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RESEARCH ARTICLE

The effects of different sewage sludge amendment rates on the heavy metal bioaccumulation, growth and biomass of cucumbers (*Cucumis sativus* L.)

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Abstract When sewage sludge is incorrectly applied, it may adversely impact agro-system productivity. Thus, this study addresses the reaction of *Cucumis sativus* L. (cucumber) to different amendment rates (0, 10, 20, 30, 40 and 50 g kg^{-1}) of sewage sludge in a greenhouse pot experiment, in which the plant growth, heavy metal uptake and biomass were evaluated. A randomized complete block design with six treatments and six replications was used as the experimental design. The soil electrical conductivity, organic matter and Cr, Fe, Zn and Ni concentrations increased, but the soil pH decreased in response to the sewage sludge applications. As approved by the Council of European Communities, all of the heavy metal concentrations in the sewage sludge were less than the permitted limit for applying sewage sludge to land. Generally, applications of sewage sludge of up to 40 g kg^{-1} resulted in a considerable increase in all of the morphometric parameters and biomass of cucumbers in contrast to plants grown on the control soil. Nevertheless, the cucumber shoot height; root length; number of leaves, internodes and fruits; leaf area; absolute growth rate and biomass decreased in response to 50 g kg^{-1} of sewage sludge. All of the heavy metal concentrations (except the Cu, Zn and Ni in the roots, Mn in the fruits and Pb in the stems) in different cucumber tissues increased with increasing sewage sludge application rates. However, all of the heavy metal concentrations (except the Cr and Fe in the roots, Fe in the leaves and Cu in the fruits) were within the normal range and did not reach phytotoxic levels. A characteristic of these cucumbers was that all of the heavy metals had a bioaccumulation factor <1.0. All of the heavy metals (except Cd, Cu and Zn) had translocation factors that were <1.0. As a result, the sewage sludge used in this study could be considered for use as a fertilizer in cucumber production systems in Saudi Arabia and can also serve as a substitute method of sewage sludge disposal.

Keywords Amendments · Biosolids · Cucumber · Environmental sustainability · Soil fertility · Trace elements

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Introduction

Sewage sludge is an unavoidable and organic carbon-rich by-product that is generated in huge quantities by wastewater treatment plants (Eid and Shaltout 2016). It contains micronutrients and macronutrients that are important for plant growth, and it is potentially an important source of organic matter for the majority of agricultural soils (see Latare et al. 2014). Nevertheless, sewage sludge can have high levels of organic pollutants and heavy metals (Waqas et al. 2015; Rastetter and Gerhardt 2017). Thus, the management of sewage sludge is a primary environmental concern (Eid et al.

2017) because, if not dealt with properly, this material may lead to environmental pollution (Singh and Agrawal 2008).

To treat sewage sludge, there are three options (Kidd et al. 2007) as follows: landfilling, incineration and land application as fertilizer or to enhance soil properties. Landfilling has the potential to pollute underground water, whereas incineration causes air pollution. Interest in applying sewage sludge to land continues to grow due to economic limitations and environmental concerns regarding landfilling and incineration (Singh and Agrawal 2008). Recently, the application of sewage sludge to agricultural land has been considered as an environmentally acceptable management strategy (Vieira et al. 2014; Bai et al. 2017). This agricultural application provides not only a means for its disposal, but it also has the capacity to enhance soil fertility and physical properties, thereby increasing crop yields (Antonious et al. 2012), and it enables nutrient recycling and may prevent the need for commercial fertilizers in cropland (Almendro-Candel et al. 2007; Willén et al. 2017). The recycling of the organic carbon component of sewage sludge is also essential for sequestering carbon from the atmosphere that is fixed in soils, which is essential for regulating climate change (Brown and Leonard 2004; Khan et al. 2013; Fusi et al. 2017).

The fertility benefits of sewage sludge improvement can be achieved by addressing the potential hazards of heavy metal contamination by screening plant sensitivity at different sewage sludge amendment rates (Singh and Agrawal 2008). Moreover, absorption, accumulation and tolerance to heavy metals may vary between different crops and at different levels of sewage sludge amendments (see Singh and Agrawal 2010a). Nonetheless, differences in the sewage sludge composition, climate, soil and management factors require more specific estimates for different cropping systems or climatic regions (Binder et al. 2002) to determine which crops can be planted in soils that have been improved with sewage sludge and the amount of sewage sludge loading that can be accepted in practice.

The impact of sewage sludge when used as a soil amendment or as a fertilizer has been considered in many studies on several crops, such as beets (Tamoutsidis et al. 2002), carrots (Tamoutsidis et al. 2002), radishes (Tamoutsidis et al. 2002), barley (Soriano-Disla et al. 2014), corn (Grotto et al. 2015; Khanmohammadi et al. 2017), rice (Khan et al. 2013; Singh and Agrawal 2010b; Fusi et al. 2017), wheat (Koutroubas et al. 2014), broccoli (Antonious et al. 2012), cabbage (Antonious et al. 2012), endive (Tamoutsidis et al. 2002), lettuce (Tamoutsidis et al. 2002), spinach (Kumar et al. 2016), French bean (Kumar and Chopra 2014), mung bean (Singh and Agrawal 2010a), fenugreek (Kumar and Chopra 2012), green gram (Chandra et al. 2008), cotton (Antoniadis et al. 2010) and tomatoes (Waqas et al. 2015). However, only one study has been performed, by Waqas et al. (2014), where they used cucumber (*Cucumis sativus* L.) to assess the extent to which the conversion of sewage sludge to sewage sludge biochar influences the bioaccumulation of polycyclic aromatic hydrocarbons and potentially toxic elements. According to the authors' knowledge, no information is available to date in cucumbers that have been grown at various sewage sludge amendment rates. Therefore, the present study was an attempt to identify the appropriate sewage sludge amendment rate for cucumbers and to determine the locations of heavy metal accumulation in cucumber tissues to be better able to make predictions regarding food chain contamination. Moreover, the heavy metal translocation, morphology, growth and biomass of cucumbers were examined for a comprehensive assessment. This information will be useful for ascertaining the suitable application rate of sewage sludge and for discovering pollutant risks that may be associated with the use of sewage sludge as well as providing a basis for future legislative decisions concerning the use of sewage sludge as a fertilizer in Saudi Arabian agriculture.

In 2017, our team published a manuscript (Eid et al. 2017) about the impact of varied applications of sewage sludge on the accumulation of heavy metals, growth and yield of a leaf vegetable crop (spinach). The present study is an extension of our former work, and it serves to investigate the agronomic potential of different application rates of sewage sludge and its impact on the soil quality, biomass, plant growth and bioavailability of heavy metals in a fruiting vegetable crop by conducting a glasshouse pot experiment and using the cucumber as the agricultural crop.

Materials and methods

Experimental design

An experiment was conducted using a plastic pot (6 L volume) in the greenhouse belonging to the Department of Biology at King Khalid University, Abha, Saudi Arabia (lat. 18° 15′ 04.65″ N, long. 42° 33′ 31.48″ E). The soil used in this study was collected from a depth of 0–20 cm from adjacent cultivated fields (lat. 18° 14′ 36.37″ N, long. 42° 33′ 58.25″ E). The sewage sludge used here was tertiary, aerobically digested municipal sewage sludge that was collected from the Abha Wastewater Treatment Plant (lat. 18° 13′ 59.19″ N, long. 42° 31′ 16.35″ E) in the Aseer region of Saudi Arabia using plastic bags. This treatment plant treats approximately 41,275 m^3 of wastewater day^{-1}, and the corresponding dry sewage sludge production was estimated at 90 t day^{-1}, with a sludge production rate of 2.18 kg m^{-3} of treated wastewater (Eid et al. 2017). The soil and sewage sludge samples underwent air drying for 2 weeks and were then ground with an agate mortar and sieved through a 2-mm sieve.

The sewage sludge was mixed with cultivated field soil at rates of 0 (which is referred to as the control soil), 10, 20, 30, 40 and 50 g kg^{-1}. Each plastic pot was filled with 4 kg of the respective treatment. The pots were set up in a randomized complete block design with six replications per treatment. The cucumber plant was chosen for this study because it is among the most widely cultivated and economically important plants in Saudi Arabia (with 226,180 t being produced each year, making Saudi Arabia the 20th highest producer in the world; Worldatlas 2016). Five cucumber seeds (Beit Alpha, USA) were handsewn in each pot on 9 April 2015. Thereafter, the plants were grown for 50 days in the greenhouse with a natural day/night regime, and sporadic drip irrigation was applied to keep the moisture level uniform in each pot. The plants were thinned manually 15 days after germination to one plant per pot, and weed control was executed using hand weeding.

Plant morphology and biomass

All the individual cucumbers were harvested on 29 May 2015. The shoot heights and root lengths were measured, and the numbers of internodes, leaves and fruits were counted. The leaf area (single sided) was measured using a leaf area meter (Dynamax AM 300, Dynamax Inc., USA). Individual cucumbers were washed under running water. The plant materials were then separated into stems, leaves, fruits and roots and oven-dried at 60 °C until a constant weight was reached, and then, the materials were ground using a metal-free plastic mill and stored until additional analysis. The biomass of the shoot referred to the sum of the stem, leaf and fruit biomass, while the total biomass referred to the sum of the root and shoot biomass. The fruit biomass (g DM $fruit^{-1}$) was calculated as the fruit biomass (g DM $individual^{-1}$) divided by the number of fruits (fruit $individual^{-1}$). The absolute growth rate (AGR) was calculated according to Radford (1967) as follows: AGR (g DM $individual^{-1}$ day^{-1}) = $(W_2 - W_1) / (t_2 - t_1)$, where W_1 and W_2 are the total biomasses (g DM $individual^{-1}$) at times (days) t_1 and t_2, respectively.

Sample analysis

After the plants were harvested, the amended soil samples were air-dried, passed through a 2-mm sieve and stored until subsequent analysis. The soil and sewage sludge samples were analysed for their organic matter contents using a loss-on-ignition method at 550 °C for 2 h (Wilke 2005). Soil-water extracts at a ratio of 1:5 were prepared to determine the electric conductivity and pH (Allen 1989). The heavy metals in the soil, sewage sludge and plant samples were extracted from 0.5–1.0 g of each sample after microwave acid digestion using HNO_3 and $HClO_4$ at a ratio of 3:1 (*v*/*v*). Blank samples were added to validate the precision and accuracy of the digestion procedure as well as successive analyses. Analytical-grade chemicals were used for sample digestion. The salinity (which is referred to as electric conductivity) and pH were measured using conductivity (Myron L Model DA-1, Myron L Company, USA) and pH meters (ICM Model 41150, ICM, USA). The Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn were ascertained using an atomic absorption spectrophotometer (Shimadzu AA-6300; Shimadzu Co. Ltd., Japan). All of these procedures are highlighted by Allen (1989).

Data analyses

A bioaccumulation factor (BF) was calculated to determine the efficiency of the cucumbers at accumulating a heavy metal from the soil (Ghosh and Singh 2005) as follows: BF = concentration of a heavy metal in the roots (mg kg^{-1}) / concentration of the same heavy metal in the soil (mg kg^{-1}). A translocation factor (TF) was calculated to determine the cucumber's ability to translocate a heavy metal from the roots to the shoot tissues (Ghosh and Singh 2005) as follows: TF = concentration of a heavy metal in the shoot tissue (mg kg^{-1}) / concentration of the same heavy metal in the roots (mg kg^{-1}).

Before a one-way analysis of variance (one-way ANOVA) was performed, the data were tested for their normality of distribution and homogeneity of variance, and when necessary, the data were log-transformed. Significant differences in the soil quality parameters, the biomass, plant morphometric parameters, and heavy metal data for the cucumber tissues, BFs and TFs under different sewage sludge amendment rates, as well as the variation in BFs and TFs among the nine heavy metals within the same amendment rate of sewage sludge, were assessed using one-way ANOVA. The significant differences between the means of the six amendment rates were identified using Tukey's HSD test at $P < 0.05$. Statistical analyses were performed using Statistica 7.1 (Statsoft 2007).

Results

The sewage sludge used in this study was acidic in nature, and it had high salinity and was rich in organic matter (Table 1). The heavy metal concentrations in the sewage sludge were ranked in the following order: Fe > Pb > Zn > Mn > Cr > Cu > Ni > Co > Cd. The sewage sludge amendment significantly changed some soil properties such as the salinity, pH, organic matter and Cr, Fe, Ni and Zn concentrations in comparison to the control soil (Table 1). The soil salinity, organic matter and Cr, Fe, Ni and Zn concentrations increased, but the soil pH decreased in response to the sewage sludge applications.

Generally, sewage sludge applications up to 40 g kg^{-1} caused a considerable increase in all of the morphometric parameters and biomass of cucumbers compared to the plants grown in the control soil (Figs. 1 and 2). However, the cucumber shoot height; root length; number of leaves, internodes and

Table 1 Means ± standard errors ($n = 6$) of selected physicochemical properties of pure sewage sludge and soil at different sewage sludge amendment rates after harvesting the cucumbers that were grown for 50 days

Properties	Sewage sludge[‡]	Sewage sludge amendment rate (g kg^{-1})						F value
		0	10	20	30	40	50	
Electric conductivity (mS cm^{-1})	2.07 ± 0.05	0.49 ± 0.01a	0.54 ± 0.01b	0.74 ± 0.01c	0.84 ± 0.01d	0.89 ± 0.01e	0.91 ± 0.01e	725.1***
pH	6.38 ± 0.01	8.39 ± 0.06c	8.38 ± 0.01c	8.08 ± 0.01b	7.97 ± 0.02a	7.93 ± 0.01a	7.91 ± 0.01a	79.9***
Organic matter (%)	65.1 ± 0.2	1.6 ± 0.1a	1.7 ± 0.1a	2.6 ± 0.1b	2.8 ± 0.1b	3.1 ± 0.2bc	3.5 ± 0.2c	30.0***
Cd (mg kg^{-1})	1.17 ± 0.08	0.82 ± 0.11a	0.83 ± 0.04a	0.88 ± 0.04a	0.89 ± 0.05a	0.90 ± 0.06a	1.05 ± 0.04a	1.8^{ns}
Co (mg kg^{-1})	27.9 ± 1.3	22.2 ± 0.4a	24.0 ± 0.8a	25.1 ± 1.4a	25.7 ± 0.7a	25.8 ± 1.7a	27.1 ± 1.2a	2.2^{ns}
Cr (mg kg^{-1})	179.1 ± 4.4	160.9 ± 7.7a	162.5 ± 4.3ab	163.3 ± 4.1ab	174.7 ± 5.8abc	178.3 ± 3.7bc	184.2 ± 6.2c	3.1*
Cu (mg kg^{-1})	162.6 ± 2.3	26.6 ± 1.4a	29.9 ± 1.5a	30.0 ± 1.9a	31.0 ± 0.4a	34.6 ± 4.5a	36.6 ± 3.9a	1.8^{ns}
Fe (mg g^{-1})	25.4 ± 0.5	22.6 ± 0.6a	24.6 ± 0.2ab	24.6 ± 1.1ab	25.1 ± 0.6ab	25.4 ± 0.3b	25.6 ± 0.5b	3.2*
Mn (mg kg^{-1})	595.7 ± 9.8	521.6 ± 8.8a	541.5 ± 25.0a	598.0 ± 25.8a	598.0 ± 39.7a	603.4 ± 27.6a	622.5 ± 16.7a	2.4^{ns}
Ni (mg kg^{-1})	138.7 ± 4.1	25.7 ± 0.2a	26.5 ± 0.3ab	27.0 ± 0.6ab	27.3 ± 0.3ab	27.4 ± 0.7ab	28.1 ± 0.4b	3.2*
Pb (mg kg^{-1})	671.2 ± 7.0	470.6 ± 13.1a	482.1 ± 8.2a	487.9 ± 10.0a	489.1 ± 8.8a	490.4 ± 5.0a	501.1 ± 8.1a	1.2^{ns}
Zn (mg kg^{-1})	667.6 ± 13.4	77.5 ± 4.3a	83.9 ± 1.4a	85.2 ± 0.9a	91.7 ± 5.3ab	93.0 ± 8.6ab	126.0 ± 17.3b	4.2*

The F values represent a one-way ANOVA, with a degree of freedom (df) = 5. Means in the same row followed by different letters are significantly different at $P < 0.05$ according to the Tukey's HSD test

ns not significant (i.e., $P > 0.05$)

[‡] Eid et al. (2017)

*$P < 0.05$; ***$P < 0.001$

fruits; leaf area; AGR and biomass decreased in response to 50 g kg^{-1} applications of sewage sludge. The cucumber shoot/root ratio did not lead to any significant change as the application rate of the sewage sludge increased.

All the concentrations of heavy metals (except those of Cu, Ni and Zn in the roots, Mn in the fruits and Pb in the stems) in different cucumber tissues increased with increasing sewage sludge application rates (Table 2). However, all of the concentrations of heavy metals (except for Cr and Fe in the roots, Fe in the leaves and Cu in the fruits) were within the normal range and did not reach phytotoxic levels. The concentrations of heavy metals were highest in the roots than in the shoot tissues (the fruits, stems and leaves) for the majority of the heavy metals. The greatest of all of the heavy metal concentrations were recorded at 50 g kg^{-1} of sewage sludge for all of the cucumber tissues.

The cucumbers were characterized by a BF < 1.0 for all of the heavy metals (Table 3). The highest BFs of Cd, Co, Cr, Fe, Mn, Ni and Pb were found in the roots of cucumbers that had been subjected to a 50 g kg^{-1} amendment rate of sewage sludge, whereas the lowest values were found in the control soil. In general, the BF of Cu was the highest, followed by Ni, Zn, Cd, Fe, Co, Mn, Cr and Pb. The TF varied among the various cucumber tissues, heavy metals and sewage sludge amendment rates (Table 3). The TFs for all of the heavy metals (except Cd, Cu and Zn) were <1.0.

Discussion

The characteristics of the sewage sludge (the physicochemical as well as biological properties) rely on the quality of the sewage, the wastewater composition and type of treatment processes that follow (Singh and Agrawal 2008). The sewerage system is frequently mixed with discharges of storm water runoff from roads and other paved areas, and industrial effluents. Therefore, many toxic materials may be present in sewage sludge such as pesticides, heavy metals, toxic organics, detergents, hormone disruptors and various salts in addition to organic material (Singh and Agrawal 2010a). The evaluation of sewage sludge heavy metals is a vital prerequisite before sludge application or disposal to farmland since there is a risk of accumulating toxic elements in the soil (Mishra and Tripathi 2008; Rastetter and Gerhardt 2017).

Soil organic matter plays an essential role in the nutrient cycle, and it affects the sustainability of soil fertility. Thus, the organic matter content can be an essential indicator of soil fertility (Wang et al. 2008). In many countries around the world, sewage sludge has been applied as a soil amendment to reclaim degraded soils or as fertilizer to replace chemical fertilizers in agriculture (Almendro-Candel et al. 2007; Willén et al. 2017). Applying sewage sludge in this study led to a considerable increase in soil organic matter, when the organic matter content in the control soil was 1.6% compared to the

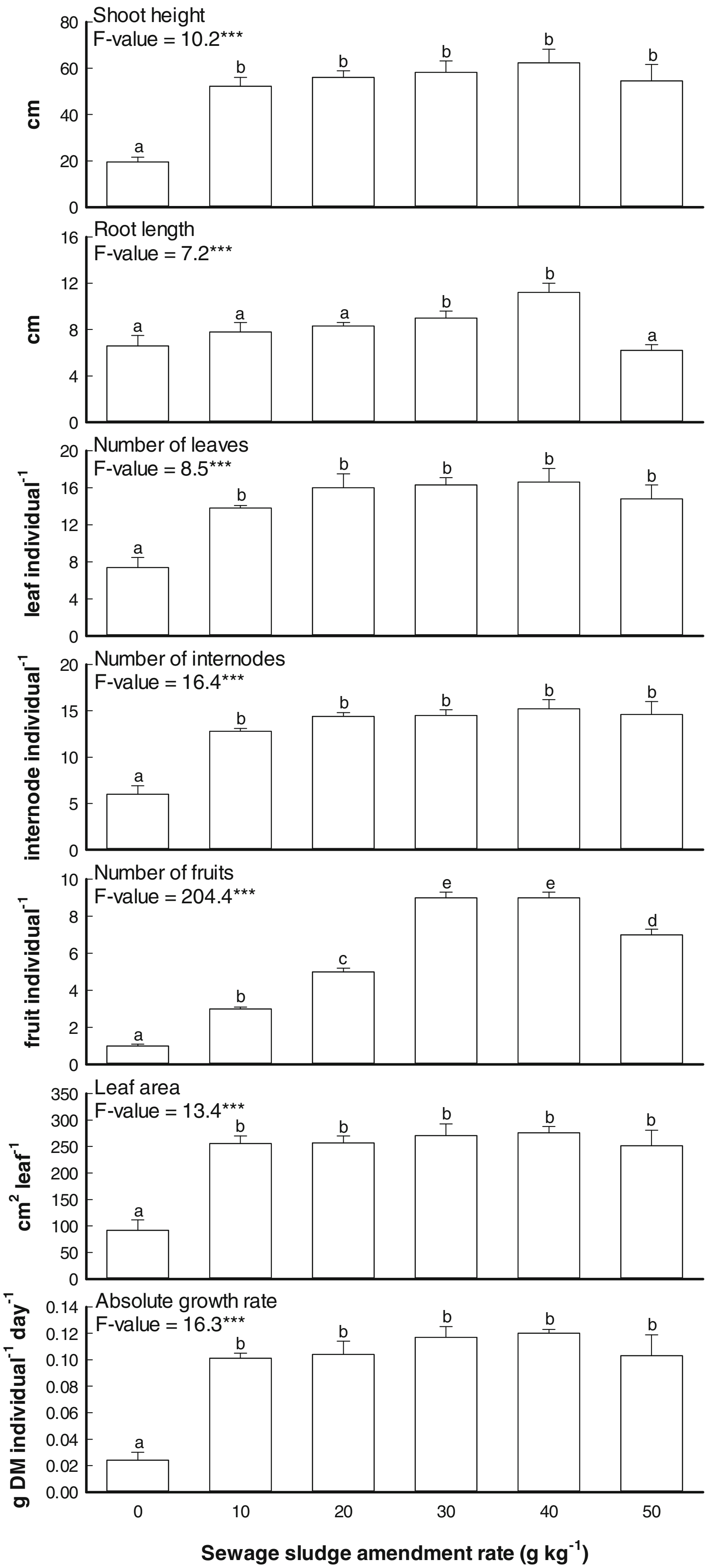

Fig. 1 Effect (mean ± standard error, $n = 6$) of different sewage sludge amendment rates on the morphometric parameters of cucumbers harvested after 50 days. The F values represent a one-way ANOVA and a degree of freedom (df) = 5. Means *followed by different letters* are significantly different at $P < 0.05$ according to Tukey's HSD test. ***$P < 0.001$

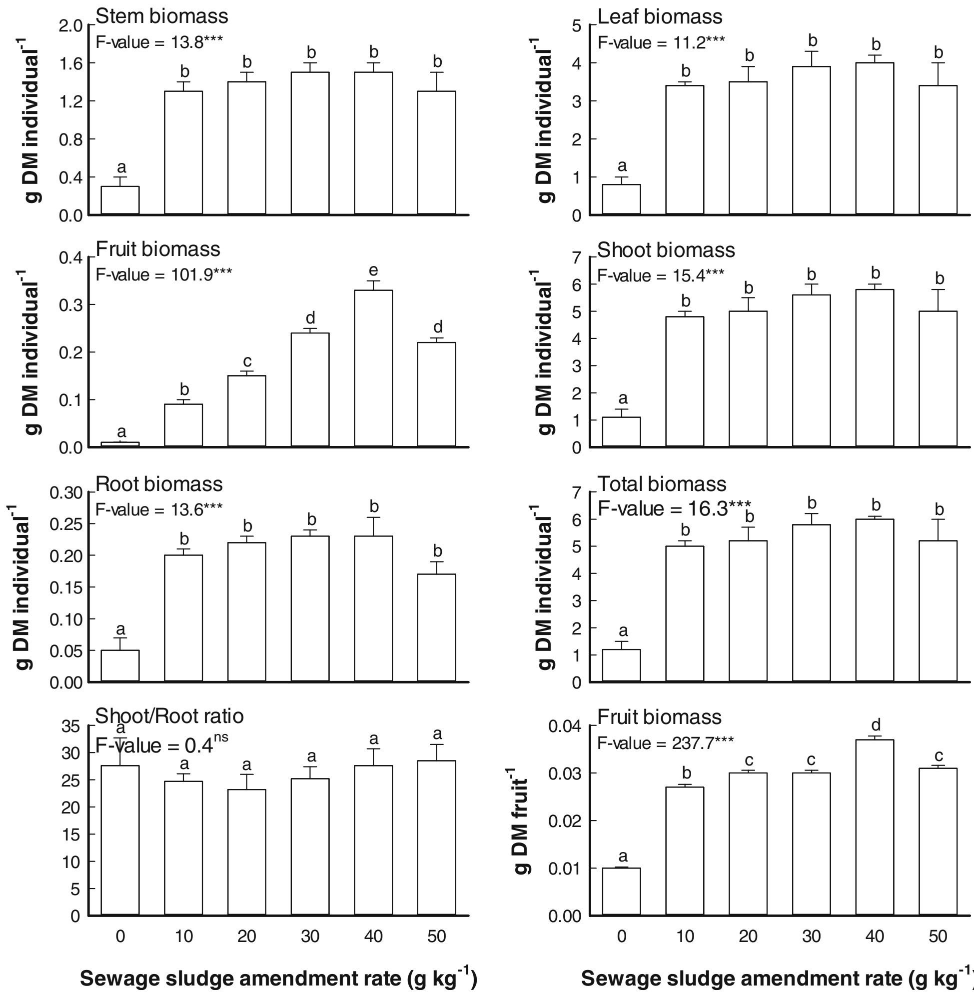

Fig. 2 Effect (mean ± standard error, $n = 6$) of different sewage sludge amendment rates on the biomass of cucumbers harvested after 50 days. *F* values represent a one-way ANOVA and a degree of freedom (*df*) = 5. Means *followed by different letters* are significantly different at $P < 0.05$ according to Tukey's HSD test. ***P <0.001 and *ns* not significant (i.e., $P < 0.05$)

1.7, 2.6, 2.8, 3.1 and 3.5% corresponding to 1.1, 1.6, 1.8, 1.9 and 2.2-fold increases at the 10, 20, 30, 40 and 50 g kg^{-1} sewage sludge amendment rates. Soil fertility improvement by sewage sludge has been reported widely in many studies (Eid et al. 2017; Bai et al. 2017; Liu et al. 2017; Singh and Agrawal 2007; Wang et al. 2008). The valuable impact of sewage sludge applications is important, especially in soils that are poor in organic matter content, such as those of the Arabian Peninsula, where high temperatures during the summer promote the high annual mineralization of organic matter.

In this study, the soil pH decreased and the salinity increased due to sewage sludge amendment. This development may be linked to the lower pH and higher salinity of sewage sludge relative to the soil. The decrease in soil pH that arises from sewage sludge amendment could also be associated with the release of humic acid because of the biodegradation of sewage sludge that is rich in organic carbon under aerobic conditions during cucumber cultivation (Singh and Agrawal 2010b). According to reports, the mineralization of the organic nitrogen added by sewage sludge produces protons through the nitrification and mineralization of compounds that are rich in S, thereby resulting in a drop in the soil pH (see Latare et al. 2014). Previous studies have found decreases in soil pH and increases in salinity with different rates of sewage sludge amendment (Eid et al. 2017; Yilmaz and Temizgül 2014).

The increase in the sewage sludge amendment rate significantly increased the Cr, Fe, Ni and Zn concentrations, which was important in comparison to the control soil. This observation may be explained by decreasing the soil pH (Sukreeyapongse et al. 2002), which made the heavy metals more available upon the increase in sewage sludge rates (Eid et al. 2017). Studies have shown an increase in heavy metal availability with reduced pH values (Singh and Agrawal 2007, 2009). According to the Statutory Instrument No. 267/2001 (Council of the European Communities 2001), the heavy metal limits (in mg kg^{-1}) for sludge use in agriculture are as follows: Cd 20–40, Co 10–100, Cr 50–1750, Cu 1000–1750, Ni 300–400, Pb 750–1200 and Zn 2500–4000. The sludge used for this study contains 1.17, 27.9, 179.1, 162.6, 138.7, 671.2 and 667.6 mg kg^{-1} of Cd, Co, Cr, Cu, Ni, Pb and Zn, respectively. Thus, the concentrations of sewage sludge heavy metals in this study were lower than the permitted limits. The low quantity of heavy metals could be a result of

Table 2 Effects (mean ± standard error, $n = 6$) of different amendment rates of sewage sludge on the heavy metal concentrations (mg kg^{-1}) in the fruits, leaves, stems and roots of cucumbers harvested after 50 days

Metal	Tissue	Sewage sludge amendment rate (g kg^{-1})						*F* value	Safe limit+	Phytotoxic range‡
		0	10	20	30	40	50			
Cd	Fruit	0.19 ± 0.01a	0.29 ± 0.00a	0.31 ± 0.01a	0.33 ± 0.06a	0.59 ± 0.09b	0.92 ± 0.04c	35.4***	0.3	5–30
	Leaf	0.09 ± 0.00a	0.10 ± 0.00a	0.10 ± 0.00a	0.10 ± 0.00a	0.15 ± 0.00b	0.15 ± 0.00b	59.7***		
	Stem	0.09 ± 0.00a	0.10 ± 0.00a	0.10 ± 0.00a	0.10 ± 0.01a	0.10 ± 0.00a	0.15 ± 0.00b	62.5***		
	Root	0.05 ± 0.00a	0.09 ± 0.01a	0.10 ± 0.01a	0.13 ± 0.01a	0.14 ± 0.01a	0.37 ± 0.06b	19.0***		
Co	Fruit	0.10 ± 0.01a	0.16 ± 0.00a	0.30 ± 0.00a	0.33 ± 0.06a	0.37 ± 0.02a	2.32 ± 0.36b	33.5***	–	30–40
	Leaf	0.43 ± 0.01a	0.53 ± 0.01b	0.55 ± 0.00b	0.65 ± 0.03c	0.75 ± 0.00d	0.80 ± 0.00d	108.9***		
	Stem	0.30 ± 0.00a	0.38 ± 0.01b	0.43 ± 0.01c	0.48 ± 0.01d	0.48 ± 0.01d	1.55 ± 0.00e	1969.7***		
	Root	3.14 ± 0.27a	4.18 ± 0.42ab	4.49 ± 0.53ab	4.67 ± 0.58ab	6.18 ± 1.04ab	7.14 ± 0.90b	4.5*		
Cr	Fruit	1.68 ± 0.04a	2.22 ± 0.11a	2.56 ± 0.01a	3.13 ± 0.12a	5.31 ± 0.79b	8.71 ± 0.61c	40.9***	5	10–100
	Leaf	3.26 ± 0.01a	4.06 ± 0.07b	4.46 ± 0.04c	4.51 ± 0.01c	6.12 ± 0.11d	7.38 ± 0.00e	731.2***		
	Stem	1.67 ± 0.05a	2.01 ± 0.07b	2.24 ± 0.09bc	2.27 ± 0.08bc	2.38 ± 0.03c	3.05 ± 0.12d	36.7***		
	Root	16.6 ± 1.4a	18.8 ± 1.9a	22.0 ± 2.8ab	25.1 ± 4.1ab	33.7 ± 6.5b	34.9 ± 5.5b	3.4*		
Cu	Fruit	17.54 ± 0.58a	17.99 ± 0.65a	18.23 ± 0.12a	20.06 ± 0.17a	23.83 ± 1.67b	25.09 ± 0.74b	15.3***	40	20–100
	Leaf	5.88 ± 0.01a	7.51 ± 0.01b	8.45 ± 0.06c	8.75 ± 0.02d	8.82 ± 0.06d	9.10 ± 0.05e	919.2***		
	Stem	7.27 ± 0.17a	7.52 ± 0.09a	8.96 ± 0.09b	9.38 ± 0.10b	9.39 ± 0.01b	10.05 ± 0.16c	93.7***		
	Root	16.4 ± 1.4a	17.1 ± 0.7a	18.3 ± 1.3a	18.4 ± 1.5a	19.2 ± 2.4a	19.8 ± 1.7a	0.6ns		
Fe	Fruit	135 ± 11a	161 ± 4a	176 ± 15a	181 ± 17a	203 ± 5a	371 ± 85b	5.4**	450	>500
	Leaf	470 ± 12a	489 ± 2a	635 ± 1b	652 ± 7b	833 ± 18c	1044 ± 1d	564.3***		
	Stem	205 ± 9a	229 ± 6ab	243 ± 13ab	275 ± 2b	278 ± 14b	405 ± 19c	35.5***		
	Root	3616 ± 329a	4105 ± 430ab	4942 ± 412ab	5383 ± 864ab	7111 ± 1374b	7463 ± 1216b	3.2*		
Mn	Fruit	24.3 ± 1.3a	25.8 ± 0.7a	26.5 ± 2.2a	30.9 ± 1.2a	32.7 ± 3.2a	38.2 ± 7.8a	2.1ns	–	>500
	Leaf	44.2 ± 0.3a	48.2 ± 0.1b	48.5 ± 0.5b	52.2 ± 0.1c	53.0 ± 0.4c	61.3 ± 0.8d	183.9***		
	Stem	15.4 ± 0.3a	18.6 ± 0.7b	19.4 ± 0.3bc	20.6 ± 0.8bc	21.2 ± 0.9bc	22.0 ± 0.4c	15.0***		
	Root	75.8 ± 6.9a	101.7 ± 10.9ab	103.0 ± 9.1abc	115.5 ± 14.9abc	122.3 ± 16.3bc	142.9 ± 20.8c	4.0*		
Ni	Fruit	1.85 ± 0.09a	2.52 ± 0.06ab	2.53 ± 0.20ab	2.58 ± 0.23ab	2.67 ± 0.05ab	3.23 ± 0.39b	4.5*	20	40–246
	Leaf	1.59 ± 0.00a	1.75 ± 0.03b	1.92 ± 0.01c	1.99 ± 0.02c	2.65 ± 0.06d	3.03 ± 0.02e	328.3***		
	Stem	1.05 ± 0.01a	1.07 ± 0.01a	1.17 ± 0.01ab	1.20 ± 0.00b	1.22 ± 0.05b	1.40 ± 0.05c	20.5***		
	Root	7.15 ± 0.63a	8.17 ± 0.68a	8.70 ± 1.24a	9.76 ± 1.41a	10.45 ± 4.18a	13.72 ± 2.26a	1.2ns		
Pb	Fruit	0.32 ± 0.09a	0.45 ± 0.01a	0.49 ± 0.11a	0.57 ± 0.13a	0.60 ± 0.01a	1.18 ± 0.18b	7.7**	5	30–300
	Leaf	0.30 ± 0.03a	0.33 ± 0.01ab	0.40 ± 0.03ab	0.45 ± 0.00b	0.45 ± 0.06b	0.65 ± 0.03c	14.6***		
	Stem	0.30 ± 0.03a	0.35 ± 0.03a	0.38 ± 0.04a	0.40 ± 0.03a	0.41 ± 0.02a	0.43 ± 0.01a	2.5ns		
	Root	0.47 ± 0.02a	0.48 ± 0.03a	0.48 ± 0.02a	0.69 ± 0.17a	0.76 ± 0.06a	4.45 ± 1.93b	4.0*		
Zn	Fruit	41.0 ± 0.6a	53.7 ± 0.9ab	56.2 ± 2.2ab	56.6 ± 0.6ab	57.7 ± 1.1ab	74.0 ± 11.0b	5.2**	60	100–400
	Leaf	13.8 ± 0.1a	15.7 ± 0.1b	19.8 ± 0.1c	20.0 ± 0.1c	22.2 ± 0.4d	23.0 ± 0.3d	277.4***		
	Stem	15.7 ± 0.2a	18.9 ± 0.9b	21.3 ± 0.7c	22.1 ± 0.4c	24.4 ± 0.2d	27.4 ± 0.2e	67.5***		
	Root	26.9 ± 3.4a	28.7 ± 3.7a	32.7 ± 1.9a	34.5 ± 3.6a	38.6 ± 4.4a	41.8 ± 3.8a	2.6ns		

The *F* values represent a one-way ANOVA, and degree of freedom (*df*) = 5. The means in the same row followed by different letters are significantly different at $P < 0.05$ according to Tukey's HSD test

ns not significant (i.e., $P > 0.05$)

+ FAO/WHO standard (Codex Alimentarious Commission 2011)

‡ Kabata-Pendias (2011)

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

the effective industrial pretreatment and monitoring by wastewater treatment facilities in Saudi Arabia (Eid et al. 2017).

Agricultural land can be improved in terms of soil fertility, physical properties and crop production by applying sewage sludge (Koutroubas et al. 2014; Liu et al. 2017). The beneficial impact of applying sewage sludge on cucumber growth was evident in this investigation as a positive response in the biomass and all of the growth parameters (except the shoot/root ratio) of cucumbers to the sewage sludge applications, at up to 40 g kg^{-1} compared to the control soil. The

Table 3 Means ± standard errors ($n = 6$) of the bioaccumulation factors (BFs), from the soil to the roots, and the translocation factors (TFs), from the roots to fruits and leaves and stems of heavy metals in cucumbers grown in soil with different sewage sludge amendment rates

Metal	Factor	Sewage sludge amendment rate (g kg^{-1})						*F* value
		0	10	20	30	40	50	
Cd	BF	0.06 ± 0.00a	0.11 ± 0.01a	0.12 ± 0.01a	0.15 ± 0.01a	0.16 ± 0.01a	0.36 ± 0.06b	16.4***
	TF_{fruit}	3.66 ± 0.18ab	3.29 ± 0.04ab	2.94 ± 0.08ab	2.53 ± 0.42a	4.11 ± 0.62b	2.44 ± 0.10a	4.2*
	TF_{leaf}	1.96 ± 0.01f	1.10 ± 0.00e	0.96 ± 0.00c	0.76 ± 0.00b	1.04 ± 0.00d	0.40 ± 0.00a	1046.8***
	TF_{stem}	1.96 ± 0.00e	1.10 ± 0.00d	0.97 ± 0.01c	0.77 ± 0.04b	0.71 ± 0.02b	0.40 ± 0.00a	760.1***
Co	BF	0.14 ± 0.01a	0.17 ± 0.02a	0.18 ± 0.02a	0.18 ± 0.02a	0.24 ± 0.04a	0.26 ± 0.03a	3.0^{ns}
	TF_{fruit}	0.03 ± 0.00a	0.04 ± 0.00a	0.07 ± 0.00a	0.07 ± 0.01a	0.06 ± 0.00a	0.33 ± 0.05b	28.5***
	TF_{leaf}	0.14 ± 0.01bc	0.13 ± 0.00abc	0.12 ± 0.00ab	0.14 ± 0.01c	0.12 ± 0.00ab	0.11 ± 0.00a	9.1**
	TF_{stem}	0.10 ± 0.00bc	0.09 ± 0.00b	0.09 ± 0.00bc	0.10 ± 0.00c	0.08 ± 0.00a	0.22 ± 0.00d	483.5***
Cr	BF	0.10 ± 0.01a	0.12 ± 0.01a	0.14 ± 0.02a	0.14 ± 0.02a	0.19 ± 0.04a	0.19 ± 0.03a	2.4^{ns}
	TF_{fruit}	0.10 ± 0.00a	0.12 ± 0.01a	0.12 ± 0.00a	0.13 ± 0.01a	0.16 ± 0.02a	0.25 ± 0.02b	19.3***
	TF_{leaf}	0.20 ± 0.00b	0.22 ± 0.00c	0.20 ± 0.00b	0.18 ± 0.00a	0.18 ± 0.00a	0.21 ± 0.00c	48.6***
	TF_{stem}	0.10 ± 0.00bcd	0.11 ± 0.00d	0.10 ± 0.00bcd	0.09 ± 0.00bc	0.07 ± 0.00a	0.09 ± 0.00b	17.6***
Cu	BF	0.62 ± 0.05a	0.57 ± 0.02a	0.61 ± 0.04a	0.59 ± 0.05a	0.55 ± 0.07a	0.54 ± 0.05a	0.4^{ns}
	TF_{fruit}	1.07 ± 0.04ab	1.05 ± 0.04ab	0.99 ± 0.01a	1.09 ± 0.01abc	1.24 ± 0.09bc	1.27 ± 0.04c	6.1**
	TF_{leaf}	0.36 ± 0.00a	0.44 ± 0.00b	0.46 ± 0.00c	0.48 ± 0.00d	0.46 ± 0.00c	0.46 ± 0.00c	417.5***
	TF_{stem}	0.44 ± 0.01a	0.44 ± 0.01a	0.49 ± 0.01b	0.51 ± 0.01b	0.49 ± 0.00b	0.51 ± 0.01b	23.9***
Fe	BF	0.16 ± 0.02a	0.17 ± 0.02a	0.20 ± 0.02a	0.22 ± 0.04a	0.28 ± 0.05a	0.29 ± 0.05a	2.6^{ns}
	TF_{fruit}	0.04 ± 0.00a	0.04 ± 0.00a	0.04 ± 0.00a	0.03 ± 0.00a	0.03 ± 0.00a	0.05 ± 0.01a	1.9^{ns}
	TF_{leaf}	0.13 ± 0.00b	0.12 ± 0.00a	0.13 ± 0.00b	0.12 ± 0.00a	0.12 ± 0.00a	0.14 ± 0.00c	23.9***
	TF_{stem}	0.06 ± 0.00b	0.06 ± 0.00b	0.05 ± 0.00b	0.05 ± 0.00b	0.04 ± 0.00a	0.05 ± 0.00b	10.0**
Mn	BF	0.15 ± 0.01a	0.19 ± 0.02a	0.17 ± 0.02a	0.19 ± 0.03a	0.20 ± 0.03a	0.23 ± 0.03a	1.5^{ns}
	TF_{fruit}	0.32 ± 0.02a	0.25 ± 0.01a	0.26 ± 0.02a	0.27 ± 0.01a	0.27 ± 0.03a	0.27 ± 0.06a	0.8^{ns}
	TF_{leaf}	0.58 ± 0.00d	0.47 ± 0.00c	0.47 ± 0.01c	0.45 ± 0.00b	0.43 ± 0.00a	0.43 ± 0.01a	253.8***
	TF_{stem}	0.20 ± 0.00c	0.18 ± 0.01bc	0.19 ± 0.00bc	0.18 ± 0.01b	0.17 ± 0.01ab	0.15 ± 0.00a	8.9**
Ni	BF	0.28 ± 0.03a	0.31 ± 0.03a	0.32 ± 0.05a	0.36 ± 0.05a	0.38 ± 0.15a	0.49 ± 0.08a	0.9^{ns}
	TF_{fruit}	0.26 ± 0.01a	0.31 ± 0.01a	0.29 ± 0.02a	0.26 ± 0.02a	0.26 ± 0.01a	0.24 ± 0.03a	2.0^{ns}
	TF_{leaf}	0.22 ± 0.00b	0.21 ± 0.00ab	0.22 ± 0.00b	0.20 ± 0.00a	0.25 ± 0.01c	0.22 ± 0.00b	30.5***
	TF_{stem}	0.15 ± 0.00d	0.13 ± 0.00c	0.13 ± 0.00c	0.12 ± 0.00bc	0.11 ± 0.00b	0.10 ± 0.00a	39.5***
Pb	BF	0.001 ± 0.000a	0.001 ± 0.000a	0.001 ± 0.000a	0.001 ± 0.000a	0.002 ± 0.000a	0.009 ± 0.004b	4.0*
	TF_{fruit}	0.67 ± 0.20ab	0.94 ± 0.03ab	1.02 ± 0.23b	0.83 ± 0.19ab	0.79 ± 0.01ab	0.26 ± 0.04a	3.2*
	TF_{leaf}	0.64 ± 0.06bc	0.68 ± 0.03bc	0.83 ± 0.06c	0.65 ± 0.00bc	0.60 ± 0.08b	0.15 ± 0.01a	22.9***
	TF_{stem}	0.64 ± 0.06b	0.74 ± 0.06b	0.78 ± 0.09b	0.58 ± 0.04b	0.54 ± 0.03b	0.10 ± 0.00a	20.1***
Zn	BF	0.35 ± 0.04a	0.34 ± 0.04a	0.38 ± 0.02a	0.38 ± 0.04a	0.42 ± 0.05a	0.33 ± 0.03a	0.7^{ns}
	TF_{fruit}	1.53 ± 0.02a	1.87 ± 0.03a	1.72 ± 0.07a	1.64 ± 0.02a	1.50 ± 0.03a	1.77 ± 0.26a	1.7^{ns}
	TF_{leaf}	0.52 ± 0.00a	0.55 ± 0.00b	0.61 ± 0.00d	0.58 ± 0.00c	0.57 ± 0.01c	0.55 ± 0.01b	31.5***
	TF_{stem}	0.59 ± 0.01a	0.66 ± 0.03a	0.65 ± 0.02a	0.64 ± 0.01a	0.63 ± 0.00a	0.66 ± 0.01a	3.0^{ns}
F value$_{BF}$		53.9***	58.0***	51.2***	28.6***	6.4**	12.2***	
F value$_{TFfruit}$		160.8***	2028.3***	133.7***	31.1***	39.3***	74.1***	
F value$_{TFleaf}$		744.2***	930.8***	232.3***	7871.4***	131.2***	1689.8***	
F value$_{TFstem}$		822.7***	259.4***	123.5***	182.0***	618.0***	2914.7***	

The *F* values represent a one-way ANOVA, and a degree of freedom (df) = 5. Means in the same row followed by different letters are significantly different at $P < 0.05$ according to Tukey's HSD test

ns not significant (i.e., $P > 0.05$)

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

amendment with 40 g kg^{-1} sewage sludge resulted in an approximately 3-fold increase in the cucumber shoot height, an approximately 2-fold increase in the root length, an approximately 2-fold increase in the number of leaves, an approximately 3-fold increase in the number of internodes, a 9-fold increase in the number of fruits, a 3-fold increase in the leaf area, an approximately 5-fold increment in the AGR and an approximately 5-fold increase in the total biomass compared to the plants grown in the control soil. This positive response may have resulted from the enhanced soil fertility (increased organic matter content), nutrient retention, soil porosity, water-holding capacity, increased aggregate stability, reduced soil evaporation, reduced bulk density and the supply of additional carbon because of the addition of soil amendments (Angin and Yaganoglu 2011; Antonious et al. 2012; Liu et al. 2017). Amendments using sewage sludge as well as sewage sludge composts have been revealed to increase the biomass of crops such as sorghum, maize and wheat (Akdeniz et al. 2006; Bozkurt et al. 2006; Uyanoz et al. 2006). Moreover, Eid et al. (2017) mentioned that the biomass and all of the growth parameters (except the shoot/root ratio) of spinach showed a positive response to the sewage sludge applications of up to 40 g kg^{-1} compared to the control soil.

In this study, the cucumber shoot height; root length; number of leaves, internodes and fruits; leaf area; AGR and biomass decreased in response to 50 g kg^{-1} of sewage sludge. A similar finding was reported in our previous study on spinach plants (Eid et al. 2017). A high sludge content was reportedly suppressive of plant growth hormones (auxin and gibberellin), which are responsible for the growth and development of plants (Chandra et al. 2008). The heavy metals entering the protoplasm may cause a reduction in plant growth at high sewage sludge concentrations, resulting in the loss of intermediary metabolites, which are important for the growth and development of plants (Khan et al. 2015). The inhibition of the morphometric parameters and biomass of cucumbers when amending the soils at higher sewage sludge concentrations could also be due to high salinity, which could create high osmotic pressure (Chandra et al. 2008). High salt concentrations increase the likely forces that retain soil water and inhibit its uptake by plant roots (Kumar and Chopra 2012). Moreover, this inhibition is also likely because of the greater heavy metal content in the greater sewage sludge concentrations. After the application of 50 g kg^{-1} sewage sludge, the average cucumber fruit's Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn concentrations increased to 484, 2320, 518, 143, 275, 157, 175, 369 and 180%, respectively, relative to the mean concentrations of the plants grown in the control soil. The higher build-up of heavy metals in plants causes a reduced photosynthetic rate, decline in transpiration rate and chlorophyll pigments, disturbed photochemical light quenching, increased lipid peroxidation, proline and protein contents and stunted growth and lowering of yield (Singh and Agrawal 2007, 2010b). Heavy metals at supraoptimal concentrations in the growth media can act as stressors, initiating physiological constraints that reduce plant vigour and limit plant growth, development and biomass (Chandra et al. 2008). The production of reactive oxygen species and free radicals in plants is stimulated by heavy metal stress (Emamverdian et al. 2015). These free radicals can disrupt the normal metabolism through oxidative damage to plant cellular components because these species have a strong oxidizing property and can attack all types of biomolecules (Singh and Agrawal 2010b).

Sewage sludge application to cropland could lead to soil contamination, phytotoxicity and the build-up of heavy metals in the food supply (Kidd et al. 2007). The scale of the problem is influenced by the inter-relationships of some factors, which include the composition of the sludge, the soil characteristics, the plant species and the frequency and rate of the applications (Mohammad and Athamneh 2004). Sludge type and sludge soil interactions affect the chemical forms of heavy metals, which then determine their availability for plant uptake. However, additional plant and soil factors further modify the uptake and the concentration of heavy metals in crops (see Kumar et al. 2016). Usually, the heavy metals in soils and plants are the priority factors to consider when applying sewage sludge to land (Eid et al. 2017). In this study, there was a considerable increase in all of the concentrations of heavy metals (except Cu, Ni and Zn in the roots, Mn in the fruits and Pb in the stems) in different cucumber tissues with increased sewage sludge application. The present findings are consistent with earlier reports by some authors who found that the plant percentage of heavy metals increased after they applied sewage sludge to the soil (Eid et al. 2017; Waqas et al. 2014, 2015). The increased bioavailability of the heavy metals might also be caused by organic matter decomposition and result in soluble organic-heavy metal complexes (Antoniadis and Alloway 2002). This finding was supported by the increased soil organic matter contents of the soil that was amended by sewage sludge. However, all of the concentrations of heavy metals (except Cr and Fe in the roots, Fe in the leaves and Cu in the fruits) in this study were within the normal range and did not reach the phytotoxic levels reported by Kabata-Pendias (2011). Moreover, all of the accumulated heavy metal concentrations except Cd and Cr in the fruits of cucumbers that were amended by sewage sludge up to 40 g kg^{-1} were lower than the safe limits indicated by FAO/WHO standard limits (Codex Alimentarious Commission 2011). Thus, the amendment of agricultural soil using sewage sludge may be practical. Nevertheless, the consistent checking of heavy metal levels in agricultural products is recommended to avoid metal build-up in the food chain.

Soil characteristics such as the soil pH, clay, organic matter content, redox conditions and moisture content determine the availability of heavy metals to plants; these parameters act by regulating the heavy metal speciation, temporary binding of heavy metals by particle surfaces (adsorption-desorption processes), precipitation reactions and the presence of heavy metals in the soil solution (Yilmaz and Temizgül 2014). Of these factors, the pH is considered as the most vital and easily controllable factor (Khan et al. 2015) because it influences the availability and uptake of heavy metals (Kumar and Chopra 2012). Elements such as Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn become more soluble under acidic conditions (Eid et al. 2017). In an earlier study by Eid and Shaltout (2016), the authors reported that the increased presence of heavy metals occurs with a decreasing pH.

The present study reported that most heavy metal concentrations were highest in the roots rather than the shoot tissues (fruits, stems and leaves). Singh and Agrawal (2007) and Eid et al. (2017) reported that the heavy metal build-up was generally greater in the roots than the shoots with sewage sludge applications. This finding may be associated with the mechanisms through which the roots trap heavy metals, for instance, the occurrence of low molecular weight proteins such as phytochelatins and phytosiderophores that act like heavy metal chelators, leading to lower heavy metal levels in the stems, leaves and fruits (Clemens 2006; Grotto et al. 2015). These results suggest the existence of a defence mechanism in the plant, and this mechanism limits the transmission of heavy metals through the food chain by their build-up in roots, or the so-called root barrier (Adriano 2001; Basta et al. 2005). Heavy metal retention in roots performs the essential role of inhibiting an excessive and toxic build-up of these metals in the edible parts of the plant (Soriano-Disla et al. 2014). Plants that use this strategy hold most of the heavy metals that have been absorbed from soils in root cells, detoxifying them by chelation in the cytoplasm or storing them in vacuoles (Singh and Agrawal 2010c). The high build-up of heavy metals in the roots may be linked to the complexation of heavy metals with sulfhydryl groups, resulting in less translocation of heavy metals to the shoots (Singh et al. 2004). The presence of greater concentrations of heavy metals in the roots than in the shoots may also be ascribed to the fact that the roots are the first target tissue to contact the heavy metals; therefore, a greater accumulation is ensued in the root tissues (Eid and Shaltout 2014).

The estimation of the BF represents a simple method to characterize the transfer of available heavy metals from the soil to the plant in a quantitative manner (Branzini et al. 2012). The overall BF of nine heavy metals in the cucumbers revealed that cucumbers were poor accumulators of Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn (BF < 1). In general, the BF of Cu was the highest, followed by Ni, Zn, Cd, Fe, Co, Mn, Cr and Pb. Therefore, this finding implies that plants do not uniformly absorb all of the heavy metals in the soil, and even absorption is not a concentration-reliant occurrence for all of the heavy metals (Singh and Agrawal 2010a). This trend is consistent with the data reported by our previous study (Eid et al. 2017) about spinach, which stated that Cu and Zn generally had the highest BF, while Fe, Cr and Pb had the lowest. An elevated BF for Cu and Zn is not unexpected since they are essential plant nutrients. It is also reported that Pb tends to accumulate poorly in plants, and plant uptake; if it occurs, most of the absorbed Pb is located within the root system of the plant (see Latare et al. 2014). The build-up of heavy metals by plants is a complex process and depends on various factors such as the soil physicochemical properties, sewage sludge composition, sludge application rate, plant species, phenology and physiology, rhizosphere biochemistry, climatic factors, chelating effects of other heavy metals and chemical speciation of heavy metals (Basta et al. 2005; Mahdy et al. 2007). The low soil pH of the soil after the sewage sludge amendment along with the higher organic matter observed during this study may have increased the presence of heavy metals and further uptake by plants during the current study.

The transfer of heavy metals from roots to shoots depends on their form, plant physiology, water transport and plant species (Kalis et al. 2008) and largely determines which fraction could enter the food chain. In this study, the transfer factor for all of the heavy metals (except Cd, Cu and Zn) was <1.0, supporting the function of the roots as a barrier to translocation and in protecting the edible portions (fruits) from toxic contamination (Mishra and Tripathi 2008). The poor translocation of Co, Cr, Fe, Mn, Ni and Pb to the fruits could be a result of the confiscation of most of these heavy metals in the root cell's vacuoles to make it non-toxic, which may be a natural protective response of this plant (Kumar and Chopra 2014). Thus, the plant appears to follow an exclusion strategy by restricting the heavy metals from translocating to the fruits, and it suggests different cellular mechanisms of heavy metal bioaccumulation, which may control their partitioning and translocation in the plant (Nawab et al. 2016).

The results of this study show that sewage sludge amendment in the soil at application rates of 40 g kg^{-1} and below may be a good option to maintain the soil health and maximize the cucumber yields. Therefore, the use of sewage sludge in agriculture would be an environmentally friendly solution for disposal problems. At higher sewage sludge rates (50 g kg^{-1}), the higher accumulation of Cd, Cr, Cu and Zn in the fruits is a major concern due to its risk to human health, which limits its suitability for human consumption. Lower sewage sludge amendment rates may be more helpful for preventing food chain contamination and risks to human health. The composition of heavy metals in the soil should be supervised on a regular basis to ensure that applying sewage sludge to the soil is a truly environmentally acceptable practice.

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