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ORIGINAL RESEARCH

Evaluation of the potential use of biosolids in corn crop in the municipality of Puebla, Mexico

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Abstract

Purpose Due to the urgent need for sustainable agro-industrial waste management, a field experiment was conducted to evaluate the application of biosolids as organic fertilizer in a corn cultivation crop. The study aimed to measure metals concentrations and assess enrichment factor (EF) in soil and corn plants as they are important factors to consider in order to achieve food security.

Method Four sites where biosolids are applied were studied and compared against a control. Physicochemical properties of soils and heavy metal contents were evaluated after one year of application of biosolids. Metal concentrations, average kernel yield and biomass were measured in corn plants.

Results The results demonstrated that the application of biosolids increased the content of organic matter, nitrogen, phosphorus, and exchangeable bases in the soil. Additionally, the concentration of heavy metals in soils with biosolids was higher than in soils without treatment, and the concentration of heavy metals in the corn kernels did not exceed the maximum recommended limits. However, EF values showed a considerable contamination level due to the accumulation of metals.

Conclusion Some of the soil physical and chemical characteristics were improved by incorporating biosolids, but the metal content in the soil increased as well. Also, the application of biosolids increased the plant height and corn yield. Therefore, biosolids can be used as organic fertilizer sources; however, it is necessary to carry out periodic evaluations to ensure low levels of enrichment in crops and soil, thus guaranteeing the safety of biosolids as soil fertilizers.

Keywords Soil amendment, Biosolids, Organic fertilizer, Heavy metals, Enrichment factor, Corn yield

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Introduction

Cities produce billions of tons of waste each year, including sludge and sewage (Mateo-Sagasta et al. 2015). At the same time, agricultural activity demands an increase in productivity to satisfy the food demand of the population that increases continuously (Ali et al. 2021). The search for alternatives to minimize and reuse the quantities of waste are some of the new challenges that humanity must address to achieve sustainability (Abdel-Shafy and Mansour 2018). Biosolids are organic materials with a high level of nutrients resulting from the digestion of human residuals and are produced in wastewater treatment facilities. (Badzmierowski et al. 2021). Due to their organic matter content, nutrients, and characteristics acquired after their stabilization, they may be susceptible to use in agriculture (Garrido-Hoyos et al. 2005). Frequently, the terms "biosolids" and "sewage sludge" (SS) are used interchangeably (Kumar et al. 2017). In some European countries, biosolids are used as a valuable resource in agriculture, and their reuse as soil improver/fertilizer in arable crops represents the most used option (Mininni et al. 2015; Collivignarelli et al. 2019). The agricultural use of good quality sludge means a way to ensure sustained growth in Europe, where sludge is used in almost 50% of the agricultural areas (Gianico et al. 2021).

Agricultural use of sludge that would otherwise be deposited in landfills can provide an alternative to increase crop yields and household farm income (da Silva et al. 2021). Biosolids can be processed to produce a high-value resource for agricultural production and to restore degraded ecosystems (Lu et al. 2012). Generally, biosolids are rich in organic matter, nitrogen, and phosphorus, which are potentially useful as fertilizers (Chambers et al. 2003). Furthermore, the addition of biosolids improves some of the soil's physical properties such as available water capacity, aggregate stability, and water infiltration rate. It also improves soil chemical properties as soil N, P, and S supply and CEC (cation exchange capacity); as well as soil biological properties like the number and weight of earthworms (Nicholson et al. 2018).

Agroecology requires the use of organic products such as fertilizers derived from the degradation of organic residues, which improve food security and the quality of the products (Nyantakyi-Frimpong et al. 2016). Furthermore, there are numerous investigations focused on identifying the potential benefits of the use of residual solids such as biosolids in their agronomic application, which would have repercussions on the consideration of these by-products as a "waste" (Chambers et al. 2003; LeBlanc et al. 2008; Kumar et al. 2017; Sharma et al. 2017; Pampana et al. 2021).

The presence of toxic metals can limit the use of sewage sludge on agricultural plots (Camargo et al. 2016). Therefore, it is necessary to quantify their contents in soils before and after their application. Among the most commonly found heavy metals are Cr, Ni, Cu, Zn, Cd, and Pb (Azevedo Silveira et al. 2003). Some of them such as Cu and Zn are essential elements for the plant and their deficiency can cause problems in crops, while if they are in excess, they imply a risk of toxicity (de Oliveira et al. 2018). Others do not have recognized physiological functions and they present potential risk, either for plants or consumers (Gerba et al. 2002; Pritchard et al. 2010; Lu et al. 2012). Thus, there is a justified need to establish quality standards for the biosolids added to the soils, mainly due to the risk of contamination and to prevent irreversible modifications to the soils.

As the use of municipal organic waste becomes more common, as outlined by Martínez-Blanco et al. (2011), most countries set legislation and studies regarding the addition of biosolids on agricultural soils that aim to regulate the use of sewage sludge in agriculture to avoid harmful effects on the soils, the environment, and human beings while promoting its appropriate use. In the case of the European Union (EU), the Council Directive of 12 June 1986 (CEC 1986) provides the limits for the concentration of heavy metals on soils and sewage sludge intended for use in agriculture. In the USA, the Environmental Protection Agency's (EPA) Part 503 rule dictates requirements for managing biosolids generated during the treatment of municipal wastewater (USEPA 1994) and includes pollutant, pathogens, and vector attraction limits that allow the classification of biosolids in different classes according to pollutant concentrations. Numerous studies have been conducted in Latin America to evaluate the use of biosolids in agricultural sites (Nogueira et al. 2013; da Mota et al. 2019; Silva-Leal et al. 2021) and regulations for the use of biosolids have also been established. For example, in Mexico, the official standard indicates limits for pollutants in biosolids (SEMARNAT 2002a) such as heavy metals, pathogens and assigns classification according to pollutant concentrations. Likewise, in Brazil, Resolution 375/06 of the National Environmental Council has established criteria and procedures for the agricultural use of sewage sludge to avoid risks to public health and the environment (CONAMA 2006). The efficiency of these biosolids as fertilizers depends on the type of soil and crop, the quality of the biosolids, and the environmental factors that directly influence the mineralization processes and the availability of nutrients for the plant (Lu et al. 2012; Shaheen et al. 2012).

The state of Puebla is the 10th producer of kernel corn in Mexico, thus making it one of the main crops for rural producers in the state (SIAP-SAGARPA 2020). In Puebla City, around 200 tons of biosolids are produced daily in different wastewater treatment plants through the municipality (González Flores et al. 2014). These biosolids can be used to fertilize agricultural soils used for planting corn in the southern part of the municipality, thus increasing the productivity of crops while favoring the local economy. Additionally, they can contribute to reducing the erosion of these soils.

Despite the rising production of biosolids and its application in agricultural areas, there is a lack of information on how biosolids can influence agricultural soils in Puebla and how they could affect crops and the environment. Therefore, the aim of this study was to evaluate soil changes to identify if the physical and chemical properties of soils are modified in the presence of biosolids; additionally, it was assessed whether these properties influence and improve the fertility of the soil. Finally, it was intended to evaluate whether the concentrations of metals in soils and maize plants exceed the established limits, with the consequent risks.

Materials and methods

Description of the experimental site

The experiment was conducted in the southern part of the municipality of Puebla in the state of Puebla, Mexico. For the study, the following localities were selected: San Francisco Totimehuacan, Santa Clara Ocoyucan, La Paz Tlaxcolpan, and San Andrés Azumiatla (Fig. 1). These areas were selected due to their importance as agricultural production centers in which the inhabitants depend mainly on the production of corn and rainfed beans. However, it has been detected that the study area also has highly degraded soils that present erosion ranging from light to very high, which is the reason for low agricultural production in the region in recent years. The climate of the area is sub-humid with rainfall during summer and medium humidity (C (w1)(w)) according to Köeppen's classification. According to the nearest corresponding isohyet, the annual precipitation was 800 mm, and the corresponding isotherm indicates that the mean annual temperature was 16 °C. The soils were classified mainly as Leptic Phaeozems and Pellic Vertisols (IUSS Working Group WRB 2015), formed by lithic materials of volcanic and sedimentary nature. Soils are shallow to moderately deep and located in a flat to undulating topography. Two experimental plots of 1000 m^2 were selected in each site, one of them treated with biosolids and the other used as a control. The analyses of soil samples were carried out at the experimental station of the Agricultural Research Department of the Autonomous University of Puebla in Mexico.

Biosolids analysis

Biosolids were obtained from the "Atoyac" wastewater treatment plant of the municipal drinking water and sewerage services operator system (Fig. 2).

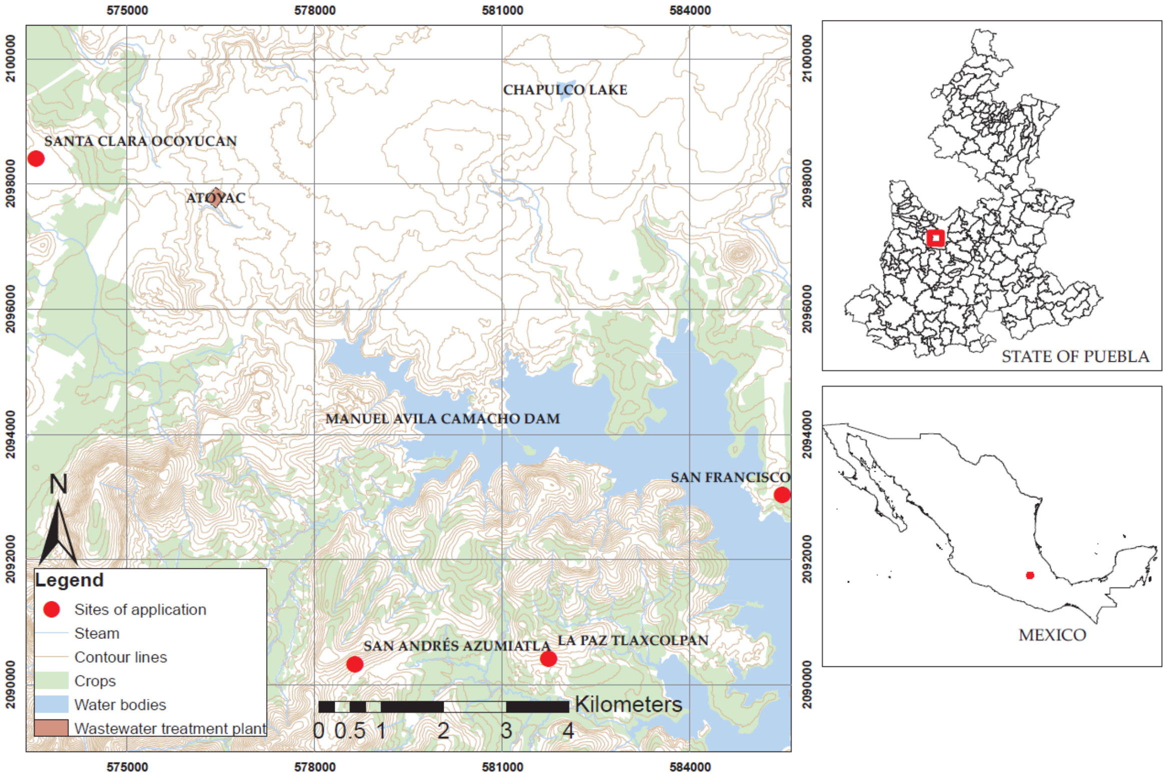

Fig. 1 Location of studied sites

Sewage sludges were stabilized by anaerobic digestion for 28 days and then dried on band filters. Biosolids must comply with the maximum established limits for heavy metals and microorganisms for their use or disposal under the official norm and obtain a minimum classification regarding their metal content according to the Mexican standard (SEMARNAT 2002a). Microwave digestion was carried out for the quantification of metals; dry samples containing 0.5 g were placed in tubes to which 5 mL of HNO_3 were added, then the equipment was turned on for 50 min at 750 W and finally the digested sample was analyzed using atomic emission spectrometry (Agilent 55B AA). The identification of *Salmonella* was conducted by an incubation period of 24 h at 37 °C in tetrathionate broth. After incubation, 0.1 mL of the previous mixture was taken and transferred to a 10 mL of medium with selenite broth and incubated for 24 hours at 41.5 °C. Then, the sample was surface seeded (0.1 mL) on Xylose Lysine Deoxycholate Agar (XLD) and Salmonella Shigella Agar (SS), selective culture media for the growth of *Salmonella sp*., and incubated for 24 hours at 37 °C to identify the colonies. Helminth eggs were detected by continuous washing, combined with various stages of filtration and flotation, separating the helminth eggs from the rest of the larger and smaller particles to identify the eggs through a microscope. The quantification of *E. coli* was done by transferring 1 mL of the initial suspension to a series of tubes containing lactose broth and incubating at 35 ± 0.5 °C and examining each tube after 24 hours. Acidification, with or without gas production (i.e. change in color from purple to yellow), from lactose fermentation in the culture medium, indicates a presumptive positive test for the presence of bacteria of the coliform group. Additionally, the biosolids were analyzed for physicochemical parameters such as pH (water 1:10 w:v), organic matter by dichromate oxidation, total nitrogen using the Kjeldahl method and ashes content obtained by incineration of biosolids in the oven at 450 ºC. Therefore, a dose of 30 tons on a dry basis corresponding to 150 tons on a wet basis was applied to each hectare studied. Once applied to the soil, they were left to dry in the sun for a month. After the biosolids were dosed, they were incorporated into the soil within the first 30 cm, and finally, the soil was prepared for agricultural activities (Fig. 2).

Soil analysis

Soil samples were taken at each study site after harvesting from both, treated and control soils. Ten individual soil subsamples were collected in each hectare within the first 30 cm depth using the zigzag sampling method, forming a composite sample. Then, the samples were air-dried and sieved through a 2 mm mesh sieve, thus obtaining the air-dried fine earth, from which the <2 mm fraction was homogenized before physicochemical analysis. The texture was determined by the Bouyoucos hydrometer method (SEMARNAT 2002b). First, 60 g of soil was treated with 40 mL hydrogen peroxide (30%), evaporated to dryness, and the process was repeated until there was no more effervescence. Next, 50 g of soil was weighed in a 250 mL beaker. Water was added to cover the surface with a 2 cm film. 5 mL of sodium oxalate (30 $g{\cdot}L^{-1}$) and 5 mL of sodium metasilicate were added (50 $g{\cdot}L^{-1}$) and allowed to stand for 15 minutes. Then the sample was shaken vigorously for five minutes and transferred to a 1000 mL cylinder to which one liter of distilled water was added along with the hydrometer into the suspension. The hydrometer was removed and then the soil was suspended for one minute. The hydrometer readings were taken at forty seconds and two hours after completing the dispersion. To take a reading, the hydrometer was placed in the measuring cylinder 20 seconds before the determination, ensuring the suspension was disturbed as little as possible; temperature is read after the hydrometer reading is taken. Corrections were made and the following equations were used to determine the content of particles:

$$\% \, Silt + \% \, Clay = \frac{First \; corrected \; reading}{Sample \; weight} * 100$$

$$\% \, Clay = \frac{Second \; corrected \; reading}{Sample \; weight} * 100$$

$$\% \, Silt = (\%Silt + \%Clay) - \%Clay$$

$$\% \, Sand + \%Silt + \%Clay = 100$$

Finally, the texture is determined using the soil texture triangle from the USDA (USDA 2001).

Fig. 2 a) Biosolids application into the soils, b) Dry of biosolids in the field, c) Incorporation of biosolids into the soil

Organic matter content was determined by the Walkley Black method; 10 mL of potassium dichromate (1 N) and 20 mL of concentrated sulfuric acid were added to 0.5 g of sieved soil. After 30 minutes, 200 mL of water and 5 mL of phosphoric acid were added; total organic carbon was determined by titration with ferrous sulfate (0.5 N) and the indicator diphenylamine until color turned green (SEMARNAT 2002b). Total nitrogen was analyzed by Kjeldahl digestion; 0.5 g of soil was digested with 50 mL H_2SO_4, then it was distilled with sodium hydroxide and recovered in a boric acid solution that was back titrated with hydrochloric acid (Weaver et al. 1994). Electrical conductivity was measured in water using a 1:5 soil to liquid ratio. To measure cation exchange capacity, 5 g of soil with 33 mL of ammonium acetate solution were added, then shaken and centrifuged for 10 minutes. The process was repeated three times; this solution was used to measure exchangeable soil basis by atomic absorption spectrometry. Then, the adsorbed ammonium was replaced with three portions of 33 mL of 10% sodium chloride, shaking for 10 minutes and centrifuging each time. Each replacement was decanted into a 100 mL volumetric flask. Next, the ammonium was determined from a 10 mL aliquot, in a Kjeldahl flask, with 8 mL of 40% NaOH and connected to the micro Kjeldahl distillation apparatus. Finally, the distillation product was collected in an Erlenmeyer flask containing 10 mL of the indicator/boric acid mixture and determined by titration with 0.01N HCl (SEMARNAT 2002b). Soil pH was measured in a 1:5 suspension of soil in water, using a combined glass electrode (ISO 2005). The extraction method with 0.5 M $NaHCO_3$ was used to estimate available P; 2.5 g of soil was extracted with 50 mL of 0.5 N $NaHCO_3$, filtered. Then, 10 mL of the previous solution was added to a mixture of 5 mL of reducing solution containing ammonium molybdate, ascorbic acid, and a small amount of ammonium potassium tartrate. The blue color intensity was measured spectrophotometrically at a wavelength of 882 nm (Olsen et al. 1954). Heavy metal concentrations in soils were determined by the acid digestion method with H_2O_2 and H_2SO_4 (Wolf 1982) using atomic emission spectrometry (Agilent 55B AA).

Plant analysis

Creole corn was planted in August and harvested at maturity in December. In each study site, total dry matter produced and kernel production per hectare was calculated. Harvesting was carried out manually when all leaves and cobs were completely dry. Before harvesting, ten corn plants were sampled randomly and their heights were measured from sites with biosolids-treated and control soils. Also, the roots, stems, leaves, flowers, and kernels of 10 plants were cleaned with distilled water and then dried at 170 °C for at least two days in an oven until total dehydration. Later, each part was milled to measure heavy metal concentrations by atomic emission spectrometry (Agilent 55B AA) while previously processed by acid digestion using H_2O_2 and H_2SO_4 (Wolf 1982). Analytical precision was controlled by repeating the analysis of individual samples three times until it was satisfactory (relative standard deviation <5%).

Statistical analysis

The arithmetic means and standard deviation of each physicochemical property and metals concentration was obtained for soils with biosolids and without treatment in the four sampling zones. Additionally, an ANOVA test ($p<0.05$) was performed to determine if the application of biosolids statistically modified physicochemical properties and metals content. All the statistical analyses were performed in R.

Enrichment factor in plants

The enrichment factor (EF) was calculated to determine the degree of soil contamination and accumulation of heavy metals in the different parts of the plants grown in soils with biosolids (i.e. treated) compared to the soil and plants grown in the control sites; values greater than one indicated site contamination (Kisku et al. 2000; Gupta et al. 2008; Embrandiri et al. 2016).

$$EF = \frac{\text{Concentration of metals in plant parts (or soil)in treated}}{\text{Concentration of metals in plant parts (or soil) in control}}$$

Results and discussion

Sewage sludge properties

Table 1 shows the results of the analysis of biosolids applied on soils and the established limits by different legislations. The characteristics of the biosolids show that most of their components were within the established parameters.

Table 1 Properties of sewage sludge applied in agricultural soils and reference values

	Values	Limits by different regulations		
Parameter	**Applied Sludge in soils**	**SEMARNAT** 2002a	**CEC** 1986	**USEPA** 1994
pH	7.2			
% Organic matter	40			
% Ashes	60			
% Nitrogen	1.29			
Metals (mg/kg)				
As	-	-	-	75
Cd	10	39-85	20-40	85
Cr	102	1200-3000	-	3000
Cu	200	1500-4300	1000-1750	4300
Pb	300	300-840	750-1200	840
Hg	-	-	-	57
Mo	-	-	-	75
Ni	110	420	300-400	420
Se	-	-	-	100
Zn	800	2800-7500	2500-4000	7500
Pathogens				
E. coli	0	<1000 MPN	-	<1000 MPN
Salmonella	0	<3 MPN	-	<3 MPN/4 g
Helminth viable eggs	0	<1/g	-	< 1/4 g

The organic matter content was significant, which is one of the reasons these materials are essential for agricultural use (Singh and Agrawal 2008). The pH values do not create restrictions for its use since nutrients such as phosphorus and some microelements are available to plants (Castro and Gómez 2001). The ash content was high, similar to other concentrations reported before (Fan et al. 2020). The chemical characteristics of the biosolids used at the test sites were similar to those of biosolids reported in other studies (Vieira et al. 2005; Rigby et al. 2016). The results revealed that the sludge was free of pathogens such as bacteria and helminth eggs. According to the results obtained and compared with the Mexican norm, the biosolids analyzed were suitable for urban uses with direct public contact during the application, forestry, soil improvement, and agricultural uses.

Properties of amended soils

The results of the soil analyses appear in Table 2. In the case of soil size particles, few differences were detected, but the texture remains loam. Some differences in pH were observed; in control soils pH was 7.0 while the soil conditioned with biosolids presented a moderately acidic pH of 6.7. This slight decrease in pH may be due to the formation of organic acids due to the addition of organic matter to the soil (Garrido-Hoyos et al. 2005). The cation exchange capacity was not modified significantly with the application of biosolids. However, soil bases increased for potassium from 5.10 to 7.87 Cmol (+) kg^{-1}, magnesium from 8.83 to 51.2 Cmol (+) kg^{-1}; sodium increased from 4.28 to 15.81 Cmol (+) kg^{-1}, calcium from 111.0 to 325.5 Cmol (+) kg^{-1} from control soils to treated soils, respectively. Also, it was observed that electrical conductivity increased from 1.22 to 6.03 µs/cm^{3}, which usually occurs due to the application of biosolids (Lloret et al. 2016).The percentage of organic matter increased from 3.39 to 16.7 in the treated soils, which is a significant parameter since it has been observed that organic fertilizers increase the organic matter content and nutrient availability in soil (Eissa et al. 2018). Total nitrogen increased from 1.2 in the control soil to 3.75 in the treated soil; an increase in soil organic matter and total organic nitrogen through biosolids has also been found in previous studies (Kabirinejad and Hoodaji 2012). The amount of phosphorus in the untreated soil was 58.9 ppm and presented a considerable increase in treated soils to 156.5 ppm. Phosphorus is considered a crucial resource in food production and is feasible to obtain from sewage sludge (Santos et al. 2021). Sepúlveda-Varas et al. (2011) found that the over-application of biosolids (i.e. 1.4 years) increased the available phosphorus content by 180% compared to a biosolids-unamended inceptisol. The potassium content remained low in soils with and without treatment, with a slight increase in soils with biosolids. Thus, studied biosolids were not a significant source of potassium, which should be carefully monitored; because, after nitrogen and phosphorus, potassium (K) is the nutrient that most likely limits plant growth (Ketterings et al. 2008). Long-term use of biosolids can lead to a substantial increase of some elements and deficiency of others, in the case of potassium it tends to decrease, affecting corn growth (Zuba-Junio et al. 2012). The properties that showed statistically significant differences between soils were clay content, soil organic matter, total nitrogen, available phosphorus and Ca^{2+} content. Regarding Mg^{2+}, Na^{+} and K^{+}, an increase was observed when adding biosolids due to sewage sludge from municipal wastewater treatment is characterized by a high content of organic matter, N and P, but also from K^{+}, Ca^{2+} and Mg^{2+} (Vaca et al. 2011). The results of the analyses of metals contents in soils compared by ANOVA are shown in Table 3 and also the reference values established by Mexican and European regulations (CEC 1986; SEMARNAT 2007) as well as mean values of metals concentrations in soils of the world (Kabata-Pendias 2011). The concentration of Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn, in soils treated with biosolids increased because of the incorporation of the residues; however, the metal contents were within the limit values for soils for agricultural use. The used biosolids contained metals; some of them functioned as trace elements, others as contaminants, all depending on the concentration in which they were found.

Table 2 Physicochemical properties of post-harvest soils with sewage sludge amendment and control soils after harvesting * $p<0.05$

Parameter		**Amendment soils**		**Control soils**		**ANOVA**	
	Units	**Mean**	**SD**	**Mean**	**SD**	**F**	**p**
Sand	%	47.0	5.77	46.5	7.14	0.01	0.92
Silt	%	40.0	12.44	29.5	5.74	2.35	0.18
Clay	%	13.0	7.02	24	3.37	7.98	0.03*
Texture		Loam		Loam			
Cation exchangeable capacity	Cmol (+) kg-1	20.00	5.31	21.13	3.57	0.12	0.74
pH soil: water 1:2		6.7	0.22	7.0	0.05	4.84	0.07
Electric conductivity	μs/cm^3	6.03	8.32	1.22	0.73	1.32	0.29
Soil organic matter	%	16.7	9.32	3.39	0.86	7.42	0.03*
Total nitrogen	%	3.75	0.55	1.2	1.09	17.53	0.01*
Available P	ppm	156.50	13.77	58.9	27.0	41.54	0.00*
Na^+	Cmol (+) kg^{-1}	15.81	8.83	4.28	5.82	4.25	0.07
Mg^{2+}	Cmol (+) kg^{-1}	51.2	27.3	8.83	13.53	7.73	0.30
Ca^{2+}	Cmol (+) kg^{-1}	325.5	33.9	111.0	27.8	95.79	0.00*
K^+	Cmol (+) kg^{-1}	7.87	1.96	5.10	2.48	4.36	0.09

Table 3 Micronutrients and metals in the amended soils after harvest and reference values, * $p<0.05$

Parameter mg/kg	**Sludge-treated soil CEC 1986**	**Kabata-Pendias 2011**	**Amendment soils**		**Control soils**		**ANOVA**	
			(mg/kg) Mean	**SD**	**Mean**	**SD**	**F**	**p**
Cd	1-3	0.4	0.13	0.13	0.03	0.03	2.12	0.20
Cr	-	60	1.14	1.06	0.86	1.0	0.15	0.71
Cu	50-140	39	52.3	20.8	4.13	6.71	19.51	0.00*
Fe	-	-	52.0	20.5	11.05	0.915	15.99	0.01*
Mn	-	488	25.03	6.63	22.57	9.52	0.18	0.69
Ni	30-75	29	52.8	25.8	5.21	0.841	13.63	0.01*
Pb	50-300	27	17.22	5.63	0.350	0.47	35.63	0.00*
Zn	150-300	70	81.5	25.1	5.45	6.52	34.45	0.00*

However, the results showed that their contents were low for those toxic elements. Heavy metals are more bioavailable for plant uptake at lower pH levels, and several researchers have demonstrated that metal sorption by soils increases with increasing pH values (Singh et al. 2011). This work observed that pH did not decrease considerably; therefore, pH would not significantly condition the release of heavy metals.

Organic matter also has a crucial role in protecting plants and the environment from metals (Kwiatkowska-Malina 2017) due to its high cation exchange capacity (CEC), and the ability to form simple and chelate compounds with heavy metals (Kinniburgh et al. 1999). Therefore, biosolids can be considered as feasible fertilizers since they also provide the plant with nitrogen and phosphorus.

Crop yield and heavy metals in maize plants

Overall, in this research, it was possible to observe the positive response of the vegetative growth of the plants to the application of biosolids to the soil. The application of biosolids increased the contents of essential macronutrients and micronutrients assimilable by plants. It has been observed that the application of biosolids positively stimulated growth in the height of the seedlings, with values like those developed in the soil treated with mineral fertilizer (Silva-Leal et al. 2021). In the same way, the high content of organic matter, nitrogen, and phosphorus make its agricultural application as an organic amendment or fertilizer a priority objective, within the concept of sustainable and ecological management of these materials. Figs 3 and 4 show an example of the obtained plants; it was evident that plants grown in soils with biosolids grew taller than those without biosolids.

Fig. 3 a) Plants of corn in the initial stage of growth in soils with biosolids, b) Plants of corn in the final stage of growth, c) Maize plant sampling

The amount of corn kernel produced in soil with biosolids exceeds the national average yield, set at 2.2 tons/ha (FIRA 2016); meanwhile, the production in control soils was lower (Table 4). Furthermore, in other studies, it has been observed that the application of biosolids yielded similar results to those of mineral fertilizers (Silva-Leal et al. 2021).

Table 5 shows data on metal concentrations in plants grown in soil with biosolids and control, it also shows approximate concentration limits of metals for the mature leaf tissue, which may differ widely for soil-plant systems (Kabata-Pendias 2011). None of the metals studied in plant tissues was above the reference values; however, an increase in the concentration of metals such as Cr, Fe, Mn, Pb and Zn was observed in plants grown in soils with biosolids. Monitoring the concentration of metals is crucial to ensure that applying biosolids to agricultural soils is safe, as heavy metals and metalloids can disturb human metabolism, contributing to morbidity and mortality (Rai et al. 2019).

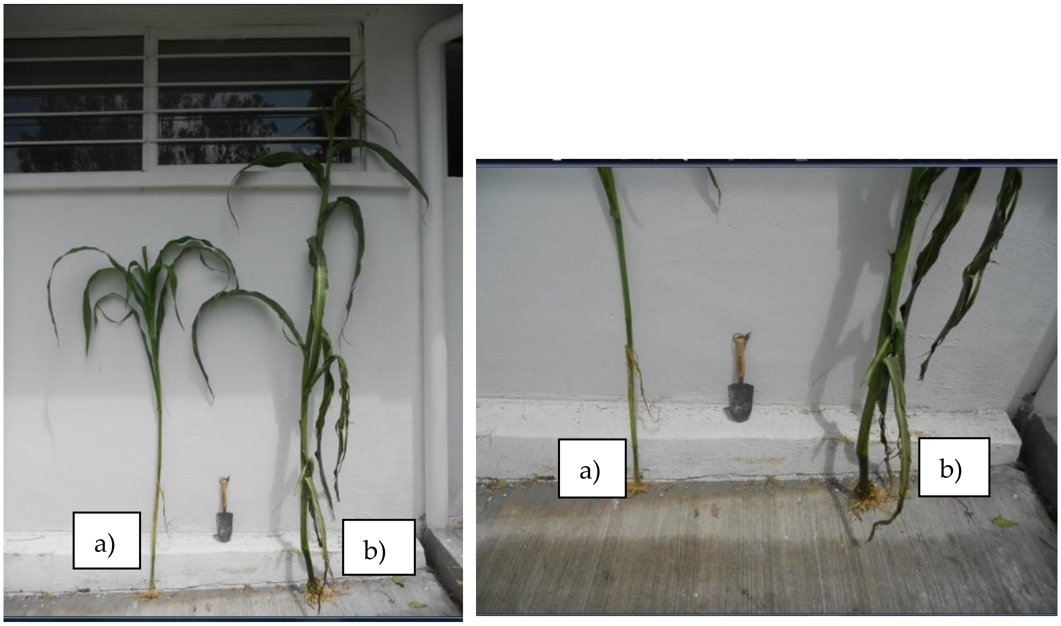

Fig. 3 a) Plants of corn from soils without biosolids, b) Plants of corn from soils with biosolids

Table 4 Mean values of corn yield,* p<0.05

Parameter	**Amended soils**		**Control soils**			
	Mean	**SD**	**Mean**	**SD**	**ANOVA**	**p**
Plant height (cm)	238.50	14.71	192.75	8.26	29.42	0.00*
Dry matter (kg/ha)	13136.7	1312	5944.4	851	86.42	0.00*
Corn kernel (kg/ha)	2785.6	251	1554.4	117.8	78.90	0.00*

Enrichment factor

Studied metals in plants and soils showed different EF; in general, high values could be observed. Table 6 shows enrichment in plants and soil. The enrichment values in the soils indicated a high accumulation capacity of all the studied metals, but it was higher for Pb, Zn and Cu. In the case of parts of plants, higher values were observed for Cd in flowers. In the case of Cr, the accumulation was substantial due to the high values of metal in the whole plant. For Cu, high accumulation was detected in roots, stems, leaves, and flowers. Iron was essentially accumulated in the kernels, root and stem. Mn enrichment values were high in the entire plant. Nickel EF was found higher at the root, followed by stem, leaves, and kernel. Lead accumulation was considerable in stems followed by leaves and lower values were observed in roots and kernel. Lastly, for Zn, accumulation was higher in the root, flower, kernel, and stem. This high enrichment (>1) indicates a higher availability and distribution of metals in the biosolids-treated soils, thus increasing the average heavy metal concentration in corn plants grown in the treated sites. Consequently, biosolids can be effectively recycled and used as soil amendments for crops because they contain several essential micro and macronutrients, however, they should only be used in agriculture if soil toxicity due to the accumulation of heavy metals can be avoided (Dad et al. 2018). The values of heavy metals in biosolids, soils and plants were found to be adequate according to reference values; however, according to the enrichment factor analysis, there is a high risk of contamination, leading to problems in the food chain and an increase of pollutants in the environment. Probably, the main problems related to the reuse of biosolids are the presence of heavy metals, organic contaminants, and pathogens in the sludge (Clarke and Smith 2011; Islam et al. 2013) and no less critical is the impact on biodiversity (Manzetti and van der Spoel 2015). As stated by Singh & Agrawal (2008), it is necessary to study the potential benefits and risks of land application of sewage sludge. Given the potential environmental impacts associated with their use, national and regional legislation standards and guidelines have been promulgated. However, it is probable that in each place where biosolids are generated, the properties of the obtained materials are different to those generated in another place; this implies that the possibilities of agricultural use might as well vary. Therefore, it is necessary to address as soon as possible the recognition of the physical, physicochemical, chemical, and biological properties of all the biosolids generated in the case of the city of Puebla, knowing that numerous tons of sewage sludge have been disposed of on agricultural soils (González Flores et al. 2014).

Conclusion

In this paper, we drew on the feasibility of applying biosolids as organic fertilizer in a corn cultivation crop in the field, finding that some physical and chem-

Table 5 Mean values and standard deviation of heavy metals content in maize plants and reference values according to Kabata-Pendias 2011

		Amended soils					Control soils				
Parameter mg/kg	**Kabata-Pendias 2011**	**Root**	**Stem**	**Leaves**	**Flower**	**Kernel**	**Root**	**Stem**	**Leaves**	**Flower**	**Kernel**
		Mean ± SD									
Cd	5-30	4.70±4.39	3.13±6.25	11.08±5.26	8.55±9.88	0.03±0.01	4.75±3.24	6.28±4.44	7.83±5.97	8.17±6.38	0.85±0.98
Cr	5-30	1.50±3.00	1.25±2.50	4.03±8.05	3.54±7.04	0.03±0.01	0.02±0.02	0.01±0.01	0.03±0.02	0.02±0.02	0.02±0.01
Cu	20-100	14.27±10.22	5.90±2.47	7.63±6.24	11.20±5.10	3.99±3.74	0.83±1.65	1.10±2.20	5.42±6.30	1.50±3.00	4.10±3.97
Fe	1000	126.9.0±9.27	6.38±4.55	14.44±2.24	15.88±4.63	7.77±6.72	104.38±6.26	6.08±2.69	16.90±56.20	17.96±6.00	17.87±10.73
Mn	400-1000	45.2±24.1	18.30±6.36	155.2±27.8	36.8±23.2	23.75±11.81	16.6±3.72	9.45±4.13	50.8±31.7	28.05±11.54	8.32±4.48
Ni	10-100	13.2±4.39	14.86±3.34	15.87±4.67	16.53±2.05	18.34±7.25	2.75±1.09	3.75±1.32	12.87±1.43	12.79±1.59	16.55±5.65
Pb	30-300	20.52±13.77	2.50±5.00	3.45±6.90	4.80±9.60	6.97±9.45	3.83±0.89	0.02±0.1	0.02±0.01	0.03±0.02	21.7±25.6
Zn	15	70.7±40.8	35.35±14.83	65.0±24.5	91.5±52.4	59.77±10.84	19.40±5.40	25.3±23.0	49.8±33.8	63.75±19.38	33.6±25.8

ical fertility characteristics improved with the incorporation of biosolids. Specifically, essential nutrients for growth increased considerably. Furthermore, although the metal content in the soil once treated with biosolids increased compared to the soils that had no treatment, they were below reference values, according to the regulations in Mexico and other countries. However, EF in plants and soil showed a considerable contamination grade due to the incorporated biosolids. In the same way, although the metal contents present in the corn plants obtained in soils treated with biosolids increased, the cultivated plants were taller and the corn yield increased significantly. However, it is necessary to carry out periodic evaluations to ensure that metals are not exceeding safe values in soils or crops and thus guarantee the safety of biosolids as soil fertilizers.

Table 6 The enrichment factor of metals in plants parts and soil

Parameter	Root	Stem	Leaves	Flower	Kernel	Soil
Cd	0.99	0.50	1.36	10.06	0.03	4.33
Cr	75.00	125.00	201.50	177.00	1.50	1.33
Cu	17.19	5.36	5.09	2.73	0.97	12.66
Fe	1.22	1.05	0.80	0.89	4.34	4.71
Mn	2.72	1.94	5.53	4.42	2.86	1.11
Ni	4.80	3.96	1.24	1.00	1.11	10.13
Pb	5.36	125.00	115.00	0.22	3.17	49.20
Zn	3.64	1.40	1.02	2.72	1.78	14.95

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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