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Abstract: The agricultural industry in Qatar is highly dependent on using soil enhancing materials due to challenging soil and climatic conditions. Hence, this work investigated the potential of industrial biosludge from the wastewater treatment plant (WWTP) of a Gas-to-Liquids (GTL) plant to enhance an arid soil compared to fertilizer and compost. A fodder crop, buffel grass (Cenchrus ciliaris), was grown in semi-controlled pots containing a typical Qatari agricultural soil and admixtures over a 12-month period. The treatments included soil plus five biosludge percentage contents: 0.75, 1.5, 3, 6 and 12%. These were compared with soil only, soil plus 20-20-20 NPK fertilizer and soil plus 3% compost controls. Analyses of soil physical and chemical properties, the resulting leachate, and plant growth characteristics were conducted at set periods. The results indicate that up to 3% biosludge content led to better plant growth compared to the controls, with the optimum at 1.5% biosludge content for all growth characteristics studied. Biosludge addition to soil increased the volume of different pore types, especially micropores, which enhanced water retention and influenced plant growth. Regression modelling identified leachate Si and Fe concentrations, and biomass K content as the most influential variables for fresh biomass weight, plant height and the number of tillers, respectively. Biosludge addition to the soil around the optimum level did not cause detrimental changes to the resulting leachate and plant biomass. The findings of this work could lead to minimization of biosludge landfilling and allow for savings in fertilizers and irrigation water in arid regions.

***Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Highlights

- Biosludge from wastewater of a gas-to-liquids plant improved arid soil behavior.
- Up to 3% biosludge content caused better grass growth than fertilizer and compost.
- The optimum level for all growth characteristics studied was 1.5% biosludge content.
- Biosludge addition increased micropores volume and enhanced soil water retention.
- The findings support waste utilization and fertilizer and irrigation water savings.

Graphical Abstract

Biosludge from wastewater of a gas-to-liquid (GTL) plant

Landfilling of biosludge

Unsustainable, minimize landfilling and recycle for forage production in arid soils

Mix ≤ 3% GTL biosludge with arid soil

Biosludge leads to better grass growth than fertilizer & compost, and enhances soil water retention

Encourages waste utilization, and fertilizer and irrigation water savings in arid regions

Recycling industrial biosludge for buffel grass production in Qatar: Impact on soil, leachate and plant characteristics

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Abstract

The agricultural industry in Qatar is highly dependent on using soil enhancing materials due to challenging soil and climatic conditions. Hence, this work investigated the potential of industrial biosludge from the wastewater treatment plant (WWTP) of a Gas-to-Liquids (GTL) plant to enhance an arid soil compared to fertilizer and compost. A fodder crop, buffel grass (*Cenchrus ciliaris*), was grown in semi-controlled pots containing a typical Qatari agricultural soil and admixtures over a 12-month period. The treatments included soil plus five biosludge percentage contents: 0.75, 1.5, 3, 6 and 12%. These were compared with soil only, soil plus 20-20-20 NPK fertilizer and soil plus 3% compost controls. Analyses of soil physical and chemical properties, the resulting leachate, and plant growth characteristics were conducted at set periods. The results

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indicate that up to 3% biosludge content led to better plant growth compared to the controls, with the optimum at 1.5% biosludge content for all growth characteristics studied. Biosludge addition to soil increased the volume of different pore types, especially micropores, which enhanced water retention and influenced plant growth. Regression modelling identified leachate Si and Fe concentrations, and biomass K content as the most influential variables for fresh biomass weight, plant height and the number of tillers, respectively. Biosludge addition to the soil around the optimum level did not cause detrimental changes to the resulting leachate and plant biomass. The findings of this work could lead to minimization of biosludge landfilling and allow for savings in fertilizers and irrigation water in arid regions.

Keywords: arid soil; fodder crop; gas-to-liquid biosludge; plant growth parameters; soil conditioner; soil pore structure.

1. Introduction

Soils in Qatar are predominantly carbonate-rich and typically with low clay content (Iyengar et al., 2012). The presence of high carbonate concentrations raises soil pH and reduces the availability of key plant nutrients such as nitrogen and phosphorus (Barber, 1995). Moreover, the low capacity of natural soils in Qatar to hold nutrients and water results in their poor fertility. Consequently, the agricultural industry in Qatar is highly dependent on using soil-enhancing materials including compost due to challenging soil and climatic conditions. In fact, Qatar ranks second in the world in terms of kilograms of fertilizer consumption per hectare of arable land (World Bank, 2016). Thus, it is important to consider relatively cheaper organic fertilizers such as biosludge as this can improve the organic content of the soil and supply nutrients, and lead to fertilizer application savings (Zhao and Liu, 2019).

Biosludge, also called biosolids, is the solid organic matter waste produced by a wastewater treatment plant during wastewater treatment. It is rich in plant macro- and micro-nutrients and organic matter. It is documented that crops very efficiently use the organic nitrogen and phosphorus found in biosludge since they are released slowly throughout the growing season. This allows for better nutrient absorption as the crop grows. It also reduces the potential of groundwater pollution by nitrogen and phosphorous – and the consequent eutrophication of ecosystems typically caused by over-fertilizing with chemically-formulated fertilizers (Lystek, 2015; Sullivan et al., 2015). However, the application of biosludge to land is limited by the concentrations of potential pollutants, such as trace metals that vary from one treatment plant to another (Kumpiene et al., 2016). The benefits and concerns of land application of biosludge have been reviewed by several authors (Laha and Parker, 2003; Lu et al., 2012; Kumar et al., 2017; Paramashivam et al., 2017).

This work utilized industrial biosludge from the wastewater treatment plant (WWTP) of a Gas-to-Liquids (GTL) plant located in Ras Laffan Industrial City, North of Doha. The annual production from the WWTP is approximately 6,000 ton of dry biosludge. The biosludge is mainly produced from industrial water, as sewage from the plant offices is not mixed with the GTL effluent. It is currently disposed of in landfills in Qatar. However, given the enormous fertilizer consumption in Qatar, recycling the industrial biosludge rather than the current management practice of landfilling would provide plant nutrients and improve soil properties.

Biosludge is reported to help in replenishment of soil organic matter, which helps promote aeration, improve soil structure and its ability to store moisture (Lystek, 2015; Wijesekara et al., 2017). Moreover, recycling the biosludge would lead to fertilizer savings, encourage waste utilization and reduce/eliminate landfilling costs.

This work uses a fodder crop, Buffel grass (*Cenchrus ciliaris, with Pennisetum ciliare as synonym*), as a sort of worst-case scenario to ascertain if biosludge utilization would cause the entry of undesirable components into the food chain. Buffel grass is known to be one of the most resilient grasses as it can grow in diverse environmental conditions and soil types similar to elephant grass (*Pennisetum purpureum*), which belongs to the same genus (Ayotamuno et al., 2006; Ayotamuno et al., 2009). Buffel grass requires good fertility, particularly with respect to N, P, and Ca. Total N levels should be over 0.1% (i.e. 1,000 mg kg^{-1}), while P levels should be over 10 mg kg^{-1} (Belgacem and Louhaichi, 2014). Buffel grass seed yield is reported to increase tenfold and more with nitrogen fertilizer typically at N rates of 100 – 200 kg ha^{-1}. The seeds require P for their establishment, hence, about 50 – 150 kg ha^{-1} superphosphate at sowing is recommended depending on soil type, fertility and rainfall. The grass is very sensitive to high levels of Al and Mn (Cook, 2007). It occurs naturally in various areas including neighbouring countries to Qatar such as Oman and Saudi Arabia (Cook et al., 2005).

To our knowledge, the impact of biosludge originating from a GTL plant's industrial water on crop yield, soil properties, and composition of leachate from the biosludge-amended soil is not well documented. Therefore, this study investigates the applicability of the aforementioned biosludge for a typical farming soil in Qatar. Further, there is dearth of literature on the use of biosludge on the arid soils of the Arabian Peninsula as most studies on biosludge amendment were conducted on arable soils. Studies have shown that the impacts of land application of biosludge depends on the biosludge composition, application rate, duration, and site-specific characteristics (e.g. climate, soils) (Jin et al., 2015; Garcia et al., 2017; Arduini et al., 2018). Some documented positive impacts of biosludge application compared to mineral fertilizers include increase in soil organic matter and porosity, higher gain yield and vegetative biomass, and positive effects on N, P, Fe and Mn concentrations in soil and plant. Moreover, a previous study in a semi-arid grassland showed that biosludge did not increase perennial forage grass species yield relative to the control in that ecosystem. Hence, an understanding of the plant community is essential (Wallace et al., 2016).

In light of the above, due to the arid climate in Qatar, this study was aimed at determining a suitable application rate for land application of the industrial biosludge. It also aimed to investigate the effect of the biosludge on buffel grass yield compared to typical fertilizer or compost amendment. The specific objectives of the study included investigating the optimum biosludge percentage for buffel grass production, the effect of the biosludge on soil properties especially nutrient and water holding capacity, and potential risks to groundwater. The study also sought to investigate possible uptake of undesirable components by the plant biomass at unacceptable levels.

2. Experimental methodology

2.1. Experimental set-up

Cylindrical pots, 92 cm long and 52 cm in diameter, were used for the experiments. Each pot is fitted with a valve connected at the bottom to permit leachate collection. The bottom layer of each pot was filled with 2 cm each of gravel and fine sand to avoid clogging and permit water movement and leachate collection as illustrated in Figure A1 in the Appendix. The bottom of the pot was also filled with glass-reinforced plastic at a slight tilt to create a slope of 6-7 degrees to direct the leachate to the collection valve. Eight treatments were considered with each treatment executed in three replicate pots arranged in a completely randomized design. Three treatments were used as controls, C1 being soil only, C2 for soil with fertilizer and C3 for soil plus 3% compost. The compost used was derived from green waste (yard, biogenous, and catering/kitchen waste) and Table B2 in the Appendix shows its chemical composition. The other five experimental treatments involved different percentage biosludge contents, namely, 0.75, 1.5, 3, 6 and 12% for treatments, E1 – E5, respectively. The pots were filled with samples of a typical Qatari arid soil used for farming and mixtures of soil with the aforementioned treatments. The particle size distribution and chemical characterization of the soil is shown subsequently (see Figure A2 and Table B3 in the Appendix). The soil was obtained from the research experimental farm of the Agricultural Department of Qatar Ministry of Municipality and Environment (MME) at Rawdat Al-Faras, Al Khor.

A commercially available 20-20-20 NPK fertilizer was used together with Urea in control treatment, C2. It was applied at 100 kg ha^{-1} for the NPK fertilizer and 75 kg ha^{-1} for Urea, which translates to 2.12 g and 1.59 g per pot for NPK and Urea, respectively. The fertilizer was applied in three doses at 2, 12 and 24 weeks after planting. A commercially available compost was used in control treatment, C3. The type and application rate of the fertilizer and compost corresponded to those typically used in the MME experimental farm in Qatar. The industrial biosludge used was obtained from Qatar Shell Research & Technology Center (QSRTC) and it had 90 – 95% dry solids. The chemical composition of the materials used is shown subsequently. The pots initially had overhead netting (see Figure A1c), which were removed after 10 weeks once the plants were established.

2.2. Sowing and irrigation

The pots were first irrigated to set the soil columns. Thereafter, buffel grass seeds were sowed at 1 cm depth at 10 locations for each pot. Irrigation was then applied to each pot manually every 3d during the winter and daily during the summer. The water application rate was based on the irrigation requirements of buffel grass for different months in line with the normal irrigation practice of the Qatar MME. The annual average irrigation requirement for buffel grass was taken as 1.36 mm/d with the lowest being 0.65 mm/d in January and the highest 2.8 mm/d in July. The characteristics of the irrigation water used are detailed in Table B1 in the Appendix.

2.3 Sample collection

Soil samples were collected from the pots for analysis using a tube sampler (auger) at the initial stage before seed sowing and at the final growth stage (i.e. after 12 months). Spatial variability of selected parameters was evaluated at the final-growth stage by collecting soil samples from the top (top 20 cm depth) and bottom (remaining depth) portions of the pots. Plant samples were collected for analysis after each cut (harvest). All pots were checked for leachate formation every

2 – 4 weeks. The entire volume of leachate drainable via the collection valve of a given pot was collected in clean glass bottles when the leachates formed. Consequently, the leachate formation and collection period lasted much longer than the plant-growth study period.

2.4 Analytical methods

A series of analyses were conducted on the soil, soil-biosludge, soil-compost, plant and leachate samples. For simplicity, planting materials containing soil and admixtures are referred to as soil in this section. The analytical methods are briefly described as follows.

The particle size distribution of the soil used was determined by merging together laser diffraction data for particles < 2 mm and sieve data for > 2 mm particles. A Beckman Coulter (Model LS 13 320) laser diffraction particle size analyser (LD-PSA), which measures across a range of 0.04 – 2000 microns in a single analysis, was employed for the analysis. Details of the laser diffraction technique are provided elsewhere (Xu, 2001). A ZSX-Primus II X-ray fluorescence (XRF) spectrometer (*Rigaku Corporation*, Tokyo, Japan) was employed for semi-quantitative analysis of the initial elemental composition of the soil samples. This identified all elements of the periodic table present in the soil from boron (B) to uranium (U). The absolute concentration of selected elements was determined using an iCAP 6000 Series ICP-OES (*Thermo Scientific*, USA) after digestion in nitric acid at the initial and final growth stages. The porosity and pore size distribution, which affect water flow through porous media (Kogbara et al., 2014), were determined by nuclear magnetic resonance (NMR) using a 2 MHz NMR rock core analyser with a 54 mm probe (*Magritek*, New Zealand). The T_2 relaxation data was determined on a water-saturated soil sample placed in a 20-ml cylindrical plastic container. The analysis was done using the Carr-Purcell-Meiboom-Gill (CPMG) sequence with 100 μs echo time, an inter-experimental delay time of 6,500 ms and 200 scans. The CPMG decay was analyzed using a Lawson and Hanson non-negative least square fit method in Prospa software (*Magritek*, New Zealand). The software also outputs the T_2 log-mean, which is a proxy for the mean pore size. Details of the technique employed are provided in Kogbara et al. (2015).

Syringe cartridge filters (0.45 micron) were used to filter leachate samples to eliminate solid particles before analysis of the leachates. The pH and conductivity of leachate samples were measured using a Mettler Toledo SevenMulti dual (conductivity/pH) meter. The chemical oxygen demand (COD) was determined by the closed reflux colorimetric method following APHA 5220D (Rice et al., 2017). An 850 Professional ion chromatography (IC, *Metrohm*, Switzerland) was used for analysis of key anions (NO_3^-, PO_4^{3-} and SO_4^{2-}) in line with ASTM D 4327 (ASTM, 2003). The total nitrogen (TN) content of the leachate samples was determined using a TOC-L series total organic carbon analyzer (*Shimadzu*, Japan) in line with APHA 5310B (Rice et al., 2017). Analysis of metals in leachate samples was conducted using an iCAP 6000 Series ICP-OES (*Thermo Scientific*, USA) after dilution with a 2% nitric acid solution following ASTM UOP714 (ASTM, 2007).

The aboveground fresh weight biomass, plant height and the number of tillers were used to evaluate plant growth performance. Biomass determination entailed collecting samples from 10 plants using a stainless steel grass shear to snip plants at about 5 cm above ground level during each cut (Hedlund et al., 2003). The fresh biomass weight was then taken. Three cuts were carried out on the plants, 3, 6 and 7 months after planting. The plant height was determined by measuring the distance from the soil level to the terminal bud of the longest stem on a given plant (Barney et al., 1974). The number of main tillers was determined by counting them from three randomly selected plants. The elemental composition of the plants was determined on biomass from plant cuts that have been dried, ground and subjected to wet digestion with nitric acid. The analysis was carried out using an iCAP 6000 Series inductively coupled plasma-optical emission spectrometry (ICP-OES) (*Thermo Scientific*, USA).

2.5 Statistical analysis

Data presentation involved simple descriptive statistics such as mean and standard deviation. Analysis of variance (ANOVA) was used to compare the mean values of different parameters over time in different treatments. Significant means at 5% probability level were separated using the Duncan's multiple range test (DMRT). Multiple linear regression was carried out to determine properties that mostly influence plant growth performance using the best model method. The adjusted coefficient of determination (R^2) was chosen as criteria to determine the best model, alongside a minimum variable of 2 and maximum variables of 4 and 5. The aforementioned plant growth characteristics were used as the dependent variables. A number of factors affect plant growth performance. Hence, the average concentrations of elements abundant in the soil, leachate and plant biomass, the average soil total porosity and mean pore size, and the sand, silt and clay contents were used as explanatory variables. The analyses were carried out using XLSTAT v2017.3 software (*Addinsoft*, New York, USA). Models that resulted in the highest adjusted R^2 value of l (i.e. explains 100% of the variability of the dependent variable) with the lowest number of maximum variables were then chosen.

3. Results and discussion

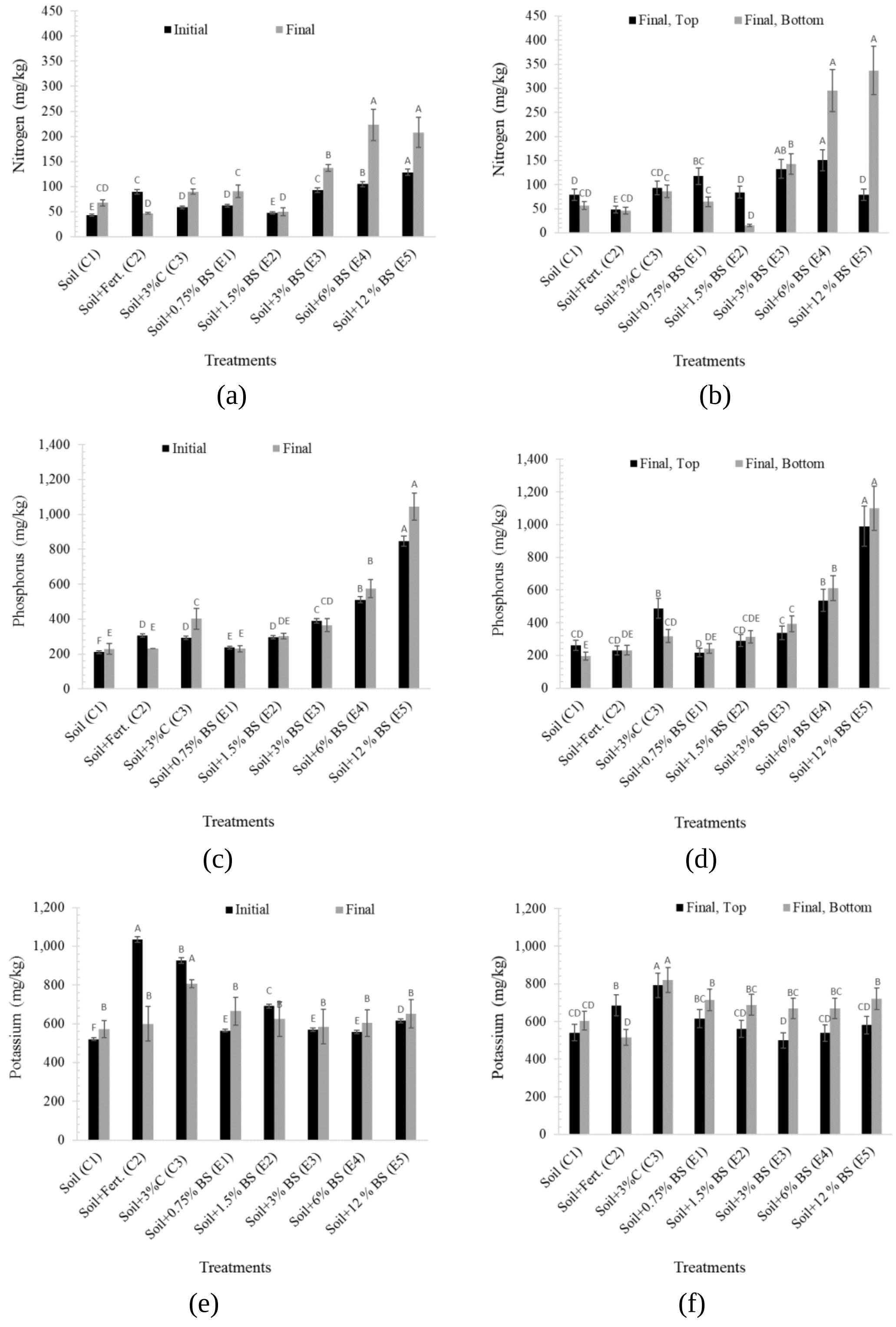
The performance of the different treatments between the initial (before planting) and final growth (after 12 months) stages are compared in this section. Letters are assigned above different columns in most of the graphs. The letters indicate significant differences between mean values based on the Duncan's multiple range test. Treatments not sharing a letter are significantly different from each other.

3.1. Particle size distribution

Figure A2 in the Appendix shows the particle size distribution of the different treatments as well as the biosludge and compost used. The majority of the particles of the soil in all treatments were mostly sand with 7 - 11% of particles within the silt and clay fractions (Figure A2a). The same applies to the biosludge and compost. The soil only treatment had 91.5% sand, 7% silt and 1.5% clay. This corresponds to a fine sand texture according to the United States Department of Agriculture (USDA) classification system. There were no significant differences ($p = 0.91$) in particle size distribution due to differences in biosludge or compost content at the initial stage. Since over 88% of particle sizes are less than 2 mm, only the LD-PSA data, which allows for better consistency, was considered at the final growth stage (Figure A2b). There were also no significant differences in particle size distribution ($p = 0.99$) between the different treatments at the final growth stage, as well as between the initial and final stages for a given treatment. However, all treatments showed 2 – 7 % increases in the sand fraction and decrease in the silt and clay fractions between the initial and final stages. This is because over 98% of the biosludge particles are within the sand fraction. As sand has more pore space between its particles compared to silt and clay, this can lead to an increase in porosity.

3.2. Analysis of elemental concentrations

The absolute concentrations of primary macronutrients in the soils of the different treatments at the initial and final growth stages, and in the top and bottom portions at the final stage are shown in Figure 1. The same is shown in Figure 2 for secondary macronutrients, Ca and Mg, and the micronutrient, Fe, which showed relatively higher concentration in the biosludge. The result of the semi-quantitative XRF analysis showing all elements initially present in the soils between B and U is shown in Table B2 in the Appendix. The absolute concentrations of all elements determined through ICP-OES are shown in Table B3. It can be seen from Table B3 that the biosludge is safe for land application as it contains lower concentrations of elements than the limits (< 300 mg kg^{-1} for each of Cr, Ni, Pb and Zn, < 100 mg kg^{-1} for Cu, and > 10,000 mg kg^{-1} for N) identified in the relevant Gulf Cooperation Council (GCC) guidelines (GSO, 1997). The concentrations are also lower than the ceiling limits (75 mg kg^{-1} for As, 3,000 mg kg^{-1} for Cr, 4,300 mg kg^{-1} for Cu, 420 mg kg^{-1} for Ni, 840 mg kg^{-1} for Pb, and 7,500 mg kg^{-1} for Zn) for the pollutant concentration category specified in the relevant United States Environmental Protection Agency (US EPA, 40 CFR Part 503) guidelines (US EPA, 1993).



(a)

(b)

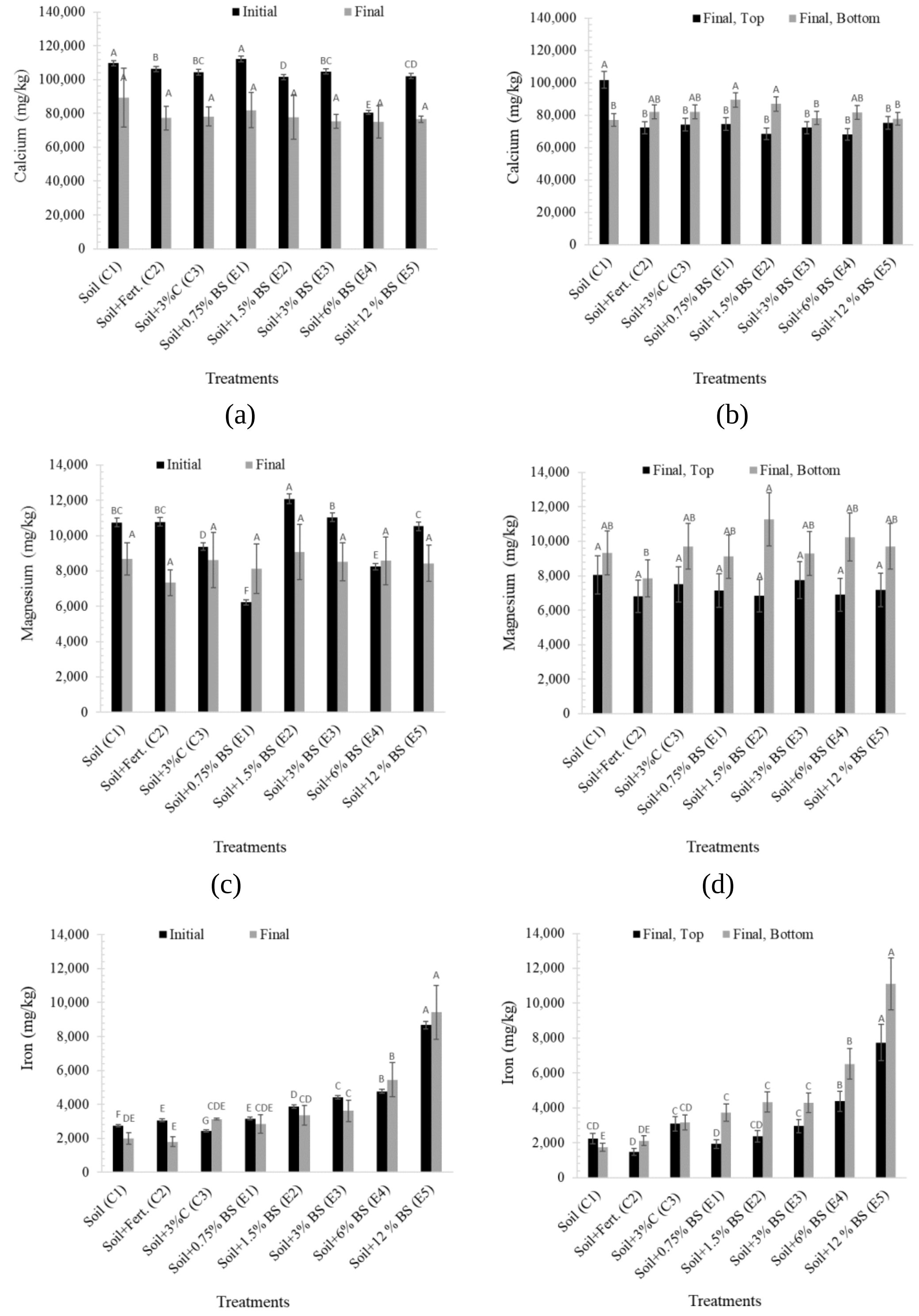
(c)

(d)

(e)

(f)

Figure 1. Concentrations of primary macronutrients, (a-b) N, (c-d) P, and (e-f) K at the initial and final growth stages, and in the top (top 20 cm) and bottom (remaining depth) layers of the soil at the final growth stage. *Note: Fert. - Fertilizer (NPK + Urea), C – Compost, BS - Biosludge. The error bars indicate the standard deviation of 3 replicates. Treatments not sharing a letter (from the Duncan's multiple range test) above the columns are significantly different from each other.*



(a) (b)

(c) (d)

(e) (f)

Figure 2. Amounts of secondary macronutrients, (a-b) Ca, and (c-d) Mg, and micronutrient, (e-f) Fe at the initial and final growth stages, and in the top (top 20 cm) and bottom (remaining depth) layers of the soil at the final growth stage. *Note: Fert. - Fertilizer (NPK + Urea), C – Compost, BS - Biosludge. The error bars indicate the standard deviation of 3 replicates. Treatments not sharing a letter (from the Duncan's multiple range test) above the columns are significantly different from each other.*

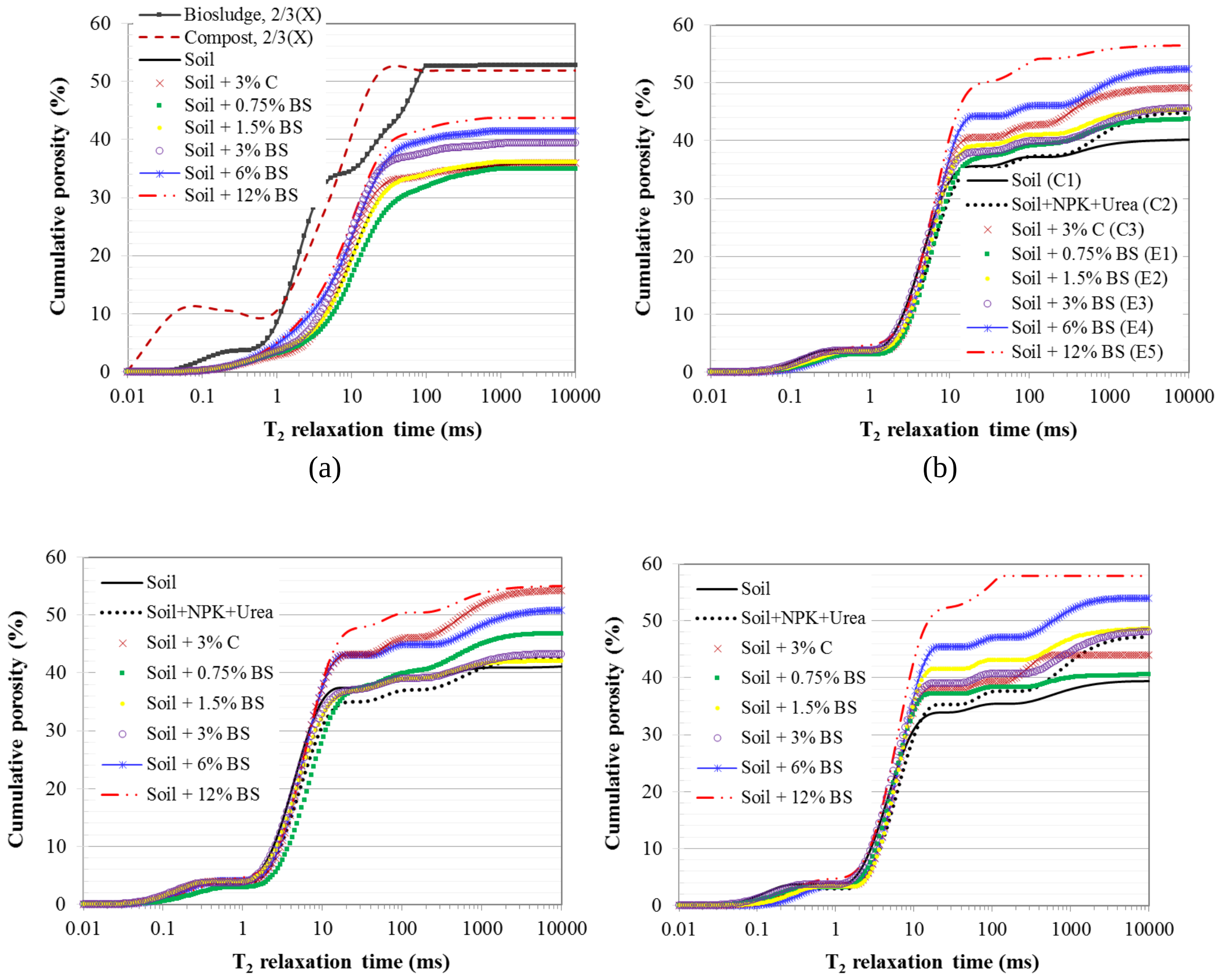
There was a general increase in the total N in almost all treatments between the initial and final growth stages, except the fertilizer treatment (C2), which showed a decrease in total N. This corroborates reports on quick loss of nutrients from soils with inorganic fertilizers. In contrast, organic fertilizers such as compost and biosludge slowly release nutrients (Sullivan et al., 2015). The fertilizer treatment also showed a similar distinctive nutrient decrease for P and particularly for K compared to other treatments (Figure 1c and 1e). The trend for P and K across the treatments was unlike that of N as both nutrients increased in some treatments and decreased in others. As regards the dynamics of the nutrients in soil layers, P and K tended to reside in the bottom than the top layer in all biosludge treatments (Figure 1d and 1f). This suggests that the biosludge was well mixed and distributed evenly in the soil and the plant's root system absorbed nutrients mainly in the top soil layer (Liu et al., 2008). The spatial variability trend for N was however not very clear, the same applies to the non-biosludge controls for P and K.

The macronutrients, Ca and Mg, generally decreased across the treatments between the initial and final stages (Figure 2a and 2c). Compounds of both elements are more or less water-soluble and could be easily leached from the soil. This is supported by the leachate data shown subsequently. The micronutrient, Fe, also decreased in most treatments but showed increases in the compost control and higher (6 and 12%) biosludge treatments (Figure 2e). All three metallic elements generally tended to reside in the bottom than the top layer. This may be due to the movement of labile fractions of the elements towards plant roots where they are absorbed and some lost to the leachate solution (Hooda, 2010). The DMRT indicated that all three metals showed significant differences among treatments at the initial stage. However, at the final growth stage, only Fe showed significant differences between treatments similar to the primary nutrients, N, P and K.

3.3. Soil pore structure parameters

Figures 3 and 4 show the data for the pore structure parameters: porosity and pore size distribution considered. The NMR T_2 distribution is used as a proxy for the pore size distribution without conversion to actual pore sizes. This is in line with the common practice especially as relaxation times are affected by paramagnetic species such as Fe, which showed high amounts in the soils (Kogbara et al., 2015). The T_2 relaxation times are related to pore sizes (diameter). Smaller pores have shorter times and larger pores have longer times. The peaks in the T_2 distribution graphs in Figure 4 represent pores of different sizes, while the amplitudes of the peaks denote the volumetric abundance of each pore type. The threshold T_2 relaxation time separating micropores and mesopores has been reported to fall between 10 and 30 ms for soil samples with various textures and organic matter content (Jaeger et al., 2009). Macroporosity corresponds to a T_2 relaxation time > 300 ms (Bayer et al., 2010), although these boundary conditions vary between publications.

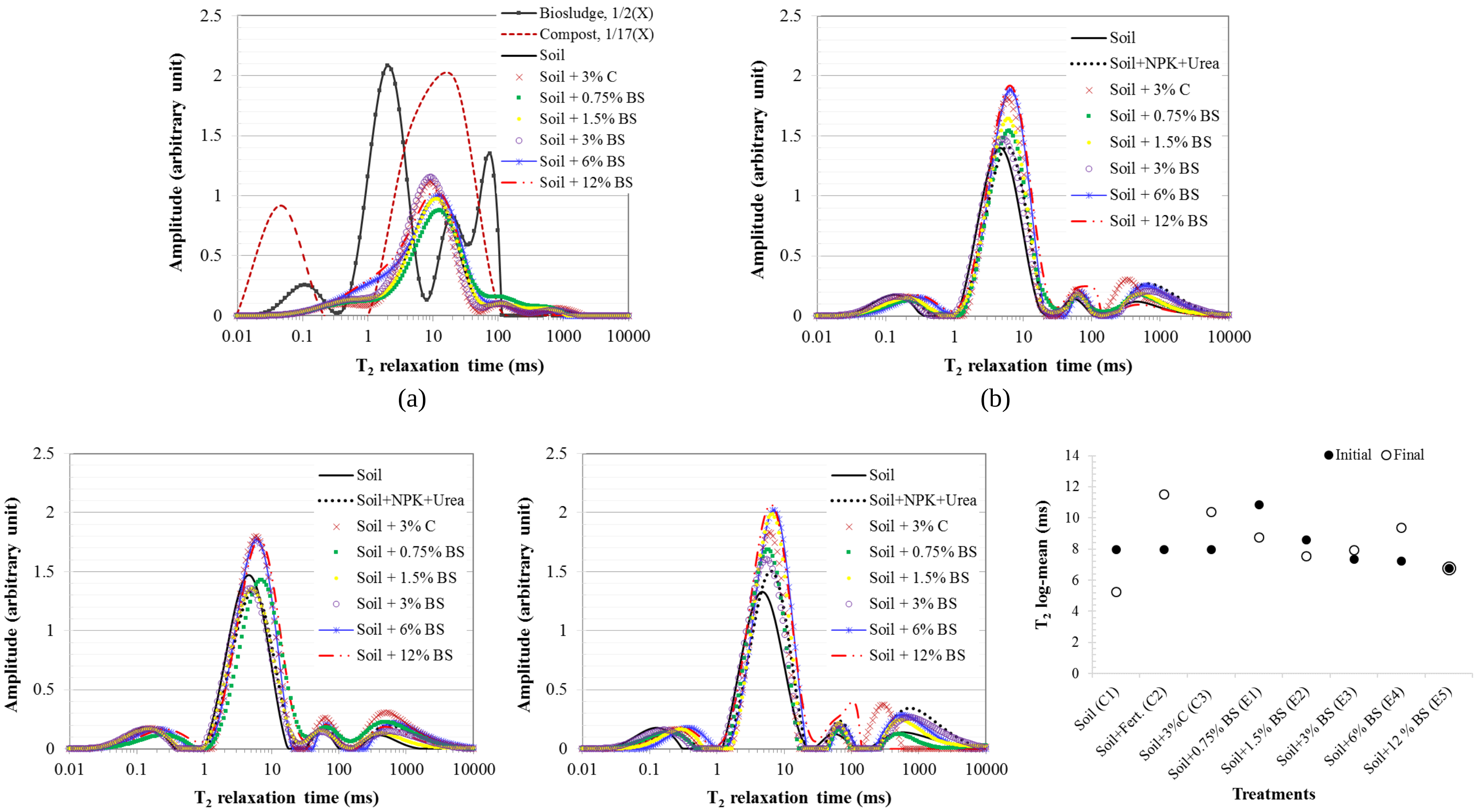
There was a noticeable increase in the cumulative (total) porosity with biosludge addition at the initial stage and between the initial and final growth stages for all treatments (Figure 3a and 3b). The increase in porosity was higher with biosludge addition, which corroborates the increase in the sand fraction of the soils observed in the particle size analysis in Section 3.1. The growth and decay of roots and the attendant reduction of root-soil contact could also increase porosity at the root-soil interface (Bodner et al., 2014). On average, the total porosities of the different treatments were similar within a narrow range (47 – 48%) in the top and bottom portions. Nevertheless, the total porosities and pore volumes were apparently higher in the bottom than in the top portion; especially with higher biosludge contents (see Figures 3c and 3d and 4c and 4d).



(a) (b)

(c) (d)

Figure 3. NMR cumulative porosity of the different treatments at the (a) initial- (before planting), and (b) final-growth stages, and in the (c) top, and (d) bottom layers at the final growth stage. *Note: BS – Biosludge, C – Compost. The data are the average of the different replicates in a given treatment. The data for biosludge and compost were reduced one and half times for easy plotting.*



(a)

(b)

(c)

(d)

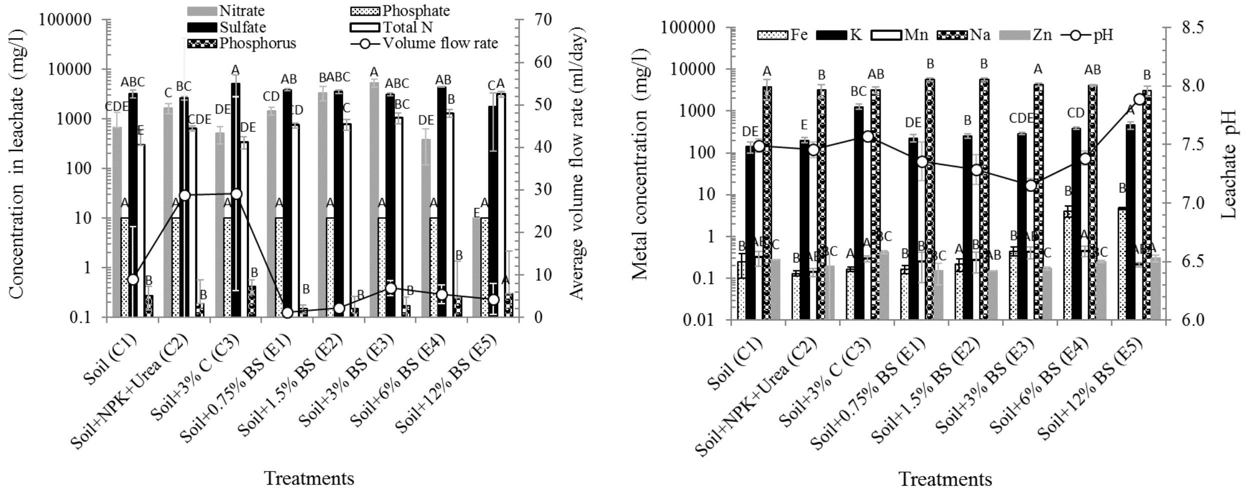
(e)

Figure 4. NMR T_2 (proxy for pore size) distribution of the different treatments at the (a) initial- (before planting) stage, (b) final growth stage; (c) top layer and (d) bottom layer at the final growth stage, and (e) T_2 log-mean (proxy for mean pore size) at the initial- and final-growth stages. *Note: BS – Biosludge, C – Compost. The initial T_2 distribution data for biosludge and compost were reduced two and seventeen times, respectively, to enable plotting on the same scale with the different treatments. The data are the averages of the different replicates in a given treatment.*

Biosludge and compost addition to soil also caused a noticeable increase in the microporosity before planting especially with the higher biosludge contents (Figure 4a) similar to the observations of a previous study (Arduini et al., 2018). The T_2 distributions show a considerable increase in the volumetric abundance of the different pore types between the initial and final growth stages. The increase was higher with micropores ($T_2 < 10 – 30$ ms) than other pore sizes and was enhanced by higher biosludge content. This probably led to a decrease in the mean pore size for the soil (C1) and most biosludge treatments, with the exception of the 3 and 6% biosludge contents, which showed a slight and high increase, respectively. In contrast, the fertilizer and compost controls, which showed the highest volumes of the largest macropores, had appreciable increases in the mean pore size over time (Figure 4e). Since micropores retain water required for plant growth (Pagliai and Vignozzi, 2006), the increase in the volume of micropores can improve water retention, which usually affects crop productivity in arid soils.

3.4. Elemental concentrations in leachates

The concentrations of selected chemical species in leachates from the different treatments are shown in Figure 5. The average volumetric flow rate derived as the ratio of the total volume of leachate from a given pot to the leachate collection period is shown on the secondary axis in Figure 5a. Similarly, the leachate pH is shown in Figure 5b. The selected chemical species in Figure 5 are primary nutrients and key elements that can possibly pollute groundwater since their concentrations are higher in biosludge than soil. All other leachate properties and elemental concentrations are shown in the Appendix (Table B5). The leachates showed higher average volumetric flow rate in the control treatments than in the biosludge treatments (Figure 5a). Interestingly, the fertilizer and compost controls, which showed an increase in mean pore size over time in the previous section, had the highest volumetric flow rates. The leachate flow rate in both treatments was over an order of magnitude higher than in the lower (0.75 and 1.5%) biosludge content treatments, which showed the least flow rates. These findings demonstrate that biosludge addition to an arid soil can help improve water retention through the aforementioned increase in micropore volume. This is supported by previous observations in which biosludge-amended soils showed increased water retention capacity relative to unamended controls (Salazar et al., 2012; Jin et al., 2015). The leachate pH generally fell within a narrow range of 7.2 – 7.9.



(a) (b)

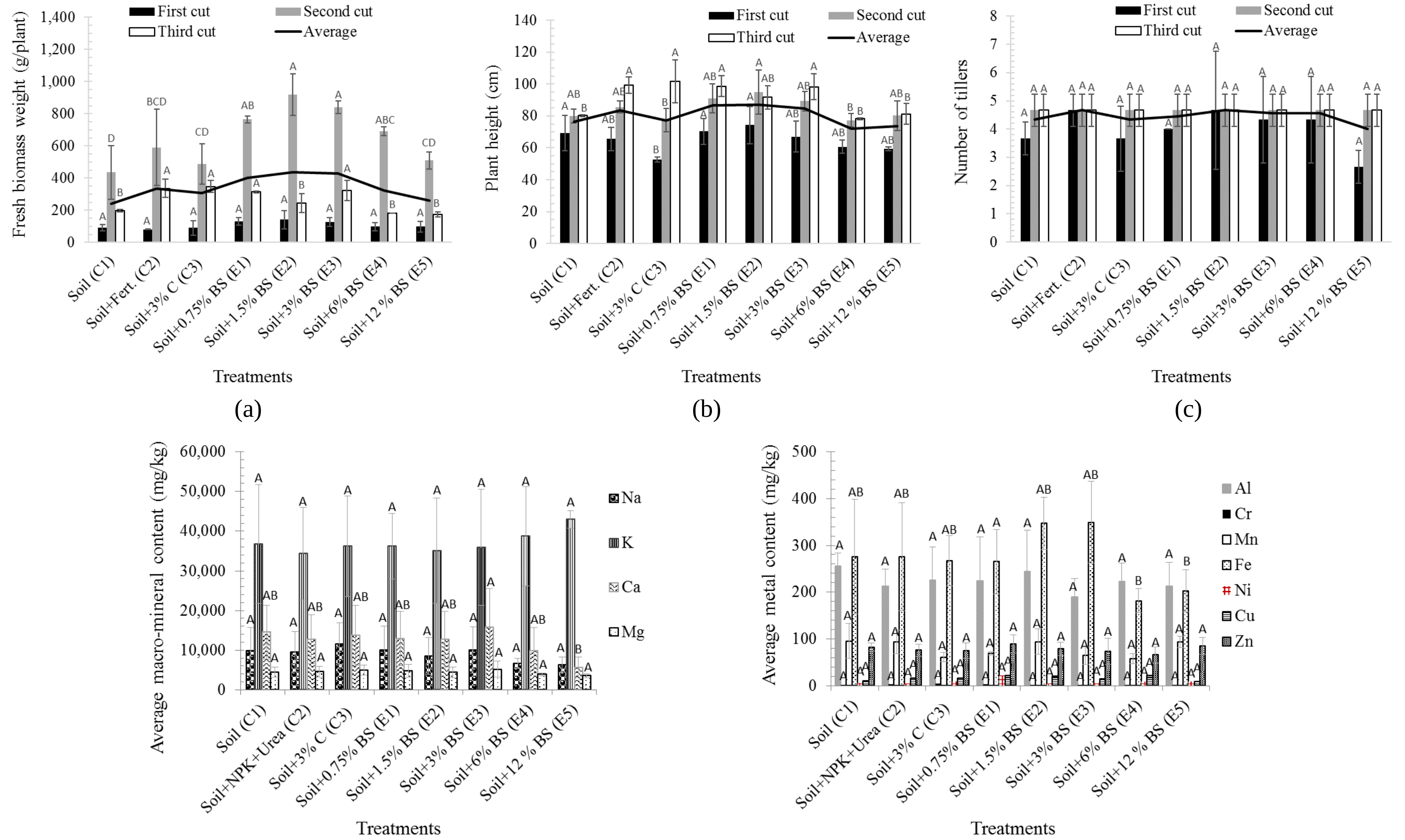
Figure 5. Leachate characteristics in terms of (a) volumetric flow rate and concentrations of anions and cations, and (d) leachate pH and concentrations of metals. *Note: BS – Biosludge, C – Compost.*

The nitrate concentration in the leachates was higher in ≤ 3% biosludge content treatments than in the controls, but lower in the higher biosludge content treatments. The total N concentration in the leachates however increased with increasing biosludge content and was higher in the biosludge treatments than the controls similar to the findings of Arduini et al. (2018). Sulfate leachability was random and higher in the biosludge treatments than in the soil and soil-fertilizer controls, but lower in the compost control. Leachate concentrations of PO_4^{3-} and P were generally low and similar in the different treatments except for the higher (6 and 12%) biosludge treatments that leached slightly higher P concentrations. The leachate concentrations of Fe, Mn and Zn were generally low (≤ 0.5 mg L^{-1}) across the different treatments except for the 6 and 12% biosludge content treatments, which showed Fe concentrations of 4 – 5 mg L^{-1}. In contrast, K and Na showed high concentrations in the leachates (Figure 5b). Potassium concentration increased with increasing biosludge content and was slightly higher than in the soil and soil-fertilizer controls similar to observations made in a previous study (Guo et al., 2012), but far lower than in the compost control. Sodium apparently decreased with increasing biosludge content and was higher than in the controls. Other species that showed higher leachate concentrations were Ca, Mg and Cl^- (see Appendix, Table B5). Nevertheless, the leachate concentrations of such species in the biosludge treatments were generally similar to those of the controls. Hence, the adverse effects of the aforementioned species in the biosludge on groundwater beyond what obtains with current practices is unlikely.

Furthermore, the COD values (2,730 – 15,316 mg L^{-1}) were quite high in treatments with 3, 6 and 12% biosludge contents (Appendix, Table B5) similar to those recorded in a previous study on biosludge from municipal solid waste (Batziaka et al., 2008). However, the 0.75 and 1.5% biosludge treatments had similar values to the controls, and even lesser than the compost control, which showed a relatively high COD value (1,426 mg L^{-1}). The high COD values from the treatments with higher organic matter content may lead to groundwater contamination. Hence, the choice of the application rate of the biosludge on soils must be restricted to the lower biosludge percentage contents.

3.5. Plant growth performance characteristics

Figure 6 shows the plant growth characteristics and the biomass elemental content. The fertilizer control showed better performance than the soil and compost control for the three plant growth characteristics. Treatments with up to 3% biosludge content were however better than all three controls especially for the fresh weight biomass and plant height. A similar observation was made in a previous study in which biosludge produced 18% higher vegetative biomass of barley compared to mineral fertilizer (Arduini et al., 2018). The fertilizer control compared favourably with the best biosludge treatment(s) for the number of tillers, although the DMRT indicated no significant differences between the different treatments. The 1.5% biosludge content treatment proved to be the optimum application level for all growth parameters. The DMRT indicated no significant differences in the biomass concentrations of macro-minerals and metals among the different treatments. Nevertheless, the biomass concentration of K apparently increased with increasing biosludge content similar to the findings of Kabirinejad and Hoodaji (2012) for *Zea mays* in sewage-sludge-amended soil. The biomass concentrations of all metals were within levels found in grasses (Kabata-Pendias and Mukherjee, 2007).



(a) (b) (c)

(d) (e)

Figure 6. Plant characteristics of the different treatments over time in terms of the (a) aboveground fresh biomass weight, (b) plant height, (c) number of tillers, (d) average content of macro-minerals, and (e) average content of metals. *Note: BS – Biosludge, C – Compost, Fert. – Fertilizer (NPK + Urea). The metal concentrations in (d) and (e) are the means and standard deviations of the first, second and third cuts of the plants.*

The details of the regression modeling are shown in Table B6 in the Appendix. Four parameters were sufficient to explain 100% of the variability of each of the plant growth characteristics as shown in Equations 1 – 3 of the models underneath Table B6. The variability of the fresh biomass weight was explained by the soil N content and leachate concentrations of Cl^-, NO_3^- and Si. The plant height was explained by the mean pore size, the leachate conductivity and leachate concentrations of SO_4^{2-} and Fe. Soil Ca content, leachate concentrations of K and Si, and biomass K concentration explained the variability of the number of tillers. The most influential variables for the plant growth characteristics were leachate Si and Fe concentrations for fresh biomass weight and plant height, respectively, and biomass K concentration for the number of tillers.

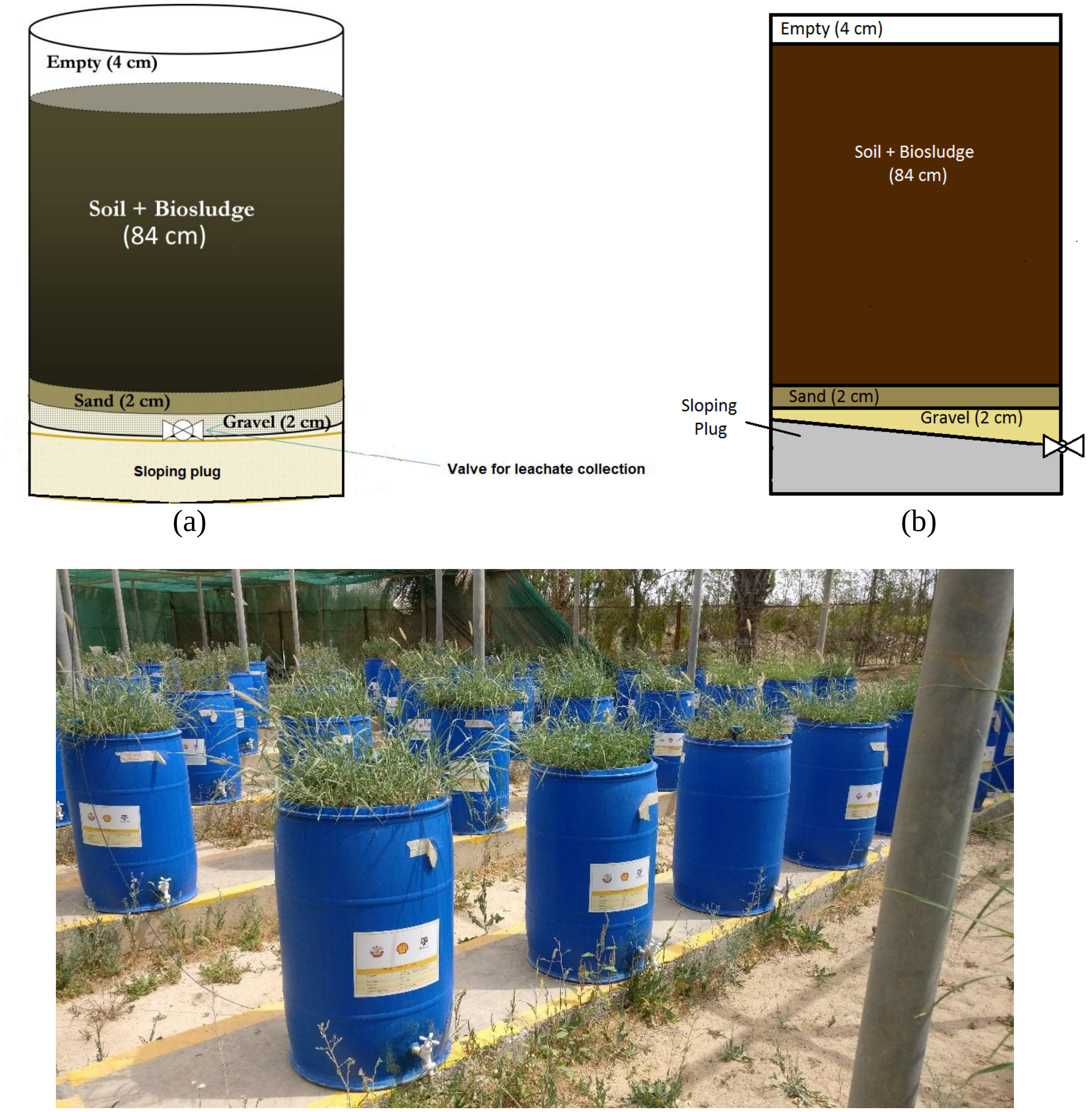
Silicon is one of the most abundant elements in the soil (see Table B2 in Appendix) and has been reported to be beneficial to plants in stressed environments (Tubaña and Heckman, 2015). Thus, the amount of Si leaching from the soil may affect plant growth and biomass production in arid climates with high-temperature stress. The soils had relatively high Fe concentration (up to 9,430 mg kg^{-1}), hence Fe concentration in the leachate increased with increasing biosludge content. Although belowground biomass (roots) was not analyzed in this work, the downward movement of Fe compounds during leaching could lead to their deposition on plant roots, which could absorb and impede the uptake of nutrients by the plant (Batty and Younger, 2003). Potassium significantly influences high temperature (and other abiotic) stress tolerance in plants by activating various processes such as photosynthesis, respiration, nutrient homeostasis, and increasing tissue water potentiality (Hasanuzzaman et al., 2018). Thus, biomass and leachate K concentration can possibly affect tillering in buffel grass in arid conditions. The influence of a key parameter such as mean pore size on water retention via volumetric increase of micropores was highlighted in Section 3.3.

4. Conclusions

The impact of land application of GTL biosludge on soil, leachate and plant characteristics were investigated in this work using semi-controlled pots containing different (0.75, 1.5, 3, 6 and 12%) biosludge contents and appropriate controls. The results of the study indicate that up to 3% biosludge content led to better plant growth characteristics, especially fresh biomass weight and plant height, compared to soil, soil-fertilizer and soil-compost controls. The 1.5% biosludge content treatment proved to be the optimum application level across all growth parameters. The higher biosludge (6 and 12%) content treatments generally showed similar performance to the soil and soil-compost controls but were outperformed by the soil-fertilizer control.

Biosludge addition to soil increased the volume of different pore types, especially the micropores, which in turn enhanced water retention compared to the controls and influenced plant growth. Regression modelling identified four variables that explained 100% of the variability of each of the plant growth characteristics studied. Leachate Si and Fe concentrations, and biomass K content were the most influential variables that affected fresh biomass weight, plant height and the number of tillers, respectively. Biosludge addition to the soil around the optimum level did not cause detrimental changes to the resulting leachates and the plant biomass. Further studies on the impact of land application of GTL biosludge will involve lysimeter and field investigations. These will improve our understanding since pot experiments have limitations that enhances the effects of nutrients compared to field conditions. Ultimately, the findings of this work could lead to the minimization of biosludge landfilling and allow for savings in fertilizers and irrigation water in arid regions.

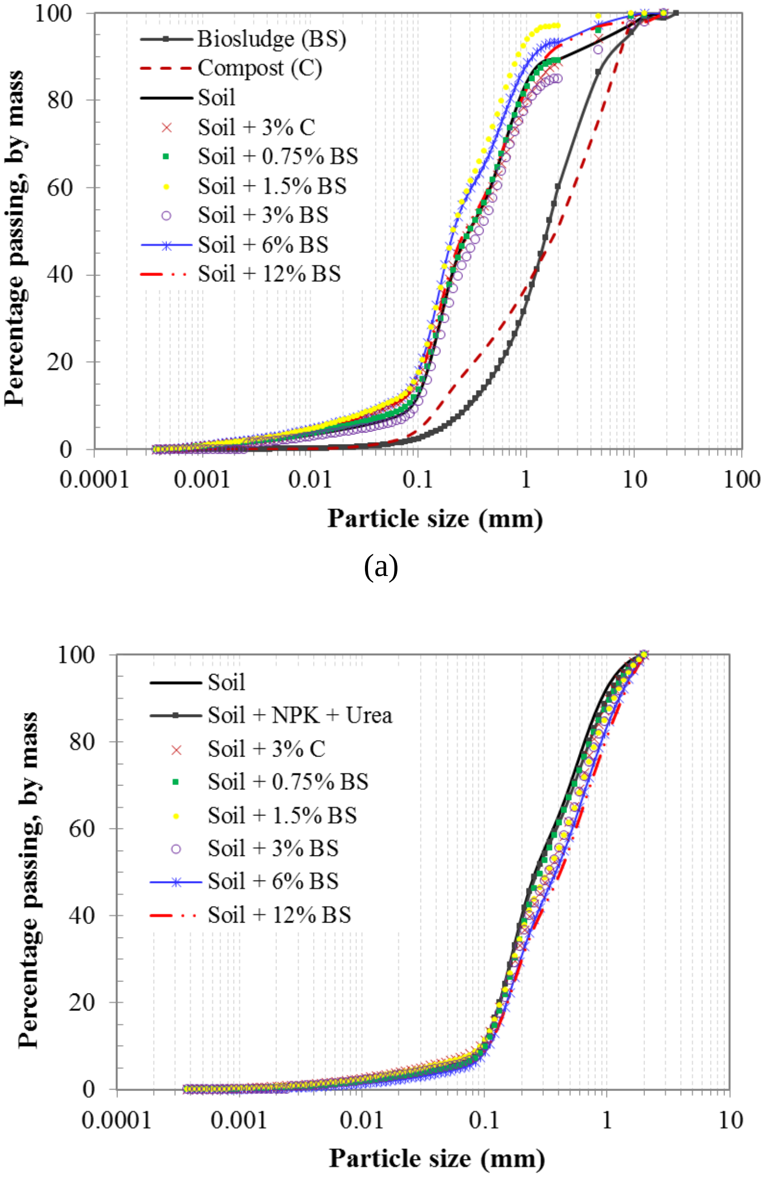
APPENDIX A – Additional figures



(a) (b)

(c)

Figure A1. Details of the pot experiments showing (a) schematic of the pot and materials inside, (b) side-view cross-section of the pot, and (c) photo of buffel grass grown in the pots.



(a)

(b)

Figure A2. Particle size distribution of the soil in the different treatments at the (a) initial stage (before planting), and (b) final growth stage for < 2 mm sizes.

APPENDIX B – Additional tables

Table B1. Characteristics of the water used for irrigation

Parameters			Anion's concentration (mg L^{-1})							Cation's concentration (mg L^{-1})			
pH	EC (dS/m)	TDS (ppm)	CO_3^{2-}	HCO_3^-	Br^-	Cl^-	SO_4^{2-}	PO_4^{3-}	NO_3^-	Ca	Mg	Na	K
7.6	4.7	3,008	Nil	288	14	730	1100	0.01	30.4	261	114	581	62

Table B2. Initial elemental composition of the biosludge, compost, soil, soil-biosludge and soil-compost mixtures determined by XRF

Element (%)	Treatment									
	BS	C	Soil (C1)	Soil + Fert. (C2)	Soil+3% C (C3)	Soil+0.75% BS (E1)	Soil+1.5% BS (E2)	Soil+3% BS (E3)	Soil+6% BS (E4)	Soil+12% BS (E5)
B	1.79	7.9	0.73	0.73	0.76	0.65	0.71	0.62	0.70	0.75
C	29.3	30	4.63	4.63	4.33	4.39	4.81	4.32	4.81	5.26
N	3.65	1.63	-	-	-	-	-	-	-	-
O	41.0	38.4	52.6	52.6	52.2	53.1	52.6	52.3	52.3	51.9
F	-	0.09	0.16	0.16	0.15	0.13	0.26	0.20	0.19	0.13
Na	0.64	1.79	0.60	0.60	0.73	0.72	0.72	0.71	0.67	0.70
Mg	0.60	1.50	2.97	2.97	2.71	2.67	2.7	2.72	2.80	2.75
Al	0.33	0.88	3.91	3.91	3.86	3.96	3.83	3.82	3.97	3.92
Si	0.75	5.48	17	17	18.4	18.3	17.9	18.5	16.8	16.5
P	1.26	1.04	0.06	0.06	0.09	0.06	0.07	0.07	0.11	0.17
S	2.22	0.78	0.09	0.09	0.11	0.10	0.16	0.12	0.21	0.31
Cl	0.33	2.27	0.04	0.04	0.14	0.05	0.07	0.05	0.08	0.09
K	0.28	3.16	0.82	0.82	1.01	0.91	0.89	0.87	0.87	0.86
Ca	4.49	4.65	14	14	13.3	12.7	12.9	13.2	13.3	12.9
Ti	0.01	0.05	0.32	0.32	0.278	0.29	0.29	0.27	0.30	0.27
Cr	0.02	0.01	0.11	0.11	0.09	0.1	0.09	0.10	0.10	0.09
Mn	0.18	0.02	0.05	0.05	0.04	0.05	0.05	0.05	0.06	0.06
Fe	12.9	0.39	1.8	1.8	1.69	1.75	1.84	1.88	2.64	3.18
Co	0.03	-	-	-	-	-	-	-	-	-
Ni	0.01	0.002	-	-	-	-	-	-	-	-
Cu	0.01	0.01	-	-	-	-	-	-	-	-
Zn	0.18	0.01	-	-	-	-	-	-	0.01	0.02
Sr	0.02	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Zr	0.001	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.02
Ba	-	-	0.06	0.06	0.06	0.05	0.05	0.06	0.06	0.06

Note: BS: Biosludge, C: Compost, Fert.: Fertilizer (NPK + Urea).

The XRF analysis was carried out on samples as received, independent of the sampling procedure. This analysis is semi-quantitative and provides information regarding the relative concentrations of elements in different samples. It mainly served to identify elements present in the soil for subsequent accurate determination of the absolute concentrations of selected elements, as shown in Tables B3 and B4.

Table B3. ICP-OES-determined absolute concentrations of elements in the biosludge, soil, soil-biosludge and soil-compost mixtures at the initial- and final-growth stages

Element (mg kg^{-1})	BS	Soil (C1)		Soil + Fert. (C2)		Soil+3% C (C3)		Soil+0.75% BS (E1)		Soil+1.5% BS (E2)		Soil+3% BS (E3)		Soil+6% BS (E4)		Soil+12% BS (E5)	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Al	753	1,869	1,523	2,111	1,395	1,677	1,756	2,086	2,018	2,278	1,986	1,960	1731	1,562	1,701	1,816	1,579
As	0.8	1.5	3.65	1.4	3.25	1.2	1.62	1.3	1.77	1.4	2.40	1.4	2.03	1.3	2.34	1.2	1.39
B	<0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2
Ba	40.4	35.7	29.25	32.1	36.2	33.3	32.25	30.0	30.25	38.8	33.05	34.0	31.95	32.5	30.35	33.2	28.25
Ca	49,773	109,662	89,488	106,230	77,225	104,328	78,212	112,110	81,970	101,452	77,857	104,820	75,332	80,538	74,956	102,065	76,590
Cd	<0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	<0.2	<0.2	0.2	<0.2	0.2
Co	1.4	0.4	0.2	0.6	0.2	0.2	0.25	1.3	0.6	1.4	1.05	3.4	1.4	4.7	3.85	10.3	12.94
Cr	6.5	9.9	0.2	11.2	0.2	9.7	4.55	11.4	5.35	13.1	5.45	12.4	3.85	12.8	6.9	15.3	8
Cu	50.9	9.9	3.03	7.1	4.18	6.0	7.10	6.4	6.73	7.4	10.21	9.2	9.58	8.3	6.53	9.7	10.75
Fe	21,129	2,730	1,988	3,065	1,794	2,443	3,128	3,166	2,831	3,879	3,351	4,420	3618	4,760	5,449	8,669	9,430
K	1,697	521	572.5	1,035	600	927	806	565	665	692	625	570	585	557	604.5	615	650.5
Mg	7,232	10,752	8,693	10,779	7,335	9,377	8,604	6,219	8,122	12,087	9,062	11,038	8,517	8,245	8,569	10,526	8,435
Mn	160	101	100	104	101	95	106.5	108	107	128	111.5	124	107	130	120.5	153	148
Mo	2.4	<0.2	0	<0.2	0	<0.2	0.1	<0.2	0.1	<0.2	0.325	1.8	0.325	4.0	4.45	9.3	12.14
N	55,400	43.12	67.64	89.88	46.90	58.46	89.82	61.80	90.93	47.22	49.66	92.94	137.58	104.92	222.81	128.62	207.99
Na	8,221	393	1,420	570	1,285	565	1,650	421	1,760	559	1,811	476	1,930	589	2,447	743	968
Ni	8.1	13.9	11.5	14.2	11.5	12.8	13.45	13.3	14.85	16.7	14.4	14.8	12.7	13.2	13.5	14.2	13.05
P	5,454	210	229	305	231	292	402.5	237	230	295	302	390	365	510	574	846	1045
Pb	<0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	1.3	0.2	<0.2	0.2	<0.2	0.2	4.5	0.2	1.2	0.2
Sr	145	162	187	162	167.5	164	206	163	218	178	178	167	170.5	156	169.5	157	175
V	12	15	14.5	16	12.5	14	14.55	15	15.85	17	14.9	16	14.35	14	14	15	14.5
Zn	192	32	52	30	49	29	47.55	32	36.45	36	64.35	45	63.85	58	77.3	90	129.8

The standard deviations between replicates were on average within 15% of the mean values. BS: Biosludge, C: Compost, Fert.: Fertilizer.

GCC standards for sewage fertilizer (dry sludge) (mg kg^{-1}) are: Cr (<300), Cu (<100), N (>10,000), Ni (<300), Pb (<300), Zn (<300).

US EPA 40 CFR Part 503 guideline for biosludge ceiling concentration limits (mg kg^{-1}) are: As (75), Cr (3,000), Cu (4,300), Ni (420), Pb (840) and Zn (7,500).

Table B4. Absolute concentrations of elements in the soil, soil-biosludge and soil-compost (C) mixtures in the top and bottom layers at the final growth stage as determined by ICP-OES

Element (mg kg^{-1})	Treatment															
	Soil (C1)		Soil + Fert. (C2)		Soil+3% C (C3)		Soil+0.75% BS (E1)		Soil+1.5% BS (E2)		Soil+3% BS (E3)		Soil+6% BS (E4)		Soil+12% BS (E5)	
	T	B	T	B	T	B	T	B	T	B	T	B	T	B	T	B
Al	1,474	1,571	1,305	1,484	1,371	2,140	1,445	2,590	1,291	2,681	1,335	2,126	1,176	2,226	1,177	1,980
As	2.9	4.4	1.9	4.6	2.2	1.044	2.3	1.25	3.5	1.292	3.4	0.654	3.3	1.38	2.1	0.675
B	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Ba	27.1	31.4	43.2	29.2	28.5	36	25.5	35	27.1	39	25.9	38	29.7	31	27.5	29
Ca	101,798	77,177	72,346	82,104	74,235	82,189	74,523	89,416	68,664	87,049	72,380	78,284	68,195	81,716	75,284	77,895
Cd	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2
Co	<0.2	<0.2	<0.2	<0.2	<0.2	0.3	<0.2	1.0	<0.2	1.9	<0.2	2.6	<0.2	7.5	11.88	14.0
Cr	<0.2	<0.2	<0.2	<0.2	<0.2	8.9	<0.2	10.5	<0.2	10.7	<0.2	7.5	<0.2	13.6	<0.2	15.8
Cu	3.88	2.18	4.41	3.94	5.09	9.1	5.96	7.5	8.12	12.3	3.76	15.4	5.16	7.9	6.60	14.9
Fe	2,230	1,746	1,478	2,109	3,097	3,158	1,926	3,735	2,373	4328	2,952	4,284	4,376	6,521	7,744	11,115
K	541	604	685	515	792	820	615	715	562	688	500	670	539	670	581	720
Mg	8,047	9,339	6,812	7,858	7,499	9,709	7,131	9,113	6,850	11,273	7,746	9,287	6,894	10,244	7,172	9,698
Mn	107	93	112	90	111	102	94	120	94	129	102	111	107	134	131	165
Mo	0	0	0	0	0	0.20	0	0.20	0	0.65	0	0.65	5.16	3.74	11	13.28
N	79.08	56.20	47.87	45.92	93.50	86.14	117.48	64.38	84.04	15.28	132.70	142.46	150.52	295.10	79.08	336.90
Na	1,138	1,702	1,689	881	2,124	1,175	1,582	1,937	1541	2,080	1,711	2,148	3,179	1,714	75	1,861
Ni	11	12	11	12	12	14.9	12	17.7	11	17.8	11	14.4	11	16.0	11	15.1
P	262	196	230	232	487	318	218	242	291	313	338	392	537	611	990	1,100
Pb	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Sr	199	175	163	172	223	189	227	209	169	187	164	177	159	180	178	172
V	14	15	12	13	14	15.1	14	17.7	12	17.8	13	15.7	12	16.0	13	16.0
Zn	65	39	52	46	64	31.1	46	26.9	87	41.7	59	68.7	91	63.6	143	116.6

BS: Biosludge, C: Compost, Fert.: Fertilizer *(NPK + Urea)*, T: Top, B: Bottom.

Table B5. Average values of leachate properties and concentrations of chemical species not included in Figure 5

Parameter	Treatment							
	Soil (C1)	Soil + Fert. (C2)	Soil+3% C (C3)	Soil+0.75% BS (E1)	Soil+1.5% BS (E2)	Soil+3% BS (E3)	Soil+6% BS (E4)	Soil+12% BS (E5)
Solvent properties								
Conductivity (mS/cm)	22.40	21.85	23.73	30.30	33.81	31.42	27.59	26.22
COD (mg L^{-1})	531.23	781.41	1,425.97	641.75	1,114.28	2,730.83	5,579.08	15,316.88
Anion (mg L^{-1}**)**								
F^-	10	10	10	10	10	10	10	10
Cl^-	6,303.53	5,585.72	5,810.93	8,626.44	8,640.93	7,898.16	6,852.66	4,988.74
Br^-	10	10	10	10	10	10	10	10
Cations (mg L^{-1}**)**								
Al	0.21	0.15	0.20	0.15	0.16	0.34	0.29	0.41
As	0.16	0.13	0.15	0.15	0.15	0.17	0.18	0.19
B	2.66	2.07	2.98	3.62	3.60	4.16	2.96	2.72
Ba	0.17	0.14	0.71	0.17	0.18	0.23	0.19	0.24
Ca	912.71	1,004.04	758.60	1,072.27	1,489.62	1,523.37	554.35	91.83
Cd	0.16	0.13	0.14	0.15	0.15	0.17	0.18	0.19
Co	0.16	0.13	0.14	0.15	0.15	0.24	0.33	0.52
Cr	0.16	0.13	0.15	0.16	0.16	0.20	0.20	0.73
Cu	0.16	0.13	0.15	0.15	0.14	0.17	0.19	0.23
Mg	1,131.50	886.57	912.43	1,355.41	1,491.22	1,370.29	1,318.48	794.01
Mo	0.16	0.14	0.14	0.18	0.29	0.29	0.75	0.65
Ni	0.15	0.13	0.41	0.18	0.29	0.61	1.54	1.90
Pb	0.16	0.13	0.29	0.15	0.15	0.17	0.18	0.19
Si	15.10	10.26	11.05	7.86	7.07	12.71	14.47	17.13
Sr	22.42	23.11	16.56	25.77	27.40	24.74	11.21	12.14
V	1.77	1.81	1.63	2.18	2.28	2.19	1.89	2.36

BS: Biosludge, C: Compost, Fert.: Fertilizer (NPK + Urea).

Table B6. Details of regression modeling outputs

Plant growth characteristics	Number of variables	Variable retained	MSE	R^2	Adjusted R^2	Akaike's AIC	Schwarz's SBC	F (Pr > F)
Fresh weight biomass	2	$\text{Conductivity}_{\text{leachate}}$ / K_{biomass}	687.395	0.911	0.875	54.503	54.742	
	3	Mean pore size / $\text{Conductivity}_{\text{leachate}}$ / $NO_3^-{}_{\text{leachate}}$	26.034	0.997	0.995	28.530	28.848	
	4	**N_{soil} / $Cl^-{}_{\text{leachate}}$ / $NO_3^-{}_{\text{leachate}}$ / Si_{leachate}**	**1.185**	**1.000**	**1.000**	**3.511**	**3.908**	**8,106.91 (< 0.0001)**
Plant height	2	Ca_{leachate} / Mn_{leachate}	5.415	0.892	0.849	15.753	15.992	
	3	Al_{soil} / Leachate volume / Sand content	0.106	0.998	0.997	-15.506	-15.188	
	4	**Mean pore size / $\text{Conductivity}_{\text{leachate}}$ / $SO_4^{2-}{}_{\text{leachate}}$ / Fe_{leachate}**	**0.002**	**1.000**	**1.000**	**-46.396**	**-45.998**	**27,173.76 (< 0.0001)**
Number of tillers	2	Fe_{leachate} / K_{biomass}	0.003	0.950	0.930	-43.099	-42.861	
	3	Ca_{soil} / K_{leachate} / K_{biomass}	0.000	0.997	0.994	-62.984	-62.667	
	4	**Ca_{soil} / K_{leachate} / Si_{leachate} / K_{biomass}**	**0.000**	**1.000**	**1.000**	**-90.946**	**-90.549**	**9,876.71 (< 0.0001)**

Note: The lines in bold font are for the best models based on the chosen selection criterion. The concentration of a chemical specie in the leachate/soil/biomass is indicated by the subscripts, leachate, soil and biomass after the chemical specie. MSE: Mean squared error, R^2: Coefficient of determination, AIC: Akaike information criterion, SBC: Schwarz's Bayesian Criterion, the lower the AIC and SBC criteria, the better the model quality in the set. F: F-statistic from the ANOVA for the plant growth characteristic, Pr > F: Significance probability. The Type III sum of squares indicated that in the best models, the most influential variables are Si_{leachate} for fresh biomass weight, Fe_{leachate} for plant height, and K_{biomass} for the number of tillers.

$$\text{Fresh Biomass weight} = 321.21 + 0.68\text{N}_{\text{Soil}} + 0.009\text{Cl}^{-}{}_{\text{leachate}} + 0.021NO_3^{-}{}_{\text{leachate}} - 15.1\text{Si}_{\text{leachate}} \qquad (1)$$

$$\text{Plant height} = 56.86 + 1.76\text{Mean pore size} + 0.75Conductivity_{\text{leachate}} - 0.003SO_4^{2-}{}_{\text{leachate}} - 2.19\text{Fe}_{\text{leachate}} \qquad (2)$$

$$\text{Number of tillers} = 8.97 - 0.000019\text{Ca}_{\text{Soil}} - 0.0002\text{K}_{\text{leachate}} + 0.0055\text{Si}_{\text{leachate}} - 0.00007\text{K}_{\text{biomass}} \qquad (3)$$

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