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Short-term residual effect of municipal sewage sludge on the soil properties and potato yield

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Abstract

Sewage sludge (SS) is one of the significant wastes of modern city lifestyle with environmental consequences. This study was conducted to determine the effect of the municipal sewage sludge on the potato plant's yield and nutrient elements and heavy metals content in a clay loam textured calcareous soil. The field treatment (corn-wheat-potato rotation) was implemented as fixed randomized blocks with 3 replications. The treatments were: control (without fertilizer), optimum fertilizer (OCF), 20, 40, 80, 100, and 120 ton ha^{-1} SS incorporation. The third-year results regarding the potato cultivation were presented. Results indicated that 4 ton ha^{-1} SS treatment resulted in a greater yield than the optimum fertilizer. The sewage sludge influenced the mineral nutrient composition of the leaves and the roots and the heavy metal concentrations in the plants were below the Turkish legal threshold values. Excessive application of SS had an inverse effect on the yield and reduced the essential nutrient concentrations of the leaves of the potato plants. This suggested that the residual effects of SS in the third year were considerable for either heavy metal concentrations or plant nutrients in the soil. Therefore, it can be concluded that a site-specific determination of the SS application rate is required to avoid potential deleterious effects of SS.

Introduction

The waste water treatment plants are significant infrastructure units for ensuring the public health in the modern city lifestyle and the number of the treatment plants is growing fast in the last decades in Turkey. Thus, sewage sludge which is the end product of these plants still has environmentally healthy and economically feasible disposal problems in the world and Turkey due to its harmful ingredients such as heavy metals (Tiruneh et al., 2014; Andreoli et al., 2007) and pathogenic and disease-causing microorganisms and other toxic compounds (Latare et al., 2014; Kotowska et al., 2012; Clarke et al., 2011). Application of sewage sludge to ag-lands, which may be a sought-after alternative for incineration method, is economical way of disposal as well as it has beneficial impacts on the soil ecosystem with some reservation (Snyman et al., 2000). For this reason, The European Union encourages the dilution of this potential environmental pollutant in the soil ecosystem to solve the problem (Kominko et al., 2018) by recycling-back it into the soil because the thermal methods are economically non-sustainable, limitation about CO_2 emissions, and accelerated nutrient cycling of organic compounds and nitrogen (Mathews & Tan, 2016). Alternatively, the SS biochar has being used for profiting its plant nutrient ingredients and for the recent years (de Figueiredo et al., 2020, 2021; Chagas et al., 2021; Fachini et al., 2021). The shortage in fertiliser resources and increasing global population leading food and fibre demand can result in alternative nutrient element sources such as SS with its current production which can meet as much as 20% of the phosphorus requirement of crop plants (http://p-rex.eu).

The recycling rate or agricultural use of SS was highly country dependent: it is 37% in the EU (EC, 2010), over 90% in Norway (Xu, 2014), about 60% in France, 57% in Belgium, as well as in Spain, UK, and Italy (EC, 2010; Wang, 2008). Whereas the regulations in Denmark, Germany, Sweden, and the Netherland are very strict about agricultural usage due to its contaminants. The characteristics and possible contaminants of SS are highly plant-dependent which is very much influenced by type and level of industrialisation, the lifestyle of the people in the hinterland of the plant, treatment technology, time of the year, etc. (Praspaliauskas & Pedisius, 2017). This nature of SS is the most significant restriction of it to safe and common usage in the ag-lands. However, their inorganic chemistry for any specific treatment plant would be similar and relatively low degree of variation at a specific period under certain treatment technology (Sharma et al., 2017; Suanon et al., 2017). Therefore, their chemistry and composition determine the potential usage of the sludge or disposal prerequisites (Praspaliauskas & Pedisius, 2017). The sewage sludge collected from non-industrial hinterlands can be recycled back to the agricultural lands more safely in terms of heavy metal contaminants and can be treated as valuable sources of plant nutrients and soil conditioner (Balanica et al., 2018; Sharma et al., 2017).

Due to high organic matter content, biosolids can improve/alter soil physico-chemical properties for example aggregate stability, bulk density, porosity, and water retention characteristics (Mujdeci et al., 2017; Wang et al., 2008) that affect nutrient balance in the soil (Brazauskiene et al., 2008; Wang et al., 2008). The incorporation of SS at differing rates promoted the growth performance parameters of broad bean (Eid et al., 2018), sugarcane (Nogueira et al., 2013), corn (Mahmoud et al., 2021), cowpea (Lopes et al., 2020) without exceeding the permitted heavy metal concentrations in soils. The sewage sludge applied at high rates increases the total heavy metal concentration in soils, however, the mobile fractions are more susceptible in coarse-textured than clay soils (Brazauskiene et al., 2008). Sewage sludge application followed by green manuring increased aboveground biomass and grain yield of corn in a mudflat soil where sludge amendment rates were detrimental for Cd and Ni concentrations in maize grain (Bai et al., 2017). This report suggested the sludge can be a remediation agent or initial fertility driver and/or soil conditioner for mudflat salt-soils or possibly salt-affected soils.

The main objectives of this study were: i) potential safely use of the biosolids, which were generated by the Wast Water Treatment Plant of İnegöl Organized Industrial Zone and which are brought into a state not harmful to the environment, in the agriculture within the context of agricultural use, ii) the determination of the fertilizer value and bio-soil regulating properties of the SS and their metallic and microbiological pollution factors, and iii) the investigation of the likely effects of the biosolids on the receiving environments.

Material and Method

Material

The domestic and urban SS or biosolids from the Treatment Plant of Inegöl Organized Industrial Zone, Bursa, Turkey was used as the organic material. Some chemical properties of the SS used in the experimental field are given in Table 1.

Table 1. Some chemical properties of sludge waste used in the field treatment

Parameters	Results	Parameters	Results
Moisture (%)	32.1	Total Fe (mg kg^{-1})	5523
Total nitrogen (%)	5.26	Total Ni (mg kg^{-1})	132
Organic matter (%)	57.9	Total Cr (mg kg^{-1})	227
Total potassium (%)	0.61	Total Pb (mg kg^{-1})	32.9
Total phosphorus (%)	1.42	Total Cd (mg kg^{-1})	2.00
pH (1/5)	6.9	Total Zn (mg kg^{-1})	225
EC (1/5) dS m^{-1}	4.15	Total Cu (mg kg^{-1})	360
		Total Mn (mg kg^{-1})	221

The data revealed that biosolids can be regarded as valuable nitrogen, phosphorus, and organic carbon source. The heavy metal concentrations of the biosolid are well in the safe range according to Turkish legislation for 'The Solid Waste Control Regulations'. This means the material can supply credible amounts of micronutrients towards treating micronutrient deficiency in calcareous soils, as the experimental soil. The pH of the biosolid has a slightly acidic nature and its salinity can be tolerated at typical application rates due to the richness of the SS in terms of ionic plant nutrients.

Method

The field trial was conducted in a fixed completely randomised block arrangement with three replications for three consecutive years. The treatments were: the control without any treatment (C), optimal chemical fertilisation (OCF, 120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}), 20, 40, 80, 100, and 120 Mg ha^{-1} SS applications. The experiment was set up in a farmer's field in Yenikent, Inegol, Turkey. The SS was only incorporated in the first year, then its residual effects were followed. The chemical fertilizations were practiced for each growing season in the cropping sequence. The parcel sizes were 3 x 5 m. The SS was evenly distributed on each plot and then immediately incorporated into 0-15 cm depth by utilizing a rototiller. Then, the corn-wheat-potatoes rotation had being practiced for three consecutive years. Here, the third-year results regarding the potato cultivation were presented. Niğde Potato: Native potato produced from Nahita potato seed is a potato type widely produced in the Niğde region. Nahita potato, which aims to expand to the countries of the world from the lands of Turkey, is typical with high yield potential. Its texture and chemical composition are suitable for frying and other consumption types. Niğde potato is a potato planted in the spring and grown at low temperatures. The in-row and between-row spaces were 35 cm and 70 cm, respectively.

Soil Sampling and Analysis

Before experimental set-up, composite soil samples from the experimental field were taken from 0-20 cm and 20-40 cm depths. A plot-based sampling was made after the harvest from both depths. Collected samples were transported to the laboratory in plastic bags and immediately air-dried and passed through a 2 mm mesh sieve for characterization (Kacar, 2012). The physical and chemical characterisation of the soil samples were performed by the following common procedures for calcareous soils given by Kacar (2012): total soluble salts (TSS) and pH were measured in saturation paste, calcium carbonate equivalent (CCE) was determined by a manometric method using Scheibler calcimeter, organic matter (%) was determined by wet oxidation method of modified Walkley-Black with $K_2Cr_2O_7$, plant available phosphorus was extracted by 0.5 M $NaHCO_3$ at pH 8.5 and colorimetrically determined, plant available potassium was extracted by molar ammonium acetate and determined by a flame photometer, plant available cationic microelements (Fe, Cu, Zn, and Mn) were extracted by 0.005 M DTPA + 0.01 M $CaCl_2$ + 0.1 M TEA at pH = 7.3 and the element concentrations of the extracts were determined by ICP-OES. For total element concentration determination, soil samples were wet-ashed (HNO_3 + HCl mixture, 3:1 V/V) and the digests were analysed for Ni, Cd, Pb, and Cr by AAS whereas total phosphorus (P) was colorimetrically measured by using a vanado-molybdate phosphoric yellow colour reagent.

Plant sampling

Youngest fully expanded leaf samples at the fourth and fifth on the main stem, counting down from the growth tip were taken from the mid-rows of each plot and immediately delivered to the laboratory in ice boxes. The possible contaminants were removed by successive washings with a dilute acid solution, tap water, and distilled water, respectively. Clean leaf samples were oven-dried to a constant weight at 65°C and homogenised by reducing the particle size below 0.5 mm. Scoops of 0.5 g leaf samples were acid digested (HNO_3:$HClO_4$ mixture, 4:1 V/V). Iron, Cu, Zn, Mn, Ni, Pb, Cd, and Cr concentrations of the digest were measured by AAS, and P concentrations were determined by a spectrophotometer (Kacar and Inal, 2010). Total nitrogen was determined by the conventional Kjeldahl method and steam distillation.

Statistical analysis

The data were subjected to one-way ANOVA after testing the normality of the data set. The mean separation between the treatments was performed by Duncan's multiple comparisons at $p \leq 0.05$ confidence level (Yurtsever, 1984).

Results and Discussion

Potatoes yield

There were no visual symptoms of excessively used SS treatments on the potatoes plant in the third growing season. The main effect of treatments on the yield was very significant ($p<0.01$) and it was possible to detect the optimal SS application rate. Besides 120 t ha^{-1} treatment and the control, the other SS application resulted in a similar yield that was comparable to the optimal chemical fertilization (Figure 1). 20 (18700 kg ha^{-1}), 40 t ha^{-1}, and 80 t ha^{-1} (16830 t ha^{-1}) treatments had an even higher yield. The yield was drastically decreased for the 120 t ha^{-1} SS treatment which was about 50% of the optimal fertilization. The increasing SS incorporation above the 40 t ha^{-1} resulted in a slightly decreasing trend above the optimal fertilization, but an apparent yield loss was observed above 100 t ha^{-1} SS treatment.

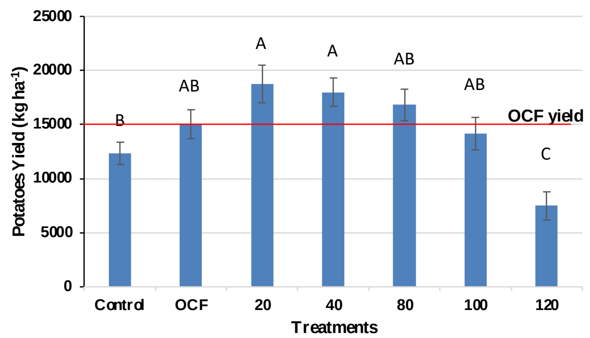

Figure 1. The effects of treatments on the potatoes yield. Different letters on the bar indicate significant difference

Nitrogen, P, and K are of most frequently deficient plant nutrients in agroecosystems. In terms of these nutrients, the SS treatments up to 80 t ha^{-1} can be regarded as a reasonable level of K addition since its concentration in the soil solution is buffered by the cation exchange mechanism, but N and P levels in excessive SS treatments were well above the possible plant uptake by the earlier crops in the rotation (Table 2). However, the experimental soils consist of very low levels of Olsen-P and possibly very high P adsorption capacity due to fine texture and high soil pH (Uygur, 2009), therefore the excessive application of SS-P can be tolerated even in the third year of the application. The available P contents were below 190 kg P_2O_5 ha^{-1} up to 80 t ha^{-1} SS treatments. Above this application rate, it reached up to 495 kg P_2O_5 ha^{-1} which is well above the optimal level (soil-P + Fertilizer should be about 120 kg P_2O_5 ha^{-1} (Gücdemir, 2006), even three years after the application, with possible deleterious effects. Nitrogen is the ultimately deficient nutrient in soils therefore it should be supplied to the plant in every growing season. Organic-N represents 99.8–99.9% of the total-N in SS and the amounts of mineral-N released in soils depended mainly on the decomposition of substances at a different rate in differing soil properties (Bertoncini et al., 2008). The higher soil pH resulted in the higher N mineralization rate from the SS either stabilised or digested. The SS incorporation into soils usually results in increased mineralization rates as readily decomposable organic matter and saprophytic micro-organisms are added (Boeira & Maximiliano, 2009; Tian et al., 2008). As excessive amounts of organic substances incorporated into soil mineralization became rate controlled. If the C: N ratio of the material favour the mineralization processes (i.e. a C: N ratio below 20 as in the current SS) and substantial amounts of N can volatilize. In the third year, relatively recalcitrant organic substances remain in the soil. Therefore, even though the added N (714-4286 kg ha^{-1}) was well above the plant uptake in the current crop sequence (Table 2) limited mineralization of recalcitrant organic substances was able to meet the N requirement of potato crop for 20-40 t ha^{-1} for the optimal yield in the third year. The larger application of SS, however, can supply excess N to the crop which leads to luxurious uptake or even toxic levels of N and possibly some other nutrients (Kacar, 2014).

Table 2. Some plant nutrients and total salt addition to the experimental field at differing treatments

Nutrients	OCF*	20	40	80	100	120
Nitrogen (kg ha^{-1})	360	714	1429	2857	3572	4286
Organic matter (kg ha^{-1})	N/A	7822	15644	31288	39110	46932
Potassium (kg ha^{-1})	N/A	83	166	331	414	497
Phosphorus (kg ha^{-1})	180	193	386	771	964	1157
Soluble salts (kg ha^{-1})**		902	1803	3607	4509	5410

*OCF, optimal chemical fertilization, ** the fertilizers mainly consist of soluble salts.

Soil properties in the third year

In the third year of the study, plot-based soil sampling was performed before the planting and after harvest. The results are provided in Table 3. The SS treatments had an impact on pH, TSS, Olsen-P, NH_4-Ac-extractable K, OM, DTPA-Zn, and total Cd, Cr, Ni, and Pb parameters (Table 3). The pH of the control and OCF plots were rather highly similar around 7.25 whereas the SS incorporated plots were apparently higher around 7.9. The rate-limited nature of the SS can result in relatively larger amounts of ammonia in even the third year after application which can be responsible for the elevated pH (Kacar, 2013). The SS material consisted of significant amounts of readily soluble nutrient elements. The calculated amounts of salt ranged between 902-5410 kg ha^{-1}. Therefore, it is an expected fact that the TTS parameter should increase as a function of application rate. However, even in the highest application rate (0.219%), the TTS was below the critical threshold of 0.35% which is equivalent to 4 dS m^{-1}. Even tough sensitive plants may be inversely affected by an EC above 2 dS m^{-1} (Usta, 1995). 5410 kg of readily soluble salt in 120 t ha^{-1} SS treatment (Table 2) can be equivalent to 2.16% of TSS in the upper layer (0-20 cm) of ordinary soil. However, the reactions of soluble ions with soil solution and solid phases after incorporation of SS into the soil, crop uptake in the preceding growth seasons, and further movements towards deeper layers may render its effect to tolerable levels.

The organic matter content of the soil which had an average of 1.82% in control and OCF plots, reached up to 3.30% in the 120 t ha^{-1} SS treatment. Theoretically, the added organic material in the SS treatments ranged between 7822-46932 kg ha^{-1} which can cause a net increase of 0.313-1.88%. The measured net OM increases, three years after its incorporation, were between 0.29-1.48% which can indicate that the SS was a relatively stable and reliable organic matter source with only 8.3-21.2% loss.

The experimental soil can be classified as K-rich soil. The addition of SS had further increased the portion of plant available K fraction from 1200 kg ha^{-1} to as high as 1530 kg ha^{-1}. Potassium amounting between 83-497 kg K_2O ha^{-1} were added with the SS treatments. The majority of the added K were likely in the readily soluble fraction in the SS and they were adsorbed by the cation exchange processes in the soil (Usta, 1995). Despite some uptake by preceding plants in the crop sequence, the plant availability was increased by a function of SS application rate. The Olsen-P (Olsen et al., 1954) concentration of experimental soil was well below the sufficiency threshold (about 120 kg P_2O_5 ha^{-1}). 193-1157 kg P_2O_5 ha^{-1} were added into the soil by SS treatments (Table 2). Even the smallest application rate was able to meet plant requirements, including the preceding plant in the crop sequence, by considering the fertilizer suggestion (Güçdemir, 2006). On the other hand,

Table 3. Soil properties three years after the experimental set-up in potatoes growing season

Treatments	ST	CCE (%)	Saturation (%)	pH	TSS (%)	OM (%)	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Fe	Cu	Zn	Mn	Cd	Cr	Ni	Pb
									mg kg^{-1}							
Control	BP	14	64 CL	7.21	0.128	1.85	23	1260	14.5	4.82	0.97	16.6	0.09	0.21	1.06	2.13
	AH	12	65 CL	7.25	0.131	1.90	18	1200	8.22	3.77	0.60	6.32	0.08	0.23	1.09	2.43
OCF	BP	13	60 CL	7.24	0.120	1.67	33	1130	16.5	5.07	1.61	26.3	0.14	0.13	1.14	2.97
	AH	13	58 CL	7.28	0.130	1.87	25	1190	8.68	3.99	0.67	7.37	0.18	0.15	1.12	2.48
20 ton ha^{-1}	BP	14	63 CL	8.00	0.159	2.44	174	1190	17.8	5.84	2.21	27.4	0.16	0.18	1.48	3.05
	AH	12	60 CL	8.02	0.156	2.11	126	1220	11.5	4.12	0.91	8.42	0.21	0.20	1.49	3.28
40 Ton/da	BP	14	64 CL	8.04	0.139	2.17	117	1080	14.8	5.55	0.99	18.2	0.14	0.27	2.80	3.27
	AH	12	62 CL	8.09	0.180	2.51	116	1250	8.77	4.27	1.17	6.38	0.17	0.33	2.85	3.32
80 ton ha^{-1}	BP	14	64 CL	7.95	0.171	2.34	225	1330	10.9	5.54	1.76	25.9	0.24	0.43	3.52	3.35
	AH	12	63 CL	7.85	0.198	2.66	168	1400	9.53	4.88	1.89	7.23	0.38	0.43	3.75	3.69
100 ton ha^{-1}	BP	14	65 CL	7.78	0.182	2.58	470	1140	18.5	6.43	3.73	28.2	0.18	0.39	3.78	2.98
	AH	13	62 CL	7.78	0.224	2.74	260	1330	9.68	5.01	2.10	8.52	0.49	0.50	3.88	3.47
120 ton ha^{-1}	BP	13	65 CL	7.89	0.219	3.30	495	1420	21.8	7.48	5.82	46.7	0.28	0.48	3.81	3.43
	AH	12	64 CL	7.90	0.213	3.18	229	1530	13.2	4.92	2.55	16.1	0.45	0.54	3.91	3.74

T sampling time, BP before planting, AH after harvest, CCE calcium carbonate equivalent, TTS total soluble salts, OM organic matter, OCF optimum chemical fertilization

organic matter, humic substances, and low molecular weight organic acid treatments can facilitate to increase in the availability of indigenous soil-P (Oral & Uygur, 2018; Uygur & Karabatak, 2009). Therefore, adding such substantial amounts of organic matter to a soil rich in P can further increase the availability of P. It reached up to 495 kg P_2O_5 ha^{-1} (Table 3) which may be regarded as an environmentally risky concentration. In general, the P availability was higher before planting than the ones after planting (Table 3) which may be related to differences in the redox potential of soil around the sampling time. Reducing conditions in the spring season can increase the availability of P whereas watertight summer season conditions can promote Ca-related recalcitrant P forms (Mahdi & Uygur, 2018).

The concentrations of DTPA-extractable cationic microelements (Fe, Cu, Mn, and Zn) were given in Table 3. They were above the deficiency threshold, 4.5, 0.21, and 0.5 mg kg^{-1} for Fe, Cu, and Zn, respectively (Lindsay & Norvell, 1978), at both sapling times. However, the concentrations of Mn were above the threshold (14 mg kg^{-1}) in the pre-planting samples whereas after harvest samples were below the sufficiency threshold, besides 120 ton ha^{-1} SS treatment. Micronutrient availabilities were apparently higher at before planting samples. The soil was wetter in the winter-spring period which resulted in more reduced environment that solubilizes oxides of Fe and Mn. These processes increase soil solution concentration and decrease soil pH towards neutrality which was promoted by organic matter addition (Ören et al., 2018). In a relatively drier and hot period, the oxidation condition operates the availability of the elements. During this period recrystallization of amorphous oxides stabilize, co-precipitate, occlude or adsorb the micronutrients with stronger bonding energy that results in lower extractability and bioavailability. Despite huge amounts of SS application, the micronutrient bioavailability did not exceed the critical toxicity levels for the DTPA-extractable concentrations which were 19, 118, and 3.4 mg kg^{-1} for Cu, Zn, and Cd in clayey soils, and 25 and 271 mg kg^{-1} for Cu and Zn respectively in the clay loam soils (Gedikoğlu et al., 1998). The application rate has notably elevated the availability above 100 t ha^{-1} SS incorporations due to micronutrient contents of SS and increased amounts of organic matter addition which can chelate with micronutrients along with other heavy metals.

Total concentrations of nonessential heavy metals (Cd, Cr, Ni, and Pb) in the soils were to increase as a function of SS application rate. However, they were well below the threshold values in Turkish legislation (Anonymous, 2001). Therefore, the currently used treatments resulting in comparable plant performances to OCF treatment can be regarded as environmentally safe.

Nutrient composition of leaves

The effects of treatments on the nutrient element composition of potato leaves were given in Table 4. The sufficiency limits for the nutrients at the beginning of the flowering period growth stage (Reuter et al., 1986) and the toxicity limits for some elements (Sener et al., 1994) are also provided. Besides N concentration all of the nutrients were within the sufficiency limits or just around these limits. Iron concentrations were exceeding the upper limit of the sufficiency threshold

Table 4. Elemental composition of potato leaves

Treatments	N	P	K	Fe	Cu	Zn	Mn	Pb	Cd	Cr	Ni
	%			mg kg^{-1}							
Control	1.91	0.23	3.17	942	23.5	28.0	69.6	0.58	0.16	0.45	1.79
OCF	2.31	0.27	4.42	1043	23.57	25.6	56.1	0.32	0.38	0.53	2.69
20 ton ha^{-1}	2.04	0.25	3.74	975	20.80	18.8	58.0	0.43	0.35	0.41	3.36
40 ton ha^{-1}	2.10	0.24	4.06	851	17.14	28.1	57.5	0.65	0.44	0.52	3.49
80 ton ha^{-1}	2.53	0.22	3.41	855	10.98	19.5	56.2	0.69	0.30	0.61	3.96
100 ton ha^{-1}	2.57	0.29	3.18	988	19.83	24.6	59.1	0.76	0.32	0.69	4.50
120 ton ha^{-1}	2.25	0.19	4.00	997	21.68	23.2	65.2	0.87	0.38	0.73	4.48
ONC	4-5	0.2-0.4	3.5-5	70-150	6-20	15-20	40-300	-	-	-	-
Toxic level	-	-	-	-	-	700	425				

OCF Optimal chemical fertilization, ONC optimal nutrient concentrations

suggesting a general reducing condition during the entire growth period (Ören et al., 2018). Incorporation of large amounts of fresh carbon sources along with excessive Fe (5523 mg kg^{-1}) in the SS such as SS up to 120 t ha^{-1} can even support the redox reaction increasing Fe availability (Lindsay, 2001) higher than the redox sensitive Mn.

The deficiency of N in all treatments was likely to be related to the sampling time difference between the study and reported limits (Reuter et al., 1986). In general, the N concentration of leaves reaches a maximum around the end of the growth stage III where flowering and tuber formation starts (Thornton, 2020). From initiation of growth stage IV to maturation the leaf N concentration is to decrease upon translocation of the element towards tubers. Therefore, late leaf sampling resulted in N concentration below the sufficiency level. Otherwise, no plant showing extreme starvation, i.e. about 50% of the optimal level (Table 4), for any element cannot complete the life cycle with economically feasible yield. However, there are reports in the literature that the N content of potatoes can range between 0.5-6.4% depending on the sampling time and plant organ (Hopkins et al., 2020).

There was no extreme accumulation of essential nutrient elements in potato tubers. Most of the treatment-induced nutrient contents were highly similar to those of OCF treatment (Table 5). There was also no clear fact suggesting the heavy metal accumulation in the tuber. Therefore, the potatoes produced using SS were chemically safe for human nutrition. The significant point here is the plant regulates ion translocation to generative organs to ensure the formation of the next generations. Therefore, even if the growth media and subsequently the leaves have a high concentration of any element, the accumulation of potentially hazardous elements in generative organs are limited by the plants through differing mechanisms.

Conclusion

The effect of sewage sludge application on the yield and mineral composition of soil, plant, and tuber was evaluated in the third year after the treatments. Up to 80 ton ha^{-1} application rates SS may be incorporated into clay loam soil without any visual or analytic side-effects since comparable yield was obtained to OCF. In terms of potato yield, 20 ton ha^{-1} SS may be suggested for sustainable crop yield. Due to the potential risks of using SS, it should be taken special care for subsequent use in the same field to avoid the potential accumulation of either nutrient elements or heavy metals. Excessive usage of SS does not lead to a toxic concentration of any elements in any parts of the potato including the edible parts but excessive and repeated usage can cause environmental problems with potential risks in the plant as well. To solve this problem, the residual effects of the SS treatments should be followed for a longer period with repeated treatments.

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Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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