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Sewage sludge enhances tomato growth and improves fruit-yield quality by restoring soil fertility

Ebrahem M. Eid[1,2], *Kamal H. Shaltout*[3], *Saad A.M. Alamri*[1], *Sulaiman A. Alrumman*[1], *Ahmed A. Hussain*[1], *Nasser Sewelam*[3]*, *Gehad A. Ragab*[3]

[1]*Biology Department, College of Science, King Khalid University, Abha, Saudi Arabia*
[2]*Botany Department, Faculty of Science, Kafrelsheikh University, Kafr El-Sheikh, Egypt*
[3]*Botany Department, Faculty of Science, Tanta University, Tanta, Egypt*
**Corresponding author: sewelam@science.tanta.edu.eg*

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Abstract: Among the various disposal strategies for sewage sludge (SS), soil application is the most suitable. This study was conducted to evaluate soil amendment with SS (0, 10, 20, 30 and 40 g/kg) and its impact on soil fertility and tomato (*Solanum lycopersicum* L.) growth. The SS significantly improved the agromorphological attributes, the number of produced fruits, and the fruit biomass of tomato plants. The 30 g/kg application of SS led to the highest growth rate and fruit yield. Considering the fruits, the best safe enrichment of metal nutrients was recorded at 30 g/kg, with a significant increase in the micronutrient metals Mn, Zn, Ni, Cu, and Fe with 624, 193, 125, 70, and 32%, respectively, compared to the control. The SS amendment enhanced soil fertility, and heavy metals were within the permissible ranges for agricultural soils. Bioaccumulation factors (BFs) indicated that SS application induced the accumulation of most of the studied metals in the roots, and the BF values of Zn, Cu, Ni, and Pb were > 1. The current study concluded that recirculating SS nutrient components to agricultural soils could offer a valid solution for the sustainable management of this organic waste and enhance plant-crop productivity.

Keywords: environmental pollution; contamination; toxic element; agriculture; organic fertilisers

The progressive production and disposal of industrial and human wastes impose serious threats to soil and water environments. Moreover, the growing population and increased urbanisation are resulting in the production of huge amounts of semisolid waste residues. Globally, the quantities of sewage sludge (SS) and their final disposal are a major environmental problem. In urban areas, solid SS byproducts are generated in enormous amounts of 120 000 tons per day (Ankush et al. 2021). Therefore, SS needs to be safely disposed or effectively exploited. The management of SS can be conducted *via* landfilling, incineration, or composting and agricultural use (Elmi et al. 2020). The majority of SS (40%) is discarded by landfilling, whereas 37% is reused in agriculture, 11% is incinerated, and 12% is redirected to other destinations (Colón et al. 2017). Landfilling practices pose hazardous effects on groundwater contamination due to leachate-polluting effluents (Costa et al. 2019). Incineration methods have high costs and result in the toxic emissions of air pollutants (Lynn et al. 2018). However, SS application in agriculture is globally accepted as a common effective practice (Eid et al. 2020a, Mercl et al. 2020).

The reuse of SS in agriculture is a crucial disposal method for enhancing soil quality. Another environmental issue is solved by recirculating SS solids in agricultural soils as a nutrient source and organic fertilising agent (Sharma et al. 2017, Jastrzębska et al. 2018). On the other hand, the production of chemical fertilisers consumes a lot of energy and depends on nonrenewable resources with distinct high costs

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(Cristina et al. 2020). Furthermore, environmental pollution is another disadvantage of the chemical-fertiliser industry due to the release and persistence of toxic metals in agricultural soils. In terms of renewable nutrient sources, soil applications of SS could compensate for chemical-fertiliser demand and decrease their contaminating impact. In average, SS contains N, P, and K quantities of 4.74, 2.27, and 0.31%, respectively (Stehouwer et al. 2000). Moreover, SS is considered to be a valuable source of organic carbon and various micronutrients such as Ca, Mg, S, Fe, Mn, Cu, and Zn, which are not represented in commercial fertilisers (Warman and Termeer 2005). Furthermore, organic constituents in SS could act as a soil conditioner to enhance soil properties and fertility, such as water-holding capacity, porosity, bulk density, and aggregate stability (Kominko et al. 2017). Thus, vital priority was given to the reuse of SS in agricultural fields, which provides a solution for waste disposal, improves soil quality, and increases crop quality and productivity.

Even though the significance and effectiveness of SS for soil application in agriculture are obvious, this practice should be controlled due to the environmental implications. SS contains many heavy metals such as Cr, Ni, Zn, Cd, Pb, Al, and As, and high levels of them in soils result in their accumulation in groundwater and crops (Bounar et al. 2020). Uncontrolled SS amendment could limit its potential as a sustainable source to enhance soil quality and recirculate nutrients in soil systems (Clarke and Smith 2011). The application of high amounts of dried SS to soils (e.g., 10–40%) improved the yield biomass of *Brassica juncea* L. but caused the toxic accumulation of certain heavy metals such as Zn, Cd, and Pb (Dar et al. 2017). Well-managed crop cultivation and controlled SS doses in rotation cycles could effectively lessen the risk of the accumulation of toxic metals. In this context, our research group evaluated the potential of SS to modify and restore soil fertility and investigated various plant-species responses to amending SS doses and heavy-metal accumulation. To complement our previous work, the tomato (*Solanum lycopersicum* L.) plant was chosen as the most exploited fruiting crop. Moreover, tomato, as a significant crop, has high nutrient and fertiliser requirements (Zucco et al. 2015). Therefore, this study was designed to investigate the capacity of SS application to safely recycle organic matter and nutrients to agricultural soils and tomato plant parts.

MATERIAL AND METHODS

Field soil and SS samples. The cultivated field soil used in the experiment was obtained at a depth of 0–20 cm from newly reclaimed neighboring areas (latitude: 18.2434, longitude: 42.5661) and appeared to have a coarse sandy loam texture. Samples of SS were collected from the municipal wastewater treatment plant of the city of Abha. SS samples were exposed to air for 2 weeks till complete dryness, ground to powder and passed through a 2 mm sieve.

Experiment design. Based on the results of a preliminary experiment, SS was fully mixed with cultivated field soil at rates of 0 (as a control), 10, 20, 30, and 40 g/kg (equivalent to 0, 30, 60, 90, and 120 t/ha). Ten seeds of tomato (Super Strain B, Bru Seeds B.V., Hem, Drechterland, the Netherlands) were planted in plastic pots, and each was filled with 4 kg of the selected treatment. Each treatment was represented by five plastic pots arranged in a complete randomised design. The experiment was conducted in the greenhouse at the Biology Department, King Khalid University, under a natural day-night cycle. Plants were continuously irrigated with tap water as required to maintain 40–50% water content in each pot. After 15 days, plants were thinned to one plant per pot and left to grow for 120 days.

Quantifying yield parameters. The growth parameters of the harvested tomato, including shoot heights and root lengths, were measured using a measuring tape, and fruits per individual were counted. Leaf area per plant was estimated using a leaf-area meter (Dynamax AM 300, Dynamax Inc., Houston, USA). All plant materials were washed under running water and deionised water and divided into roots, fruits, stems, and leaves. The partitioned plant materials were dried at 60 °C for 1 week, and the dry mass was documented. Samples were ground in a plastic mill (Philips HR2221/01, Philips, Shanghai, China) to obtain a fine powder and kept until analysed. Total biomass (sum of fruit, stem, leaf, and root biomass) was calculated. Absolute growth rate (AGR) was determined according to Radford (1967):

$$\text{AGR (g DM/individual/day)} = (W_2 - W_1)/(t_2 - t_1)$$

where: W_1 and W_2 – total biomasses (g DM (dry matter)/individual) at times (days) t_1 and t_2, respectively.

Physicochemical analysis of SS, soil, and plant samples. The SS and soil samples were collected prior to cultivation and postharvest after the end of the experiment. Collected samples from each replicate were air-dried for 2 weeks, ground, and passed through a 2 mm sieve. All samples were analysed for their organic-matter contents using a loss-on-ignition method at 550 °C for 2 h as described by Wilke (2005), and for N using a CHN Elemental Analyser (Yanako CHN Corder MT-5, Kyoto, Japan and Auto Sampler MTA-3, Kyoto, Japan). Electrical conductivity (EC) and pH were recorded in 1:5 soil/water extracts (Allen et al. 1989). Regarding the estimation of P, K, and heavy-metal contents, about 0.5 g of each sample was digested using a mix digestion technique (HNO_3:H_2SO_4:$HClO_4$; 5:1:1, *v*/*v*/*v*). Samples were digested using a microwave sample-preparation system (PerkinElmer Titan MPS, PerkinElmer Inc., Waltham, USA). The contents of seven HMs (Fe, Cu, Mn, Zn, Ni, Al and Pb) were estimated by inductively coupled plasma optical emission spectrometry (ICP-OES) (Thermo Scientific iCAP 7000 Plus Series; Thermo Fisher Scientific, Waltham, USA). Detection limits for these HMs (μg/L) were as follows: 6.0 for Ni; 2.0 for Cu; 1.0 for Fe, Pb, and Zn; 0.3 for Mn; and 20.0 for Al. K was measured by atomic absorption (Shimadzu AA-6300, Shimadzu Co. Ltd., Kyoto, Japan), and P by spectrophotometer (CECIL CE 1021, Cecil Instruments Limited, Milton, Cambridge, UK), utilising the ammonium molybdate method. Standard solutions with known K and heavy metal contents were prepared to calibrate the systems. All these methods were conducted according to Allen et al. (1989).

Heavy-metal bioaccumulation and translocation factors. To estimate the potential of tomato to accumulate heavy metals in roots, the bioaccumulation factor (BF) was calculated: BF = the heavy metals content in the root (mg/kg)/the same heavy metal content in the soil (mg/kg). The translocation factor (TF) is determined to evaluate the potential of tomato to transfer heavy metals from the roots to aerial shoot tissue (stems, leaves, and fruits) and calculated as follows: TF = the content of heavy metal in aerial tissue (mg/kg)/the content of the same heavy metal in the roots (mg/kg) (Eid and Shaltout 2016).

Statistical analysis. The data were assessed for normality of distribution and variance homogeneity using Shapiro-Wilk's W and Levene's tests, respectively (data not presented). Log transformation was performed where necessary. Significant differences in all results were statistically evaluated using a one-way analysis of variance (ANOVA-1). Tukey's honestly significant difference (*HSD*) test at $P < 0.05$ was applied to identify significant differences between treatment means. SPSS 15 was utilised for all statistical analyses (SPSS 2006).

RESULTS AND DISCUSSION

Characteristics of cultivation soil and SS samples. The application of SS to agricultural lands could secure nutrient recycling for plants and food chains and enhance agricultural production (Singh and Agrawal 2008, Sharma et al. 2017, Nahar and Hossen 2021). Pre-cultivation soil exhibited low organic matter (1.81%) and an EC level of 0.39 mS/cm, with a pH value of 8.55 (Table 1). Analysed macronutrients N, P, and K had soil values of 0.28, 2.69, and 14.83 g/kg, respectively, while metal micronutrients (Fe, Cu, Mn, Zn, and Ni) showed insufficient levels according to Kabata-Pendias (2011).

On the other hand, applied SS contained a high level of organic matter (65%) and had a semi-neutral nature (pH = 6.68) and an EC of 4.68 mS/cm (Table 1). The quantified macronutrients (N and P) and micronutrients in the applied SS revealed very rich contents within the acceptable limits for agricultural use (He et al. 2005). The studied metal micronutrients (Fe, Cu, Mn, Zn, and Ni) were within safe limits for agricultural purposes (He et al. 2005). Furthermore, the nonessential heavy metals Al and Pb showed very low levels, even lower than those in the cultivation soils (Table 1). The land application of SS to poor soils is acceptable due to the valuable recycling of biosolid ingredients such as organic matter, N, P, and other plant micronutrients (Sharma et al. 2017).

SS application enhances plant growth and fruit yield. Our results showed that SS application improved tomato plant growth when compared to that grown in nonamended soils (Figure 1). The application rates of SS (10, 20, 30, and 40 g/kg) significantly increased shoot and root lengths and leaf area over the control. Growth parameters exhibited higher values at 30 g/kg SS compared to the control and other SS rates. The dry matter of shoots, roots, and leaves was enhanced with SS amendment and showed the highest values at 30 g/kg SS compared to the control. The number of obtained fruits per plant, fruit biomass, and total biomasses were significantly increased by SS amendment, with the 30 g/kg SS leading to the most significant increase (Figure 1). In addition, soil amendment with SS greatly improved the absolute growth rate, with the highest recorded rate at 30 g/kg SS. These results indicated that 30 g/kg SS could

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Table 1. Main physicochemical properties of agricultural soil and sewage sludge used in the pot experiment (means ± standard error, n = 5)

Property	Agricultural soil		Sewage sludge	
	measured values	average normal limits[1]	measured values	permissible limits[2]
Organic matter (%)	1.81 ± 0.06	–	65.22 ± 2.07	–
pH	8.55 ± 0.27	–	6.68 ± 0.21	–
EC (mS/cm)	0.39 ± 0.02	–	4.68 ± 0.15	–
N (g/kg)	0.28 ± 0.01	–	56.39 ± 3.93	–
P (g/kg)	2.69 ± 0.09	–	16.15 ± 0.04	–
K (g/kg)	14.83 ± 0.55	–	6.06 ± 0.16	–
Fe (mg/g)	15.70 ± 0.51	39.2	4.11 ± 0.08	–
Cu (mg/kg)	28.33 ± 0.90	105	119.73 ± 1.48	1 000–1 750
Mn (mg/kg)	317.16 ± 10.05	775	74.83 ± 0.29	–
Zn (mg/kg)	42.55 ± 1.63	200	402.63 ± 4.35	2 500–4 000
Ni (mg/kg)	19.41 ± 1.93	40	38.86 ± 5.85	300–400
Al (mg/g)	65.23 ± 2.07	–	8.35 ± 0.08	–
Pb (mg/kg)	26.52 ± 1.04	160	7.08 ± 0.22	750–1 200

[1]Kabata-Pendias (2011); [2]He et al. (2005); EC – electrical conductivity

be recommended for tomato crop fertilisation. The improved growth and dry matter at the optimal SS rate can be attributed to the higher availability of nutrients and improved soil fertility, which significantly enhance fruit biomass (Elmi et al. 2020).

Plant mineral contents under different SS rates. To study the contents of various heavy metals in plants grown on SS-amended soil, the levels of certain essential (Fe, Cu, Mn, Zn, Ni) and nonessential (Al and Pb) minerals were measured in different plant parts (Table 2). The accumulation of essential metals in different plant parts, including roots, stems, leaves, and fruits, indicated their linear increase with a rising SS rate compared to the control. The 30 g/kg SS dose clearly increased the levels of Mn, Zn, Ni, Cu, and Fe in the fruits by 624, 193, 125, 70 and 32%, respectively, compared to the control (Table 2). These metal nutrients are essential for various critical plant physiological functions. For instance, Mn showed higher abundance in the obtained fruits at the recommended SS dose (30 g/kg) by 624% compared to the control fruits. Induced Mn uptake capacity could increase plant productivity by providing satisfactory quantities of Mn to crucial reactions and mainly improving photosynthetic efficiency (Alejandro et al. 2020). Zn is a pivotal component of several enzymes that are involved in the metabolism of carbohydrates, proteins, and phosphates (Broadley et al. 2007, Eid et al. 2020b).

Zn is also incorporated in the biosynthesis of growth hormones, especially auxins and gibberellins (Kasim et al. 2017). Ni, at appropriate contents, is required for the activation of urease and for nitrogen metabolism (Sabir et al. 2011). Furthermore, the optimal concentration of Cu is vital for photosynthetic electron transport, respiration, and cell-wall metabolism hormone signaling (Emamverdian et al. 2015). Fe is the key metal in energy transformations and is essential for the synthesis of many proteins (ferredoxin and cytochromes) that are involved in photosynthetic and respiratory electron transfer (Kabata-Pendias 2011). The nonessential metals (Pb and Al) significantly increased by the favourable dose (30 g/kg SS) but not to phytotoxic thresholds in the fruits, according to Kabata-Pendias (2011). These outcomes could support the positive effect of SS application to enhance plant growth and nutritional value, sustainably recirculate micronutrients to ecosystems and thus suppress their severe deficiency. At the highest SS rate (40 g/kg), none of the measured heavy metals exceeded the toxicity limits in the produced fruits except for Zn and Ni (Table 2).

Physicochemical analysis of postharvest soils. Our data showed that various applied SS doses had a pronounced impact on the quality of cultivation soils (Table 3). All SS doses significantly improved organic-matter percentage and EC, while pH values showed a nonsignificant decrease compared to the

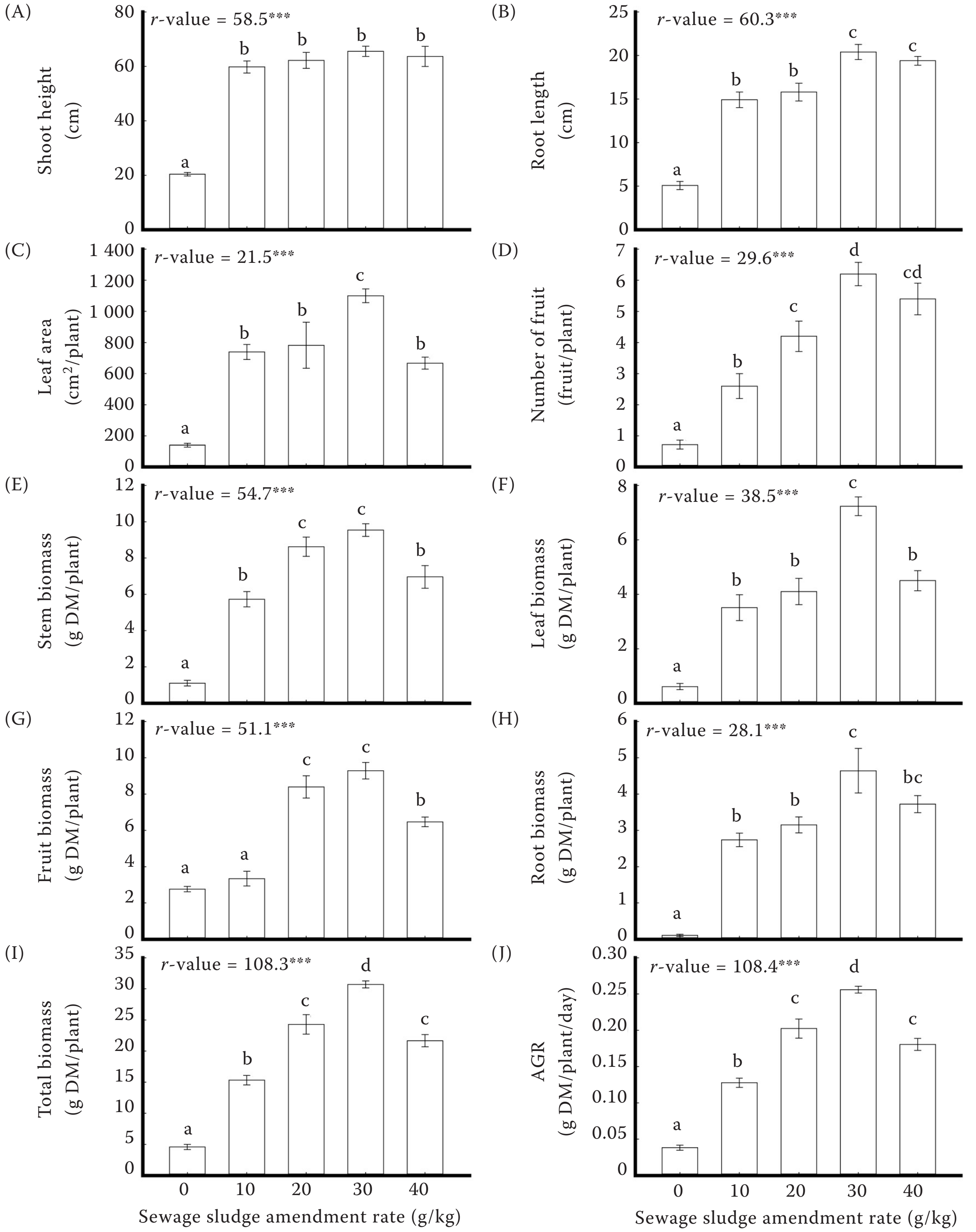

Figure 1. Effect of different rates of the sewage-sludge amendment on morphometric parameters and biomass components: (A) shoot height; (B) root length; (C) leaf area; (D) number of fruits; (E) stem biomass; (F) leaf biomass; (G) fruit biomass; (H) root biomass; (I) total biomass, and (J) absolute growth rate (AGR) of tomato plants grown for 120 days (mean ± standard error, *n* = 5). *F*-values represent one-way ANOVA, degrees of freedom = 4. Means followed by different letters were significantly different at $P < 0.05$ according to Tukey's honestly significant difference (*HSD*) test. ***$P < 0.001$; DM – dry matter

Table 2. Effects of different amendment rates of sewage sludge on nutrient and heavy metal contents in fruits, leaves, stems, and roots of tomato plants that were harvested after 120 days (means ± standard error, *n* = 5)

HM	Tissue	Sewage sludge amendment rate (g/kg)					*F*-value	Phytotoxic range^{1}
		0	10	20	30	40		
Fe	fruit	9.0 ± 0.4^{a}	10.0 ± 0.5^{ab}	10.9 ± 0.5^{abc}	11.9 ± 0.5^{bc}	12.8 ± 0.6^{c}	9.2***	> 1 000
	leaf	147.1 ± 13.0^{a}	346.0 ± 12.8^{b}	354.0 ± 11.5^{b}	364.0 ± 11.5^{b}	458.8 ± 14.5^{c}	80.4***	
	stem	55.4 ± 1.8^{a}	61.1 ± 2.7^{ab}	66.9 ± 3.0^{bc}	72.7 ± 3.3^{cd}	78.4 ± 3.5^{d}	9.9***	
	root	1 290.3 ± 41.7^{a}	4 511.2 ± 142.7^{b}	5 143.6 ± 162.9^{b}	6 757.8 ± 219.9^{c}	10 204.5 ± 358.2^{d}	235.8***	
Cu	fruit	11.3 ± 0.5^{a}	12.5 ± 1.4^{a}	17.5 ± 1.2^{b}	19.6 ± 1.3^{b}	19.8 ± 0.8^{b}	13.4***	20–100
	leaf	10.9 ± 0.8^{a}	20.5 ± 2.1^{b}	23.4 ± 1.4^{b}	24.8 ± 0.9^{b}	26.3 ± 1.7^{b}	17.3***	
	stem	14.8 ± 0.9^{a}	15.4 ± 0.5^{a}	16.1 ± 0.7^{ab}	18.8 ± 1.3^{bc}	19.7 ± 0.6^{c}	6.3**	
	root	24.0 ± 1.0^{a}	57.2 ± 2.6^{b}	70.8 ± 4.6^{c}	72.0 ± 3.5^{c}	74.2 ± 2.4^{c}	46.9***	
Mn	fruit	11.4 ± 0.7^{a}	65.7 ± 3.2^{b}	75.6 ± 3.8^{bc}	82.6 ± 3.3^{cd}	91.0 ± 2.9^{d}	112.8***	> 400
	leaf	67.9 ± 6.3^{a}	73.5 ± 5.8^{a}	140.8 ± 5.2^{b}	207.4 ± 7.8^{c}	224.9 ± 7.1^{c}	125.4***	
	stem	17.7 ± 0.8^{a}	23.8 ± 1.7^{a}	53.7 ± 2.0^{b}	57.2 ± 2.1^{b}	87.4 ± 3.6^{c}	161.2***	
	root	38.2 ± 2.5^{a}	219.6 ± 10.6^{b}	252.9 ± 12.6^{bc}	276.2 ± 11.2^{cd}	304.3 ± 9.6^{d}	112.6***	
Zn	fruit	28.0 ± 1.3^{a}	40.5 ± 3.0^{a}	42.6 ± 1.8^{a}	81.9 ± 3.0^{b}	116.3 ± 8.2^{c}	74.4***	100–500
	leaf	14.7 ± 1.0^{a}	27.9 ± 3.2^{b}	40.0 ± 1.7^{c}	43.5 ± 1.5^{cd}	48.6 ± 1.7^{d}	48.8***	
	stem	32.1 ± 2.3^{a}	63.9 ± 3.2^{b}	75.1 ± 7.0^{bc}	89.3 ± 4.8^{c}	91.4 ± 3.1^{c}	30.2***	
	root	27.2 ± 0.9^{a}	164.0 ± 10.7^{b}	183.9 ± 7.7^{bc}	202.3 ± 6.4^{c}	323.6 ± 10.6^{d}	170.2***	
Ni	fruit	13.9 ± 1.2^{a}	19.0 ± 1.2^{a}	30.5 ± 2.5^{b}	31.3 ± 1.4^{b}	65.5 ± 3.3^{c}	91.8***	40–246
	leaf	47.8 ± 2.1^{a}	91.8 ± 4.1^{b}	125.6 ± 5.6^{c}	159.4 ± 7.3^{d}	213.6 ± 9.6^{e}	102.0***	
	stem	1.2 ± 0.1^{a}	19.2 ± 0.9^{b}	41.5 ± 1.9^{c}	46.3 ± 2.1^{c}	99.2 ± 4.4^{d}	243.1***	
	root	31.0 ± 2.7^{a}	42.4 ± 2.6^{a}	68.0 ± 5.6^{b}	69.7 ± 3.1^{b}	145.9 ± 7.3^{c}	91.7***	
Al	fruit	458.4 ± 20.5^{a}	481.3 ± 69.3^{ab}	551.1 ± 17.5^{ab}	621.3 ± 28.8^{b}	793.7 ± 29.1^{c}	12.6***	> 1 000
	leaf	862.3 ± 56.7^{a}	1 205.6 ± 70.7^{ab}	1 383.1 ± 50.7^{b}	1 776.5 ± 197.0^{c}	2 164.6 ± 92.9^{d}	22.0***	
	stem	506.3 ± 24.8^{a}	602.4 ± 40.8^{a}	623.9 ± 55.6^{a}	643.4 ± 33.9^{a}	1 088.8 ± 86.3^{b}	18.5***	
	root	1 909.3 ± 105.7^{a}	3 509.9 ± 205.5^{b}	3 676.3 ± 245.9^{b}	4 248.8 ± 278.5^{b}	6 592.3 ± 260.3^{c}	55.5***	
Pb	fruit	5.2 ± 0.2^{a}	11.4 ± 0.5^{b}	17.4 ± 1.2^{c}	29.0 ± 1.5^{d}	29.8 ± 1.8^{d}	81.1***	30–300
	leaf	6.6 ± 0.4^{a}	12.3 ± 0.4^{b}	16.8 ± 0.5^{c}	16.9 ± 0.5^{c}	18.0 ± 0.8^{c}	73.0***	
	stem	3.8 ± 0.2^{a}	4.3 ± 0.2^{a}	15.8 ± 0.9^{b}	18.2 ± 0.8^{c}	20.7 ± 0.9^{d}	138.1***	
	root	16.7 ± 0.5^{a}	19.5 ± 0.9^{a}	32.1 ± 1.3^{b}	44.0 ± 2.0^{c}	67.0 ± 1.6^{d}	226.6***	

F-values represent one-way ANOVA, degrees of freedom = 4. Means in same row followed by different letters were significantly different at $P < 0.05$ according to Tukey's *HSD* (honestly significant difference) test. $^{**}P < 0.01$; $^{***}P < 0.001$; ^{1}Kabata-Pendias (2011); HM – heavy metal

non-treated soils. The dose of 30 g/kg SS increased soil organic matter and EC by 48.5% and 93.5%, respectively, relative to nonamended soil. Taking into account the high content of organic matter in the sludge, the soil application of SS effectively improves soil fertility and crop productivity better than commercial fertilisers can (Singh and Agrawal 2008). Similarly, previous results reported that the SS amendment significantly enhanced organic carbon in soils (Delibacak and Ongun 2016). Indeed, the application of organic matter could enhance physical soil properties such as structure and porosity, water-holding capacity, cation-exchange capacity, and humus content (Kominko et al. 2017). The decrease in soil pH after SS application was reported to enhance nutrient bioavailability (Alvarenga et al. 2016), which might be ascribed to the production of humic acids during the biodegradation of organic-carbon-rich biosolids (Singh et al. 2011).

Moreover, various SS rates enhanced N and K levels, while P showed no significant change. A moderate SS dose (30 g/kg) increased N and K levels by 158% and

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Table 3. Selected chemical properties of soil at different sewage-sludge amendment rates after harvesting tomato plants that had been grown for 120 days (means ± standard error, n = 5)

Property	Sewage sludge amendment rate (g/kg)					*F*-value
	0	10	20	30	40	
Organic matter (%)	1.71 ± 0.06^{a}	1.74 ± 0.05^{a}	2.37 ± 0.08^{b}	2.54 ± 0.09^{bc}	2.70 ± 0.09^{c}	39.2***
pH	8.31 ± 0.26^{a}	8.27 ± 0.26^{a}	8.17 ± 0.26^{a}	8.05 ± 0.25^{a}	7.98 ± 0.25^{a}	0.3^{ns}
EC (mS/cm)	0.31 ± 0.01^{a}	0.40 ± 0.01^{b}	0.59 ± 0.02^{c}	0.60 ± 0.02^{c}	0.61 ± 0.02^{c}	65.3***
N (g/kg)	0.74 ± 0.04^{a}	1.60 ± 0.34^{ab}	1.72 ± 0.28^{b}	1.91 ± 0.20^{b}	1.98 ± 0.27^{b}	4.1*
P (g/kg)	2.69 ± 0.09^{a}	2.69 ± 0.09^{a}	2.70 ± 0.09^{a}	2.70 ± 0.09^{a}	2.70 ± 0.09^{a}	0.0^{ns}
K (g/kg)	6.25 ± 0.23^{a}	6.59 ± 0.22^{a}	8.19 ± 0.49^{ab}	9.47 ± 0.89^{b}	9.68 ± 0.37^{b}	9.9***
Fe (mg/g)	15.45 ± 0.49^{a}	16.32 ± 0.56^{ab}	16.61 ± 0.67^{ab}	17.83 ± 0.72^{ab}	18.72 ± 0.62^{b}	4.4*
Cu (mg/kg)	27.59 ± 1.19^{a}	29.05 ± 1.05^{a}	29.33 ± 1.03^{a}	30.19 ± 0.98^{ab}	33.98 ± 1.09^{b}	5.0**
Mn (mg/kg)	312.33 ± 9.94^{a}	320.27 ± 11.34^{a}	327.10 ± 12.67^{a}	331.59 ± 11.52^{a}	363.71 ± 15.81^{a}	2.5^{ns}
Zn (mg/kg)	48.34 ± 1.84^{a}	52.05 ± 3.11^{ab}	52.61 ± 1.75^{ab}	57.76 ± 2.91^{ab}	61.65 ± 2.63^{b}	4.3*
Ni (mg/kg)	13.98 ± 1.83^{a}	17.56 ± 1.79^{ab}	17.75 ± 0.57^{ab}	19.12 ± 2.02^{ab}	23.79 ± 1.46^{b}	4.8**
Al (mg/g)	65.75 ± 2.12^{a}	65.88 ± 2.15^{a}	67.29 ± 2.29^{a}	67.76 ± 2.18^{a}	69.04 ± 2.18^{a}	0.4^{ns}
Pb (mg/kg)	8.46 ± 0.27^{a}	16.98 ± 0.54^{b}	22.46 ± 1.96^{c}	24.05 ± 0.86^{c}	30.87 ± 1.97^{d}	39.7***

F-values represent one-way ANOVA, degrees of freedom = 4. Means in same row followed by different letters were significantly different at $P < 0.05$ according to Tukey's honestly significant difference (*HSD*) test. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ns – not significant (i.e., $P > 0.05$); EC – electrical conductivity

51.5%, respectively, over the control soil. Regarding metal micronutrients (Fe, Cu, Mn, Zn, Ni) and non-essential metals (Al and Pb), SS application caused a linear increase by raising SS quantity except for Mn and Al, which showed a nonsignificant increase compared to in the control soil. The increments in metal levels after the SS amendment were within safe limits and far from the phytotoxic thresholds for cultivation soils. Similarly, soil amended with increasing rates of SS had an increased EC value (Nahar and Hossen 2021). Adequate organic-matter levels and nutrients due to SS application were reported to enhance soil microbial (Bettiol and Ghini 2011) and biochemical (Roig et al. 2012) activity.

Bioaccumulation and translocation factors for heavy metals in plant parts. The allocation of heavy metals between various parts of the tomato plant was studied to assess the potential risk of SS application to agricultural lands. Overall, the current study showed that the roots of tomato plants grown on control soils had a high affinity to absorb Ni and Pb with BF > 1 (Table 4), while this ability was modified by the SS amendment. At 30 g/kg SS, the BF for Ni was significantly increased, thus causing higher translocation to shoot parts, especially leaves, compared to the control. However, the fruits did not accumulate toxic levels of Ni compared to the control (Table 2), which supports the selective uptake of plants to metals and changes their subsequent transfer factor (Tasrina et al. 2015). Pb's high uptake by the control roots, represented by a BF value of 1.97, decreased by the application of low and moderate levels of SS, while it was increased by 40 g/kg SS (Table 4). The application of SS could enrich soil organic biosolids, thereby limiting the bioavailability of metals by forming metallo-organic complexes (Sharma et al. 2017).

Obtained data showed that BF values for Fe, Mn, and Al were significantly increased by increasing SS rate relative to that of the control but were less than 1 (Table 4). However, obtained data indicated that soil amendment with SS rates enhanced the root uptake of Zn and Cu (BF > 1) with values of 3.52 and 2.39 at the 30 g/kg SS dose compared to their limited uptake from the control soil (BF < 1). These results may suggest the higher phytoavailability of these metals around root zones, as BF values tend to increase with increasing SS rates. Alternatively, with the SS amendment, the ability of tomato plants to translocate metals to shoot parts and fruits is lower, with TF < 1 for all metals (except Ni). This result manifested the tendency of metal accumulation in the roots rather than their upper uptake, which indicated their safe limits in the fruits and a low health risk.

Table 4. Bioaccumulation factors (BFs) for soil to root transport, and translocation factors (TFs) for transport from roots to fruits, leaves, and stems of heavy metals (HM) in tomato plants grown in soil with different sewage-sludge amendment rates (means ± standard error, $n = 5$)

HM	Factor	Sewage sludge amendment rate (g/kg)					F-value
		0	10	20	30	40	
Fe	BF	0.084 ± 0.000^{a}	0.277 ± 0.004^{b}	0.310 ± 0.008^{c}	0.380 ± 0.007^{d}	0.546 ± 0.013^{e}	451.3***
	TF$_{fruit}$	0.007 ± 0.000^{c}	0.002 ± 0.000^{b}	0.002 ± 0.000^{b}	0.002 ± 0.000^{b}	0.001 ± 0.000^{a}	519.9***
	TF$_{leaf}$	0.114 ± 0.009^{c}	0.077 ± 0.002^{b}	0.069 ± 0.001^{b}	0.054 ± 0.001^{a}	0.045 ± 0.001^{a}	43.3***
	TF$_{stem}$	0.043 ± 0.000^{d}	0.014 ± 0.000^{c}	0.013 ± 0.000^{c}	0.011 ± 0.000^{b}	0.008 ± 0.000^{a}	1 824.9***
Cu	BF	0.870 ± 0.004^{a}	1.977 ± 0.094^{b}	2.423 ± 0.169^{c}	2.393 ± 0.089^{c}	2.189 ± 0.007^{bc}	45.1***
	TF$_{fruit}$	0.475 ± 0.026^{b}	0.223 ± 0.032^{a}	0.253 ± 0.028^{a}	0.272 ± 0.014^{a}	0.266 ± 0.005^{a}	19.3***
	TF$_{leaf}$	0.457 ± 0.029^{b}	0.365 ± 0.048^{ab}	0.332 ± 0.011^{a}	0.345 ± 0.012^{ab}	0.353 ± 0.022^{ab}	3.1*
	TF$_{stem}$	0.620 ± 0.045^{b}	0.270 ± 0.006^{a}	0.231 ± 0.016^{a}	0.260 ± 0.006^{a}	0.265 ± 0.002^{a}	56.6***
Mn	BF	0.122 ± 0.007^{a}	0.688 ± 0.034^{b}	0.775 ± 0.035^{bc}	0.833 ± 0.015^{c}	0.839 ± 0.024^{c}	140.0***
	TF$_{fruit}$	0.309 ± 0.038^{a}	0.299 ± 0.011^{a}	0.299 ± 0.004^{a}	0.299 ± 0.005^{a}	0.301 ± 0.014^{a}	0.1^{ns}
	TF$_{leaf}$	1.823 ± 0.253^{b}	0.339 ± 0.034^{a}	0.559 ± 0.019^{a}	0.751 ± 0.007^{a}	0.739 ± 0.001^{a}	25.1***
	TF$_{stem}$	0.466 ± 0.011^{d}	0.108 ± 0.003^{a}	0.213 ± 0.004^{b}	0.208 ± 0.009^{b}	0.287 ± 0.008^{c}	298.4***
Zn	BF	0.565 ± 0.012^{a}	3.214 ± 0.316^{b}	3.496 ± 0.093^{b}	3.523 ± 0.134^{b}	5.271 ± 0.187^{c}	88.4***
	TF$_{fruit}$	1.027 ± 0.032^{c}	0.247 ± 0.005^{a}	0.233 ± 0.013^{a}	0.405 ± 0.008^{b}	0.359 ± 0.019^{b}	317.2***
	TF$_{leaf}$	0.541 ± 0.035^{b}	0.175 ± 0.027^{a}	0.218 ± 0.009^{a}	0.215 ± 0.003^{a}	0.150 ± 0.001^{a}	64.0***
	TF$_{stem}$	1.178 ± 0.076^{b}	0.398 ± 0.037^{a}	0.414 ± 0.049^{a}	0.442 ± 0.019^{a}	0.283 ± 0.005^{a}	64.9***
Ni	BF	2.315 ± 0.232^{a}	2.539 ± 0.373^{a}	3.823 ± 0.278^{a}	3.885 ± 0.619^{a}	6.084 ± 0.397^{b}	14.8***
	TF$_{fruit}$	0.454 ± 0.034^{a}	0.461 ± 0.053^{a}	0.470 ± 0.071^{a}	0.453 ± 0.032^{a}	0.449 ± 0.007^{a}	0.1^{ns}
	TF$_{leaf}$	1.579 ± 0.132^{ab}	2.209 ± 0.201^{bc}	1.921 ± 0.238^{abc}	2.307 ± 0.149^{c}	1.466 ± 0.029^{a}	5.0**
	TF$_{stem}$	0.041 ± 0.005^{a}	0.461 ± 0.042^{b}	0.634 ± 0.079^{c}	0.666 ± 0.022^{c}	0.681 ± 0.014^{c}	41.9***
Al	BF	0.029 ± 0.001^{a}	0.053 ± 0.002^{b}	0.055 ± 0.004^{b}	0.063 ± 0.003^{b}	0.096 ± 0.002^{c}	73.5***
	TF$_{fruit}$	0.241 ± 0.011^{b}	0.142 ± 0.024^{a}	0.152 ± 0.009^{a}	0.147 ± 0.004^{a}	0.121 ± 0.005^{a}	13.1***
	TF$_{leaf}$	0.456 ± 0.036^{a}	0.349 ± 0.032^{a}	0.383 ± 0.029^{a}	0.417 ± 0.038^{a}	0.329 ± 0.015^{a}	2.7^{ns}
	TF$_{stem}$	0.267 ± 0.013^{b}	0.175 ± 0.018^{a}	0.175 ± 0.023^{a}	0.152 ± 0.002^{a}	0.165 ± 0.010^{a}	9.2***
Pb	BF	1.973 ± 0.001^{bc}	1.149 ± 0.036^{a}	1.464 ± 0.105^{a}	1.831 ± 0.050^{b}	2.212 ± 0.162^{c}	21.4***
	TF$_{fruit}$	0.314 ± 0.009^{a}	0.585 ± 0.002^{cd}	0.547 ± 0.044^{c}	0.659 ± 0.014^{d}	0.445 ± 0.029^{b}	29.7***
	TF$_{leaf}$	0.396 ± 0.020^{b}	0.632 ± 0.020^{d}	0.525 ± 0.015^{c}	0.385 ± 0.012^{b}	0.269 ± 0.016^{a}	67.9***
	TF$_{stem}$	0.227 ± 0.007^{a}	0.223 ± 0.012^{a}	0.494 ± 0.031^{d}	0.415 ± 0.013^{c}	0.309 ± 0.017^{b}	44.0***
F-value$_{BF}$		15.2***	24.0***	197.5***	34.4***	220.0***	
F-value$_{TFfruit}$		149.8***	57.0***	30.5***	202.8***	126.2***	
F-value$_{TFleaf}$		37.9***	82.9***	46.9***	173.1***	920.4***	
F-value$_{TFstem}$		151.9***	54.4***	33.4***	274.9***	229.2***	

F-values represent one-way ANOVA, degrees of freedom = 4. Means in same row followed by different letters were significantly different at $P < 0.05$ according to Tukey's *HSD* (honestly significant difference) test. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ns – not significant (i.e., $P > 0.05$)

In conclusion, the data presented here indicate that the soil application of SS significantly enhances the growth of tomato plants. The 30 g/kg (or 90 t/ha) soil amendment rate of SS led to the highest growth rate and fruit yield. Importantly, the application of SS increased, within the safe limits, the contents of important micronutrient metals such as Mn, Zn, Ni, Cu, and Fe in the yielded tomato fruits, with the most absorbed amounts of heavy metals are accumulated in the roots. Furthermore, the application of SS improves soil quality with safe levels of heavy metals in post-harvest soils. Accordingly, our findings propose that monitored soil application of SS can provide a sustainable, safe practice for SS disposal and meanwhile recirculate important micronutrients to food chains. In future work, field experiments would be important to determine suitable rotations of cultivation cycles to minimise any negative effects on soil structure and to prevent the accumulation of toxic levels of heavy metals and other possible contaminants in agriculture soils.

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