects whether the soil can provide sufficient nutrients for crops [28,29]. RW can affect soil physicochemical properties, such as pH, EC, TN, TP, etc., by reducing the effectiveness of phosphorus at low soil pH, for instance [30]. Table 3 shows that the pH of the RW treatment was significantly higher than that of the TW treatment, indicating that the elements contained in the reclaimed water cause an increase in the pH of the soil [31]. Our results supported the conclusion of pervious findings where reclaimed water significantly increased soil pH [32–34].

The outcomes of this experiment concur with those found in the literature. SOM is one of the important indicators of soil nutrients, and was higher in the RW treatment compared to TW treatment (Table 3). The same conclusion was drawn by previous researchers, who used reclaimed water to irrigate soil and found increased contents of SOM [29]. Different cadmium contamination concentrations caused damage to nutrient cycling and inhibited nutrient supply status in the soil [35]. But by irrigating with reclaimed water, our results showed the higher values of TN, TP, AK, and AP when using reclaimed water to irrigate the soil with different concentrations of cadmium as compared to TW to the corresponding soils as depicted in Table 3. This may be because reclaimed water is complex in composition and contains many nutrients, where nutrients from reclaimed water are transferred to the soil through irrigation. It indicates that irrigation of reclaimed water with different concentrations of cadmium-contaminated soil compensates for the loss of soil nutrients due to cadmium stress [36–38]. Based on our findings, it is concluded that cadmium-contaminated soil irrigated with reclaimed water showed enhanced level of nutrients as compared to the corresponding soil irrigated with tap water.

Table 3 also shows that the soil cadmium content of all treatments did not exceed the original cadmium content setting range of the experiment, and did not show significant differences ($p < 0.05$) between treatments, indicating that irrigation of cadmium-contaminated soil with reclaimed water did not increase soil cadmium pollution in the short term [18,39]. Reclaimed water has the same safety as tap water for irrigating cadmium-contaminated soil.

4.2. Effect of Different Irrigation Water Sources on the Yield and Quality of Tomatoes Grown in Soils Contaminated with Different Cadmium Concentrations

The quality and yield of tomatoes are influenced by many factors: soil quality and irrigation water sources can affect the growth and development of tomatoes, which in turn affects tomato quality and yield. Our results showed a significantly inverse correlation between soil pH and EC and a moderate sensitive to salinity [40], which ultimately affect the quality of tomatoes. A slight change in EC of soil resulted significant alteration in the quality and yield of tomatoes [41].

The TA of tomatoes is one of the important indicators of tomato quality and it can affect the taste of tomatoes to some extent [42]. Table 4 showed that the TA of tomatoes treated with reclaimed water irrigation was lower than that of the TW treatment, but did not reach the level of significant difference between treatments ($p < 0.05$), indicating that a certain taste of tomatoes was maintained under RW treatment [43]. The results of one study also showed that RW did not have a significant adverse effect on tomato quality compared to clear water irrigation [13,44]. Our results supported the conclusion of pervious findings.

In existing studies, the yield of crops grown in soils under prolonged cadmium stress has been reduced or affected [45]. The results of our study showed that the yield of tomatoes in the RW treatment was significantly higher than that in the TW treatment ($p < 0.05$), indicating that RW had a boosting effect on tomato yield (Table 3) [43,46]. Its promoting effect alleviated the inhibition of tomato yield by cadmium. Figure 1 shows significant and highly significant relationships ($p < 0.01$, 0.05) between tomato quality indicators (TA, SS, yield) and soil physicochemical property indicators, so RW indirectly affects tomato quality and yield under the premise that it can change different cadmium-contaminated soil physicochemical properties, and there are also studies that proved that reclaimed irrigation can affect tomato quality and yield [47].

4.3. Changes in Tomato Rhizosphere Soil Microbial Community by Different Irrigation Water Sources

Differences and changes in soil microbial community diversity are the result of a combination of different soil environments and anthropogenic measures [48,49]. However, our experimental results showed that the rhizosphere soil microbial community diversity was higher in different cadmium-contaminated soils RW than in the TW treatment; as shown in Table 5, the Chao1 index, Shannon index, PD whole tree, and Simpson index of the RW treatment were higher than those of the TW treatment, indicating that the abundance of microbial species and their community diversity in different cadmium-contaminated soils treated with RW were higher than those of the TW treatment, similar to the findings of previous studies that reclaimed water irrigation can increase soil microbial community diversity [14,50,51]. Soil microbial diversity is known to be reduced when soils are subjected to cadmium stress [52,53], and RW mitigates the reduction phenomenon of microbial community diversity. These results indicate that RW can increase soil microbial diversity, and to some extent, can mitigate the effect of cadmium on soil microbial community diversity.

NMDS plots (Figure 3) showed significant differences in the composition of microbial community diversity under RW treatment and TW treatment [54]. At the phylum level, the composition of dominant phylum of bacterial diversity in the RW treatment and TW treatment was similar, but their relative abundance was different. For example, some dominant phylums were *Proteobacteria*, *Bacteroidetes, Actinobacteria*, and *Acidobacteria*, similar to the results of existing studies [55]. In addition, our study confirmed that the relative abundance of *Proteobacteria, Gemmatimonadetes*, and *Bacteroidetes* were higher in the RW treatment than in the TW treatment at different cadmium concentrations (Figure 2), because *Proteobacteria* are involved in nutrient metabolism activities such as the soil nitrogen cycle [56]. In contrast, all nutrient indicators of the RW treatment were higher than those of the TW treatment (Table 3), indicating that the bacteria of the phylum *Proteobacteria*, involved in nutrient cycling, were more active in the RW treatment. It did not inhibit the activity of *Proteobacteria* in contaminated soil with different cadmium concentrations.

Our study showed that the relative abundance of *Gemmatimonadetes* showed an increasing trend with increasing cadmium concentration between treatments (Figure 2). It is possible that due to the irrigation of cadmium-contaminated soil with reclaimed water, some synergistic effect of heavy metal stress and reclaimed water, which may act in the same way as some soil conditioners, will increase the relative abundance of *Gemmatimonadetes* [55]. Moreover, the pH of the RW treatment was higher than that of the TW treatment (Table 3), and the relative abundance of *Gemmatimonadetes* in soils with high pH would be higher than that of soils with low pH, in agreement with the results of previous studies [57].

At the genus level, *Bacillus* is the dominant species and it is among the common pathogens in TW areas. Figure 2 also shows that the relative abundance of *Bacillus* was higher in the TW treatment than in the RW treatment, and Figure 5 confirms that it was highly significantly negatively correlated ($p < 0.01$) with AP, and that the AP was also lower in all TW treatments than in the RW treatment (Table 3), which may be explained by the fact that RW improved the quality of the soil and reduced its relative abundance, which inhibited its activity. The genus *Flavisolibacter* under the phylum *Bacteroidetes* showed a highly significant negative correlation ($p < 0.01$) with the indicators of TP and AP of the soil. The reason for this may be that the dominant group under the genus classification is more dominant in the phylum *Proteobacteria*, and the metabolism of the phylum *Proteobacteria* requires the participation of phosphorus, which also consumes phosphorus content. Therefore, it will inhibit the growth of some genera, and also promote the growth of other genera, forming a competitive relationship with the phylum *Proteobacteria* [58].

5. Conclusions

Different water sources irrigating tomatoes grown on soils contaminated with different cadmium concentrations reveal differences between their treatments. Compared to tap water irrigation of cadmium-contaminated soil, reclaimed water irrigation improves soil physicochemical indicators and increases its nutrients, and also promotes tomato yield, with insignificant differences in tomato TA ($p < 0.05$); thus, RW irrigation retains the original taste of tomatoes to some extent.. To some extent, the threat of cadmium stress to tomato yield was mitigated.

Reclaimed water irrigation of cadmium-contaminated soil increases the diversity of microbial communities, and reclaimed water irrigation of cadmium-contaminated soil promotes the activity of *Proteobacteria* and *Bacteroidetes*, while inhibiting the activity of *Actinobacteria*, and also increases the relative abundance of *Gemmatimonadetes*, a pathogenic bacterium Bacillus. However, irrigation with reclaimed water does worsen the amount of damage by a soil's pathogenic bacteria.

Irrigation of tomatoes with reclaimed water on light to moderate cadmium-contaminated soil resulted in an overall improvement in soil nutrients and fertility and did not worsen the degree of soil contamination; moreover, irrigation with reclaimed water also stimulated changes in the soil microenvironment. However, more in-depth research is needed to find the best irrigation system with reclaimed water and in different cadmium-contaminated soils. Thus, reclaimed water can replace tap water sources for agricultural production on cadmium-contaminated soil. It alleviates the shortage of water resources and makes effective use of land resources.

Author Contributions: J.C.: Conceptualization, Data curation, Visualization, Writing—original draft. P.L.: Methodology, Validation, Funding acquisition, Project administration, Writing—review and editing. X.Q.: Supervision, Writing—review and editing, Funding acquisition. W.G.: Resources, Investigation, Formal analysis, S.U.R.: Formal analysis, Writing—review and editing, Methodology. All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful to the Collaborative Innovation Project of Science and Technology Innovation Engineering of the Chinese Academy of Agricultural Sciences (CAAS-ASTIP) and the National Natural Science Foundation of China (NO: 51679241).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The bacterial raw sequences of this study have been submitted to SRA of NCBI database, with the accession number PRJNA853724.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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