Soil and Food Crops Irrigated with Wastewater

Subjects: Water Resources

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Wastewater is actively used for irrigation of vegetable and forage crops in arid lands due to water scarcity and cost advantages. The objective of this review was to assess the effect of wastewater (mixture sources) reuse in irrigation on soil, crop (vegetable and forage crops), animal products, and human health.

forage crops vegetable crops toxic metals

1. Wastewater Quality for Reuse in Irrigation of Agricultural Crops

High demands for water in dry lands plus frequent drought encourage policymakers and governments to assess alternative management practices to sustain water resources and achieve greater production [1]. Water scarcity and unreliable rainfall (**Table 1**) make water management practices, such as rainfall water harvesting and the use of non-conventional water of lower quality (saline and wastewater), viable investment for water supply and food production in drylands [2][3][4]. Sustainable land management requires comprehensive attention and a long-term vision to both bio-physical and socio-economic aspects [5]. The upgrade of water supply systems coupled with public awareness to reduce residential water use and saving as well as the reuse of domestic waste and greywater have been increased recently [2][6][7]. In fact, the direct use of treated and untreated municipal wastewater for irrigation purposes has been increased recently worldwide to compensate the water shortage crises. In 2018, the total annual wastewater (10^9 m^3/year) in Mexico was 5.71, India 1.23, China 1.26, and Jordan 0.1 (**Table 1**). Interestingly, several countries have developed wastewater irrigation systems for direct reuse. Worldwide, the total irrigated area equipped for direct use of wastewater is about 8.42 million ha; of this amount, untreated wastewater is 4.14 million ha and treated wastewater is 4.28 million ha [8].

Table 1. Total cultivated area, annual precipitation, total volume of wastewater used for irrigation and total area equipped for wastewater irrigation for some countries that use wastewater for irrigation [8].

Country	Rain-Fed Cultivated Area (1000 ha)	Irrigated Cultivated Area (1000 ha)	Annual Precipitation in Volume (10^9 m^3/Year)	Annual Precipitation in Depth (mm/Year)	Wastewater (Treated and Non-Treated) for Irrigation (10^9 m^3/Year)	Total Irrigated Area Equipped for Direct Use of Treated Wastewater (1000 ha)
India	76,742	92,575	3560	1083	1.23	1.32
Pakistan	12,710	18,590	393	494	1.02	32.5

Country	Rain-Fed Cultivated Area (1000 ha)	Irrigated Cultivated Area (1000 ha)	Annual Precipitation in Volume (10^9 m^3/Year)	Annual Precipitation in Depth (mm/Year)	Wastewater (Treated and Non-Treated) for Irrigation (10^9 m^3/Year)	Total Irrigated Area Equipped for Direct Use of Treated Wastewater (1000 ha)
Iran	8544	8893	86	228	0.33	240
China	40,190	95,486	6192	645	1.26	3618
Australia	29,008	2298	4133	534	0.14	-
Japan	1463	2957	630	1668	0.11	-
Jordan	197	83	9.9	111	0.103	3.7
Palestine	62	124	2.4	402	0.013	-
Iraq	3107	2143	93.7	216	1.08	-
Saudi Arabia	2641	954	127	59	0.53	51.92
Turkey	18,974	4206	466	593	0.05	9.16
Bahrain	4.0	0.6	0.06	83	0.009	1.25
Algeria	7658	858	212	212	0.01	1.2
Egypt	1339	2497	18.1	75	0.29	35.5
Morocco	7815	1711	155	346	0.01	-
Argentina	31,400	2301	1643	591	0.091	20
Mexico	16,276	6331	1489	758	5.71	70
Bolivia	4449	278	1259	1146	0.016	1.56
Brazil	55,107	8411	14,995	1761	0.008	-

... nt in arid ... [9][10] ... efined as ... eins) and ... esidential ... n clothes washers, bathtubs, showers, and sinks, without wastewater from toilets [11]. The use of greywater for irrigation would reduce the demand on water resources and alleviate the pressure on wastewater treatment plants [11].

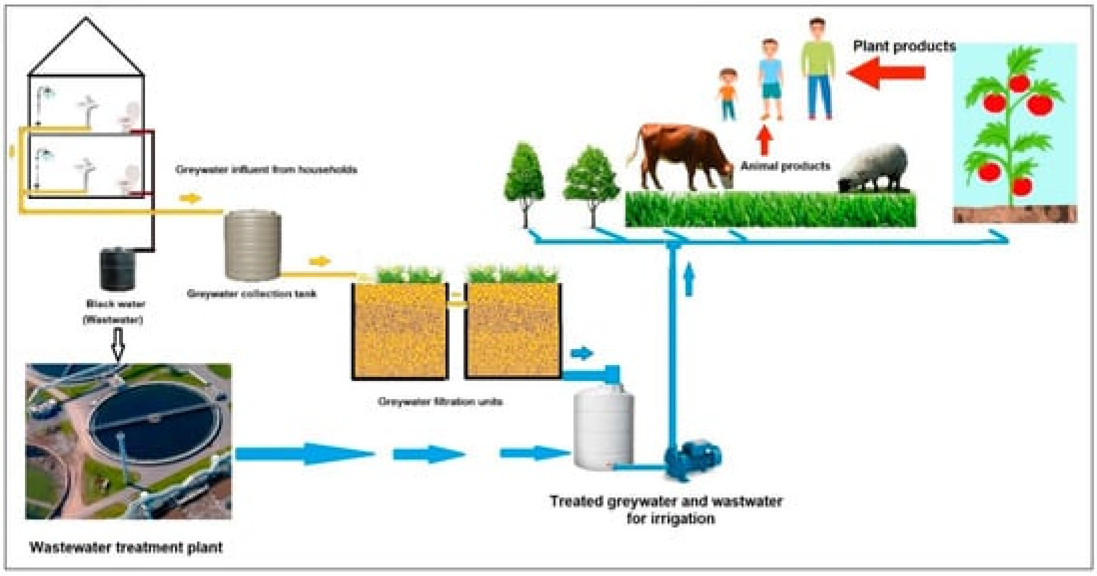

Figure 1. Schematic diagram for wastewater and greywater reuse in agriculture.

Numerous wastewater treatment and quality assessment methods have been used worldwide [12]. Microbial contaminants, such as total and fecal coliforms, normally exceed the recommended levels due to unrestricted entry of untreated wastewater into the environment; therefore, the use of suitable purification treatments with high removal efficiency for microbial agents are critical [13]. In addition, wastewater treatment plants might emit several microbiological contaminants in the air, including mesophilic, psychrophilic and coliform bacteria [14]. However, the abundance of these microbes in the air and the purified wastewater depends on the treatment plant capacity and purification system [14]. In Iran, the assessment of wastewater treatment systems (activated sludge, stabilization ponds, wetlands, and low and medium pressure UV disinfection systems) for microbial removal revealed that the active sludge systems was not efficient in reducing coliforms (total and fecal) compared to stabilization pond systems [15]. Udayanga et al. [16] found that thermal processing of sewage sludge, especially pyrolysis, valorized the carbon rich organic fraction of the sludge, while successfully reducing its volume. Ozonation-based disinfection methods can effectively remove antibiotic resistant bacteria from aqueous solutions [17]. However, the process efficiency was affected by the ozone dose as well as the wastewater solids and pH [17]. Biological treatments of wastewater normally remove microbial pollutants but these methods fail to eliminate numerous chemical compounds, such as pharmaceuticals [14]. Therefore, additional treatment process is necessary to remove these pollutants, including membrane filtration, adsorption, coagulation, electrochemical treatment, or advanced oxidation [14]. For example, adsorption onto activated carbons has been selected as the procedure to remove different chemical contaminant at the industrial scale [13]. Overall, wastewater treatment systems involve a combination of physical, biological, and chemical processes to purify the effluent efficiently [13].

The use of wastewater for irrigation of food crops is controversial. The economic and energetic assessment of wastewater reuse as viable complementary sources of water represent a possible opportunity [6]. In the arid regions, research studies have recommended the reuse (with precautions) of wastewater for irrigation in urban landscape and forage crop production [2][10][18]. However, analysis of this type of water depends on its source. The use of wastewater for irrigation might generate substantial environmental contamination and toxicology problem especially when farmers use untreated wastewater [19][20]. Wastewater contains toxic microorganisms and heavy metals such as Ni, Cd, Cr, and Pb that can induce severe risks to humans and the environment [19].

The chemical composition of tertiary treated wastewater are often within the World Health Organization (WHO) allowable limits, but heavy metal concentrations (i.e., Ni, Cd, Pb, As, and Cr) has exceeded the maximum limits in several regions of the world, especially in regions that use untreated wastewater for irrigation (**Table 2**). Microbial levels depend on wastewater sources and might contain pathogens, such as Pseudomonas, Salmonella, Aeromonas, and Staphylococcus; therefore, should not be reused for irrigation without treatment [21]. **Table 2** shows that levels of total coliforms, fecal coliforms, and *Escherichia coli* have also exceeded the maximum world limits in untreated wastewater. In addition, treated wastewater microbial levels (total coliforms, fecal coliforms, and *Escherichia coli*) and some heavy metals (Cu, Cd, Cr, and Ni) were higher than the standard limits. Akoto et al. [20] found that irrigation of farmlands with untreated wastewater contaminated the soil by Ni, Pb, Cr, and Cd and transferred these contaminants to the farm products (lettuce). A study conducted by Qishlaqi et al. [9] showed that excessive accumulation of Ni and Pb was found in wheat tissues irrigated with untreated wastewater. They concluded that strict protection measures and rigorous integrated systems are essential to alleviate the negative effect of wastewater reuse in agriculture, especially the regions irrigated with untreated wastewater. The global assessment of irrigated croplands affected by urban wastewater (treated and untreated) revealed that about 36 million ha of irrigated croplands were located in wastewater dependent catchments [22]. In addition, about 82% of these affected croplands (29.3 million ha) were located in countries (China, India, Pakistan, Mexico, and Iran) in which less than 75% of wastewater is normally treated [22]. Considering the microbial and chemical analysis of untreated and treated wastewater exceeding the world standard limits in some regions of the world as well as the recommendations of previous studies, untreated wastewater should be restricted (wastewater treatment is essential) with a periodic water analysis to reduce the transfer of heavy metals to crops, animals, and humans.

Table 2. Quality of un-treated and treated wastewater compared with fresh and allowable word standard limit for irrigation. World standards represent the range limits for the WHO and the following countries: Canada, India, Jordan, Italy, Australia, Japan, China, Slovenia, Germany, and Great Britain. Bold values indicate where wastewater variable exceeded the standards limits.

Parameter	Symbol and Unit	Untreated Wastewater	Treated Wastewater	Fresh Water	Word Standards	Reference
Potential of Hydrogen (H^+)	pH	5–10	6–8	7.1–7.6	5.5–9.5	[2][9][11][6][23][24]
Electrical conductivity	EC_w (dS m^{-1})	0.5–10	0.4–0.8	0.3–4.0	0.7–10	[2][11][6][23][24]
Total Dissolved Solids	TDS (mg L^{-1})	279–**2444**	100–429	80–154	450–2000	[2][11][25]
Total Suspended Solids	TSS (mg L^{-1})	2–987	2–312	0–21	-	[6][23][26]

Parameter	Symbol and Unit	Untreated Wastewater	Treated Wastewater	Fresh Water	Word Standards	Reference
Sodium Adsorption Ratio	SAR	2–**90**	1–**21.9**	3.0–8.0	9–13	[2][11][25]
Turbidity	T (NTU)	3–**444**	-	Not detected	1–10	[11][6][23][26]
Biological Oxygen Demand (5 days)	BOD_5 (mg L^{-1})	**135–4450**	10–**942**	0.0–225	60–300	[2][9][11][6][23][26][27]
Chemical Oxygen Demand	COD (mg L^{-1})	15–**4155**	5–**1700**	Not detected	120–500	[2][11][6][23][26][27]
Fat, Oil and Grease	FOG (mg L^{-1})	8–**232**	-	Not detected	8	[11][26]
Anionic surfactants	ASR (mg L^{-1})	1–80.5	0.3–1.0	Not detected	0.1–100	[11][6][26]
Methylene Blue Active Substances	MBAS (mg L^{-1})	1.6–**118**	0.3–**39**	Not detected	25	[11]
Total Coliforms	TC (CFU 100 mL^{-1})	1000–**1.9×10^8**	200–**2×10^7**	0.0–2.0	10–1000	[11][6][25][26]
Fecal Coliforms	FC (CFU 100 mL^{-1})	200–**2×10^7**	10–**4×10^6**	0.0–2.0	2–1000	[11][6][25][26]
Escherichia coli	*E. coli* (CFU 100 mL^{-1})	1000–**8×10^8**	408–**4×10^5**	0.0–1.0	1000–10^5	[2][11][6][25][26]
Bicarbonate	HCO_3 (mg L^{-1})	2–223	-	-	520	[11][26]
Orthophosphate	PO_4 (mg L^{-1})	0–**52**	0.2–3.2	0.03–0.8	30	[24][28]
Nitrate	NO_3 (mg L^{-1})	10–**52**	0.1–7.0	0.0–0.004	45–50	[11][6][23][24][26]
Sulfate	SO_4 (mg L^{-1})	1–22	0.5–28	0.0–0.1	500	[11][29][24][25][26]
Total nitrogen	TN (mg L^{-1})	1–**61**	0.5–17.7	2.0–10	5–50	[2][11][6][18][24][26][27]
Potassium	K^+ (mg L^{-1})	20–39	1–10	0.0–12	80	[2][9][11][18][24][25]

Parameter	Symbol and Unit	Untreated Wastewater	Treated Wastewater	Fresh Water	Word Standards	Reference
Phosphorus	P (mg L^{-1})	26–38	0.05–1.2	0.01–1.0	-	[2][9][18][25][26][27]
Calcium	Ca^{+2} (mg L^{-1})	1–100	0.1–72	1.5–15	230–400	[2][9][11][18][25][26]
Magnesium	Mg^{+2} (mg L^{-1})	1–60	0.1–23	0.0–10	60	[2][9][11][18][25][26]
Manganese	Mn (mg L^{-1})	0.02–0.16	0.0002–0.06	0.0–0.17	0.2	[9][11][27][30][31][32]
Iron	Fe (mg L^{-1})	0.1–2.7	0.1–0.4	0.0–0.1	0.1–5	[2][9][11][18][27][30][31]
Zinc	Zn (mg L^{-1})	<0.002–**13.0**	0.01–0.7	0.0–0.17	2.0	[2][9][11][30][31]
chloride	Cl^{-} (mg L^{-1})	9–**450**	63–205	1.0–18	140–400	[2][11][26][27]
Sodium	Na^{+} (mg L^{-1})	2–**667**	1.0–136	2.0–19	69–230	[2][11][25]
Copper	Cu (mg L^{-1})	0.001–**91**	0.001–**24**	0.001–0.02	0.2	[11][27][30][31]
Boron	B (mg L^{-1})	0.02–0.44	0.001–0.04	0.0–0.1	0.7–3.0	[2][11][6][26][33]
Aluminum	Al (mg L^{-1})	0.0–**21**	0.0–1.5	0.0–0.03	5.0	[2][11][25][26][33]
Cadmium	Cd (mg L^{-1})	<0.001–**4.0**	<0.002–**0.4**	0.0–**0.03**	0.01	[2][9][11][30][31][32][34]
Lead	Pb (mg L^{-1})	<0.003–**84**	<0.01–1.3	0.003–5.0	5.0	[2][9][11][30][31][32][34]
Chromium	Cr (mg L^{-1})	<0.004–**42**	0.0–**4.0**	<0.008–0.8	0.1	[9][11][26][30][32][33][34]
Arsenic	As (mg L^{-1})	0.0001–**6.0**	[2][35] 0.001–0.002	<0.0025	[6][7][21] 0.1	[2][11][25][26][30][33]
Nickel	Ni (mg L^{-1})	0.04–**70**	0.01–**9.0**	<0.001–**6.0**	0.2	[9][11][18][30][31][32]
Cobalt	Co (mg L^{-1})	0.0–0.01	0.0–<0.0001	Not detected	0.05	[25][26][27][33]

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variables are measured and the probability of having non-measured toxic substances is high [36][38]. In Australia, 22 organic micro-pollutants including triclosan, caffeine, paracetamol, acesulfame, and salicylic acid were found in greywater and thus the reuse of this recycled-irrigation water can act as a source of microbial pollutant to soil, plants, and groundwater [29]. Similarly, in Palestine, the antibiotic and herbicide analysis of residential greywater

Parameter	Symbol and Unit	Untreated Wastewater	Treated Wastewater	Fresh Water	Word Standards	Reference
Selenium	Se (mg L^{-1})	<0.001	<0.001	Not detected [38]	0.02	[26]
Vanadium	V (mg L^{-1})	0.0001–0.004	-	Not detected	0.1	[33]
Mercury	Hg (mg L^{-1})	0.001	-	Not detected	0.0001–0.01	[34]

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of overexploited aquifers, water scarcity, and cost considerations [20][39]. In many arid and semi-arid regions (e.g., Jordan, Iraq, Ghana Saudi Arabia, and India), irrigation is essential to overcome the prolonged drought periods during the summer. In salt-affected arid lands (due to overexploitation of aquifers), farmers are turning to wastewater as a source of low saline water [39]. The reuse of wastewater for irrigation may have several beneficial effects for plants because it increases the levels of some beneficial elements (N, P, K, Fe, Zn, Ca, and Mg) in the soil [39]. **Table 2** shows that micronutrients concentration (N, P, K, and Ca) in untreated wastewater are much higher than fresh water. Higher nutrient and organic matter in the soil lead to a higher growth rates and production. The use of treated wastewater in irrigation effectively increased stem height and the dry matter of *Panicum maximum* compared to those irrigated with fresh water [39]. The higher performance of the wastewater treatment can be explained by its higher nutritive content, especially in N [39].

Heavy metals such as Cd, Cr, Pb, and Ni are metallic elements, have relatively higher weight than water, are extremely soluble in the aquatic environments, and consequently, they can be uptake easily by living organisms (plant, animal, human) [34]. Turner et al. [33] found that the use of greywater for irrigation gradually increased soil (B, Cr, As, and Cu) and groundwater metals (Al, As, Cr, Cu, Fe, Mn, Ni, and Zn) exceeded safe limits standards after four years.

Vegetables are an essential component of our daily diet. However, the ability of vegetable growers to provide the ever-growing population with the required amount is limited by the unpredicted rainfall pattern and unsuitable irrigation systems [20]. Therefore, farmers tend to use wastewater, which is readily available alternative for irrigation in most dryland regions. However, wastewater contains a substantial amount of pollutants, such as heavy metals. **Figure 2** shows the metadata analysis results of previous studies that assess the accumulation of heavy metals in wastewater irrigated vegetables; leafy-green (lettuce, spinach, parcel, mint, cabbage, pudina, and coriander), bulbs and tubers (onion, garlic, potato, radish, and carrot), and fruits (tomato, pepper, cauliflower, okra, and eggplant). Although heavy metals in wastewater were within the standard limits, the concentration of those toxic elements (Pb, Cd, Ni, Cr, As, and Zn) exceeded the allowable limits in both soil and vegetables edible parts (**Figure 2**). In fact, the concentration of heavy metals in vegetable edible parts increased by 3–9 fold compared to those irrigated with fresh water. For example, leafy-green from wastewater-irrigated fields increased Pb concentration by 5 fold, Cd by 7 fold, Ni by 8 fold, Cr, As, and Zn by about 6 fold compared to those irrigated with fresh water. Khan et al. [32] used wastewater for irrigation of vegetable crops (spinach, coriander, carrot, tomato, and cauliflower). They found that all tested leafy-green, root, and fruit vegetable samples were contaminated with high levels of Pb, Ni, and Cd; higher than WHO limits. Qureshi et al. [23] found that the concentration of Zn and Cr in leafy-green vegetables (lettuce and spinach) was higher than root and fruit (tomato, eggplant, radish, and carrots) vegetables. Therefore, selecting suitable crops can potentially reduce the health risk for humans. In this review, the metadata analysis showed that the concentrations of Pb and As were similar across vegetable types while leafy-green had higher Ni, Cr, and Zn than bulb, tubers, and fruit vegetables (**Figure 2**). Overall, although the concentration of heavy metals in wastewater used for irrigation were within the WHO limits, the long-term reuse of this recycled water led to excessive build-up of those toxic metals in the soil. Therefore, rigorous and continuous testing (wastewater, soil, plant) is required in cultivated farms to prevent the translocation of heavy metals in the food chain [40].

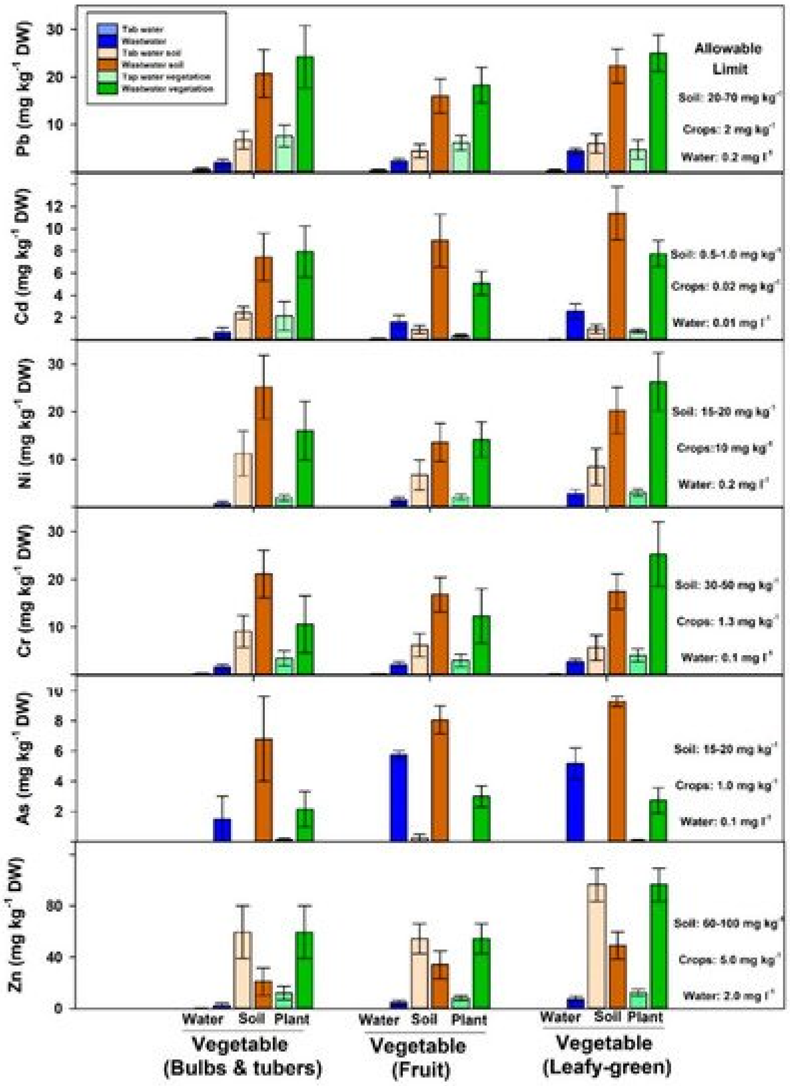

Figure 2. Heavy metals concentration in fresh and wastewater soil and vegetables [10][20][23][24][27][30][31][32][39][41][42][43][44][45][46][47][48][49][50]. Leafy-greens represent lettuce, spinach, parcel, mint, cabbage, pudina, and coriander; bulbs and tubers represent onion, garlic, radish, potato and carrot; fruits vegetables represent tomato, pepper, cauliflower, okra, and eggplant. Bars represent mean ± SE.

Soil is the key component for developing an integrated and sustainable wastewater management system. This is because the chemistry and physics of the soil can significantly affect the levels of toxic materials in the soil and consequently the quality of the crops. The reviews of previous studies, conducted on wastewater reuse in agriculture, revealed that most studies that positively recommended the reuse of wastewater were (1) short-term studies (less than 4 years) or/and (2) assuming that the analysis of wastewater only is sufficient for safe use in agriculture and thus could maintain the level of heavy metals in the crops within the recommended WHO limits [2][18][24][27]. However, long-term studies on wastewater reuse found that several heavy metals significantly increase across years leading to potential soil contamination. The long-term irrigation (~20 years) of wastewater in Shiraz, Iran increased organic matter of the soil by 20–30%, pH by 2–3 units, and heavy metals levels by more than 100%; exceeded the WHO limits [9]. Although the wastewater quality was acceptable in that study (Ni 0.19; Zn 0.06; Cd 0.004; Pb 0.33; Cr 0.1 mg kg^{-1}), the frequent irrigation led to accumulation of contaminated soil in the top 10 cm soil; Pb 441 mg kg^{-1} (soil limits: 20–70 mg kg^{-1}), Cd 3.2 mg kg^{-1} (limits: 0.5–1.0 mg kg^{-1}), Ni 297 mg kg^{-1} (limits: 15–20 mg kg^{-1}), Cr 29 mg kg^{-1} (limits: 30–50 mg kg^{-1}) and Zn 170 mg kg^{-1} (limits: 60–100 mg kg^{-1}) [9]. In Nigeria, the vertical distribution analysis and modeling of heavy metals in vegetable farms irrigated with wastewater showed that these gardens will not be suitable for human consumption after 10–20 years if the heavy metal balances (input from wastewater and output metal taken out by plant biomass or leaching) remain unchanged [51].

Heavy metals accumulation potential is different between plant species. The transfer factor is normally used to estimate the translocation of those toxic metals from the soil to plant species [52]. The transfer factor is the ratio between the heavy metal concentrations in the edible part of vegetables (mg kg^{-1}) to the concentration of the metal in soil. Interestingly, Meng et al. [52] found that the transfer factor of heavy metals (especially, Cd and Pb) from soil to vegetables was extremely high. For example, the transfer factor of Cd for cabbage was 1.82 and for potato was 1.52. Similar results were found by Tiwari et al. [30] who found that transfer of toxic metals (As, Cd, Cr, Pb, and Ni) from soil to edible parts of vegetables (pepper, cabbage, spinach, radish, and tomato) was high and unsafe due to possible transfer in the food chain leading to health hazards for humans. They suggested that only vegetable crops that restrict heavy metals in non-edible ports may be cultivated [30]. Overall, to guarantee food safety and the safe use of wastewater for irrigation, urgent attention is necessary to apply appropriate permanent monitoring and pollution control [52].

Although treated wastewater is bacterially safe and has a positive impact on plant growth, microbiological contamination of vegetable crops irrigated with wastewater has been reported in many regions of the world [53][54] *Escherichia coli* is a coliform group of bacteria that is used to represent the bacterial pathogens in the reused wastewater and their behavior is expected to reflect enteric pathogens [11]. In this review, the mean total Escherichia coli in wastewater-irrigated soil was found to be about 2×10^6 (CFU g^{-1}) and about 15 (CFU g^{-1}) in vegetable edible parts (leaf, bulb, tuber, and fruit) (**Figure 3**). In addition, the mean total coliforms were about 1.4×10^6 (CFU g^{-1}) and about 55 (CFU g^{-1}) in vegetable edible parts (**Figure 3**). Qureshi et al. [23] found that all vegetables irrigated with wastewater had different levels of microbial loading in their edible part. The highest level of contamination of total coliform were found in spinach, radish, and eggplant while the lowest concentrations were found in lettuce and tomatoes. In addition, the *Escherichia coli* counts on lettuce, tomatoes, eggplant, and carrot were higher than spinach. They concluded that the tertiary-level of wastewater treatment does not fully remove pathogenic bacteria (total coliform and *Escherichia coli*) from the reused wastewater nor the edible parts of the vegetables [23].

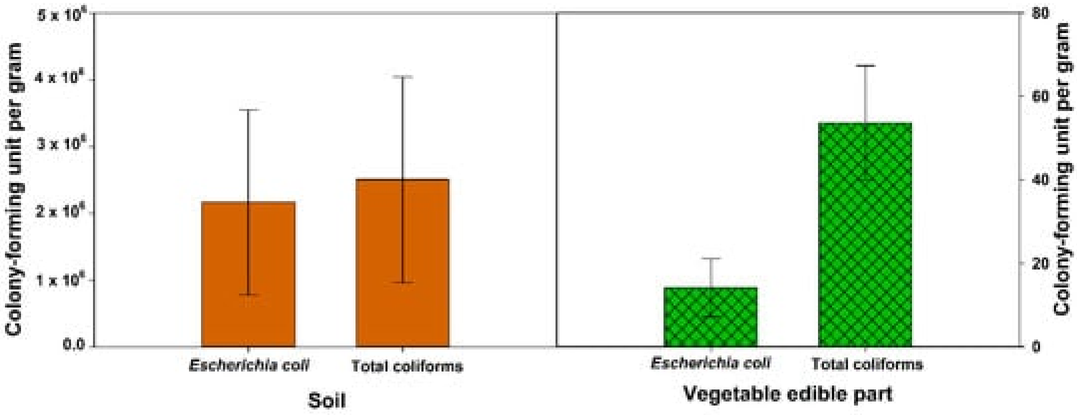

Figure 3. Microbial pathogen (*Escherichia coli* and total coliforms) levels in soil and vegetables irrigated with wastewater [23][25][53][54][55][56][57].

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