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Characterization of Sewage Sludge Generated from Wastewater Treatment Plants in Swaziland in Relation to Agricultural Uses

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Abstract Sewage sludge generated from wastewater treatment plants are being merited greater attention in light of their potential for improving soil properties and for providing important nutrient and trace element supplements that are essential for plant growth. Because of the differences in sludge characteristics among sludges that undergo different levels of treatment as well as the extensive and variable nature of pollutant inputs to wastewater, the fertilizer potential and pollutant risk of sewage sludge intended for agricultural application has to be specifically evaluated for each sludge. Sewage sludge generated from seven wastewater treatment plants in Swaziland were analysed for a range of physico-chemical characteristics including organic matter, nutrients, cation exchange capacity, pH and trace elements. Despite the differences in sludge processing and sludge storage ages, the sludge samples generally show high levels of organic matter, nutrients and trace elements needed for plant growth. The potential risk of heavy metal toxicity was evaluated by comparing the levels of heavy metals in the sludge samples with widely quoted and well known regulatory limits of a number of countries and the levels were found to be within acceptable risk level with respect to agricultural application. The research results indicate a positive outcome for the wastewater treatment plants in Swaziland that currently keep large piles of unused dried sludge within their premises.

Keywords Sewage sludge, Nutrient value, Organic fertilizer, Soil amendment, Sludge reuse, Nitrogen, Phosphorus

1. Introduction

Sewage sludge is known to be rich in nutrients (nitrogen and phosphorous), organic matter and trace elements that are beneficial for plant growth and better yield [58, 17]. Sewage sludge is also considered a suitable substitute for commercial fertilizers and the use of sewage sludge as a fertilizer decreases the requirement for commercial fertilizers [37]. Commercial fertilizers require large amount of phosphorous whereas phosphorous is known to be a limited resource [54]. Even though the nitrogen available in commercial fertilizers may not be a limited resource, the production of nitrogen fertilizers demand significant amount of energy [52]. The organic carbon in sludge amended soil can increase as far as three fold compared to inorganic fertilizer amended soils [40, 32]. Inorganic fertilizers usually reduce soil pH and increase the rate of soil acidification as well as increasing the percentage of aluminium saturation [36]. The decrease in pH of soils is traced possibly to the ammonium in the fertilizer [30]. In situations where sewage sludge may not contain the optimum nutrient ratio for growth, it can be combined with commercial fertilizers [33].

Application of sludge has been observed to improve the physico-chemical and biological properties of soils which in turn facilitates better growth of plants [1, 24]. Sludge increases the humus content of the soil [33]. The porosity, field capacity and wilting point all increase as a result of application of sewage sludge [7]. Organic matter which forms over half of the mass of sewage sludge also improves the physical condition of soils [18]. An increase in organic matter reduces the bulk density, increases aggregate stability, increases water holding capacity of soils and promotes greater water infiltration [21]. Organic matter also influences nutrient storage and turnover, soil biota and diversity as well as vulnerability to erosion, [5]. Infiltration capacity and air recirculation increase in fine textured soils as result of sludge application [12, 46]. By contrast, the increased bulk density of fine textured soils without sludge amendmet causes poor aeration which adversely affects plant growth [10].Macro elements are essential for plants and soil fauna [22]. Treated sewage sludge can enrich soil with macronutrients such as phosphorus, potassium, sulfur, calcium, magnesium and micro nutrients [62]. For example, a macro nutrient imbalance in the form of high exchangeable sodium percentage can cause nutritional disturbances in plants and

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impair the uptake of calcium [48]. Sodic soils are also known to have deficiencies in zinc and manganese [14].Exchangeable calcium is the major reserve of soil calcium available to plant roots [15]. Tomato and corn plants can be affected by deficiency in exchangeable calcium [6]. Field crop growth may also be affected by extractable magnesium [15]. Exchangeable forms of potassium are considered the primary source for plant uptake. Minimum adequate levels for exchangeable potassium of 40–80 mg/kg are recommended for crop growth [15]. Manganese deficiency occurs in some soils, due to oxidation of manganese when the pH is raised above 6.2. Manganese uptake in plants is, therefore, generally limited in alkaline soils [2, 13]. Acidic soils exhibit deficiencies in Ca, K, Mg, N, P, S and Mo and excess of Cu, Fe, Mn, Zn and Co as well as aluminium toxicity that limit conditions for crop development [53]. Sewage sludge, however, is deficient in potassium [33].

Application of sewage sludge at higher rates also increases the cation exchange capacity, CEC, of soils [43]. The increase in CEC provides adsorption sites for essential nutrients within the root zone. An increase in the cation exchange capacity also helps in restricting the bioavailability of toxic heavy metals [21, 19]. The fauna and micro flora portions of soils are also altered after sewage addition [28]. According to Zaman, et al. [62], soil microbial biomass, carbon, nitrogen, carbon dioxide evolution, protease, deaminase, and urease activities become significantly higher in sludge composts than in chemical fertilizers treatments due to the greater availability of organic substrates which stimulate microbial activity.

The biomass yields of plants grown on sludge amended soils have also been observed to increase. The shoot length, root length, biomass and total chlorophyll contents of plants increase with increasing rate of sewage sludge application [24]. Application of sewage sludge also has long term after effects on soil properties and crop yields except for sandy soils which may not be the case due to the increased aeration and faster decomposition of organic matter in sandy and loamy soils [33].

The pH of sewage sludge may vary between slightly acidic to neutral and alkaline ranges depending on the degree of treatment and application of sludge conditioners [61]. Sludge application may reduce the pH of soils due to humic acid release and may increase the electrical conductivity of soils [29]. However, acidic soils have been observed to experience increase in pH following sludge amendment [34, 60]. In addition the pH of soils may increase due to the exchangeable calcium and other cations present in sewage sludge [51]. The application of sewage sludge especially of high pH sludge to low pH soils has been observed to reduce the aluminum saturation in the interstitial complex, Al/IC, considerably [26]. Agricultural crops grow well when soil pH is between 6 and 7 because nutrients are available more at pH of around 6.5 [27, 41]. It is commonly recommended that soil pH should be maintained above 6.5 for sludge amended soils [16].

Sewage sludge is a reliable source of nitrogen and phosphorous for plants. Nitrogen is an essential nutrient for plant growth since it is a constituent of all proteins and nucleic acids and therefore protoplasm [44]. Normally crop yield increases with increase in the application of sewage sludge and nitrogen is often the rate limiting factor in the application of sewage sludge to agricultural lands. The content of total nitrogen in sewage sludge reaches 40 – 50 kg/ton [33]. Anaerobic digestion process increases the total nitrogen concentration of sewage sludge. This is due to volume reduction because of the conversion of organic matter to gases and the resulting concentration of the remaining solids of which nitrogen is a part [45]. Only a small part of the total nitrogen is immediately available for plants after application of sewage sludge. In the course of mineralization of sewage sludge, nitrogen is transformed into available forms [33]. Sludge decomposition is reported to occur within 28 days [50]. The amount of nitrogen mineralized is inversely proportional to the carbon to nitrogen (C/N ratio). Soils with large C/N ratio result in low quantities of mineralized nitrogen [23]. Composting of sludge can also cause nitrogen immobilization [49]. Nitrate leaching to ground water as a result of sewage sludge application may be limited due to the limited nitrate form of nitrogen available and the loss of ammonia is mainly due to denitrification and immobilization [42]. Inorganic fertilizers, by contrast increase the C/N ratio which increases organic matter mineralization and nitrate leaching [57].

Phosphorous is an essential nutrient needed for plant growth and is required in large quantities by plants while it is relatively immobile in soils. Phosphorous availability can be as high as 50% in the year of sewage sludge application [8]. Nyamangara and Mzezewa [32] reported that phosphorus increase in sludge amended soils was observed from the original 2-4 mg/kg of phosphorous in soil to 29-114 mg/kg of phosphorus in sludge amended soil. Soil phosphorous availability can be reduced in low pH soils in which the organic matter in the soil carries a positive charge attracting phosphorous and causing immobilization. Plantation growth in such low phosphorus environment leads to poor yield [26].

The electrical conductivity of soils amended with sludge (with or without lime) also increases mainly due to the high level of salts present in sewage sludge. High salinity is also a factor that can inhibit plant growth in soils [38]. Soil characteristics such as pH, clay content, organic matter and moisture content are factors that influence the availability of heavy metals in plants by controlling metal speciation, binding of metals on surfaces (absorption-desorption), precipitation reactions and availability of metals in soil solution [11, 31]. Other properties such as cation exchange capacity and redox potential also affect plant uptake, solubility and mobility of heavy metals [43]. Sludge amendment with or without lime addition can provide extra buffering against soil acidity and reduce the inhibitory effects of sewage sludge especially on the availability of heavy metals [60]. Table A1 and A2 given in the Appendix at the end of this paper show the physical and chemical properties of sewage sludge as reported from a number of countries.

The data shown in Table A1 and Table A2 display variability in sewage sludge characteristics in terms of the majority of the parameters indicated. For example the organic matter content shows range of variation between 25 and 50%. Nutrient and trace element availability as well as heavy metal contents with possible effect of toxicity also show variability. Sewage characteristics in general is location specific and the data in the tables reinforce the need for determining sewage sludge characteristics in order to assess the potential for reuse of sewage sludge in agriculture as well as for determining the risk that may be present as a result of heavy metal toxicity.

This research had the objective of assessing the physico-chemical characteristics of sewage sludge generated from the various wastewater treatment plants in Swaziland, investigate their nutrient and agricultural potential and determine whether these sludges can be recommended as soil conditioner in agriculture as one viable and sustainable means of sludge disposal. The research also set out to establish the restriction that can be imposed on sewage sludge application for agriculture based on the heavy metal contents of the sludge.

2. Materials and Methods

The methodology adopted in this research was quantitative and experimental. The research set up was designed with the objective of determining whether land application of dry sewage sludge generated from wastewater treatment plants in Swaziland can be recommended as soil conditioner in agriculture on the basis of their organic matter, nutrients and trace element contents. In addition the heavy metal concentrations in sludge were determined to ascertain the restriction that may have to be imposed on the dry sewage sludge in land application for agricultural uses. Laboratory experiments were carried out for the determination of physico-chemical properties of sewage sludge that best describes the nutrient and agricultural potential of sewage sludge. In addition, heavy metal determination were carried out for a a number of heavy metal elements that are known to have toxicity effects on humans, animals, plants and the soil ecological environment.

For the purpose of determination of physico-chemical characteristics, sewage sludge samples were collected from seven wastewater treatment plants in Swaziland. The wastewater treatment processes that take place in each of the treatment plants sampled are given in Table 1.

Samples were collected using plastic bags that were pretreated with dilute nitric acid and rinsed with distilled deionized water. Some of the sludge samples collected such as the ones from Matsapha and Ezulwini wastewater treatment plants represent different ages as the sludge samples were stored over a period of several years. Therefore, samples from both the fresh and old dried sludge portions were collected separately in order to investigate the trend in the variation of metals contents as well as sludge characteristics over time. The sludge samples collected were dried at room temperature and there after stored in a refrigerator at 4℃.

Sample Pretreatment

The dried sludge samples were first passed through a 2 mm sieve eliminating roots, stones, plastics, grass and other impurities. The samples were then powdered to fine sizes using mortar and pestle and thoroughly mixed to achieve homogeneity. The powdered sludge samples were then sieved mechanically to obtain fractions that were less than 63μm. The sludge samples following these steps were stored in plastic containers at room temperature until they were analyzed further.

Determination of sludge physico-chemical characteristics

A minimum of three replicates from each of the prepared samples following the steps described in sample pretreatment above were taken for the determination of physico-chemical characteristics of sludge samples. The parameters determined included: pH, electrical conductivity, moisture content, percentage of dry solids, volatile and fixed solids, organic matter, organic carbon, available nitrogen, available phosphorous and cation exchange capacity. The pH values of the sludge samples were determined using a calibrated pH meter after mixing the sludge samples in a 1:2.5 (W/V) solution of distilled water after stirring the solution for 30 minutes using glass rod. The electrical conductivity of the sludge sample was measured using the sample solution prepared for pH. A conductivity meter was used for the measurement. The meter was calibrated using a potassium chloride solution having a conductivity of 1412 $\mu mho.cm^{-1}$ at 25 ℃. Cation exchange capacity was determined using the USEPA method 9081 (sodium and ammonium acetate extractions). Total fixed and volatile solids were determined using gravimetric method [55]. Organic carbon was determined by Walkey and Black method [56]. Available nitrogen was determined by the Alkaline-Permanganate method [47]. The available phosphorous was determined using the Bray and Kurtz method [4]. Total metals were determined by the inductively coupled plasma atomic emission spectrometry, ICP-OES.

3. Results and Discussion

The results of the analysis of sludge samples collected from the seven wastewater treatment plants in Swaziland are presented in Table 2, Table 3 and Table 4. The organic matter and nutrient contents were found mostly in high concentrations in the majority of sludge samples analyzed irrespective of the wastewater treatment types and the extent to which the sludge were stabilized. The organic matter content of the sludge samples varies in the range 20-60% with a median average of 46%. Sludge collected from anaerobically digested samples show approximately 50% organic matter despite the loss of organic matter by anaerobic digestion. With respect to organic matter, the sludge samples from Matsapha waste stabilization ponds show the lowest content of organic matter including low percentage of nitrogen. The sludge collected from the anaerobic pond of the Matsapha waste stabilization pond may have undergone through greater level of biodegradation because of the fact that the sludge has been retained in the pond for long time under wet (active) conditions before it is desludged. The cation exchange capacity values shown in Table 2 are generally high and application of these sludges to soil is expected to increase the cation exchange capacity of soils particularly of sandy and loamy soils that lack clay and thus have poor cation binding capacity. It is known that organic matter behave partially as amphoteric substance with the negative charge attracting cations and hence increasing the cation exchange capacity of sludge.

Figure 1 shows that the cation exchange capacity has significant correlation with nitrogen data with Pearson's correlation coefficient of over 0.82 at p= 0.01 significance level (SPSS version 20). This correlation excludes some of the data from Ezulwni and Nhlambeni wastewater treatment plants which plot within the dotted circle shown Figure 1. The data from these wastewater treatment plants plot as outliers to the regression line that was obtained based on the remaining data and is shown in Figure 1. The sludges from these treatment plants have undergone anaerobic digestion. The high nitrogen content despite the low cation exchange capacity may be related to the mineralization of nitrogen through the breakdown of organic nitrogen by anaerobic digestion process that resulted in higher nitrogen concentration. It is reported that the cation exchange capacity influences the speciation equilibrium between NH_3 and $NH4^+$ [20] Moreover, the presence of greater concentration of calcium and magnesium increases the struvite precipitation of ammonium.

The high percentage of nitrogen content bound to organic matter in sewage sludge is a measure of the importance of sewage sludge for agricultural purposes. The carbon to nitrogen, ratio, C/N, of samples taken from the waste stabilization ponds (samples from Matsapha, Nhlangano and PiggsPeak) were higher than samples taken from the anaerobically digested sludges. The Matsapha samples though have lower C/N ratios than the Nhlangano and Pigspeak samples as these sludge samples have undergone greater stabilization and are taken from stored sludge pile. Higher C/N ratios of sludge ensure that there is limited mobilization of nitrogen by incorporation into cell mass and making this nitrogen available at a later period when nitrogen is needed most for plants during the growing period.

The nitrogen percentage is the highest in the anaerobically digested sludge samples taken from Ezulwini and Nhlambeni wastewater treatment plants. The high nitrogen percentage is expected for sludge samples that underwent sludge stabilization using anaerobic digestion because of the loss of biodegradable sludge mass into gases (methane and carbon dioxide) by the action of anaerobic bacteria and the concentration of the remaining sludge mass. Moreover, anaerobically digested sludge contains greater levels of ammonia that increase the easily available portion of nitrogen in the sludge mass. The results also indicate limited ammonia volatilization of anaerobically digested samples both during the digestion process as well as during storage and drying of the sludge samples. It is to be noted that some of the sludge samples from Ezulwini wastewater treatment plant have been stored over a long period of time. The higher percentage of nitrogen in such samples is an indication of the limited ammonia volatilization despite long storage times.

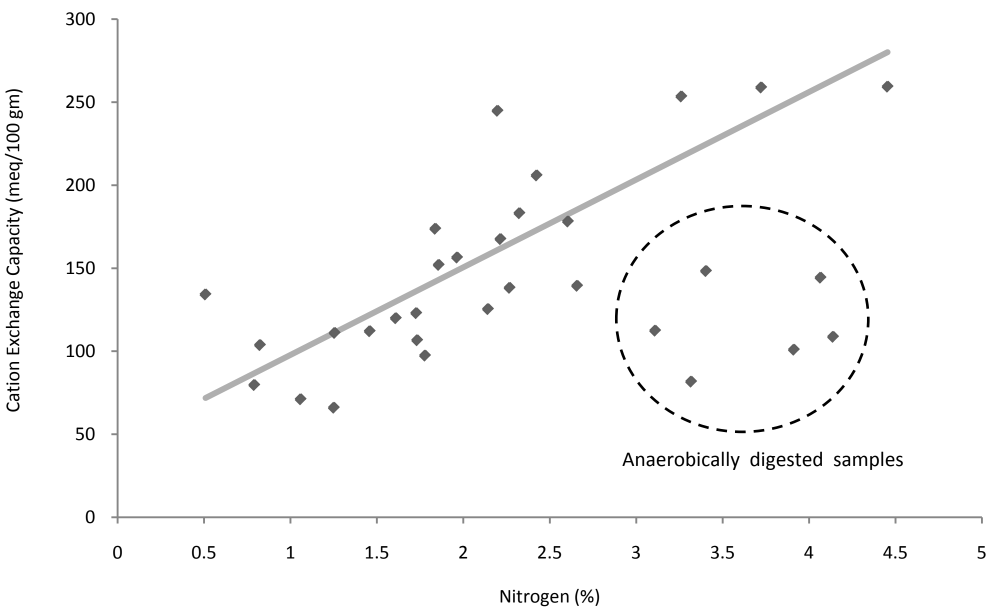

Figure 1. Variation of nitrogen with cation exchange capacity in sludge samples

Table 1. Wastewater treatment processes that take place at the seven wastewater treatment plants in Swaziland where sampling took place

	Location	Wastewater treatment processes	Sludge collected from
1	Hlathukulu	Settlement tank, waste stabilization pond, constructed wetland.	From sludge pile taken from waste pond
2	Matsapha	Waste stabilization pond	From stored sludge pile taken from waste pond
3	Nhlambeni	Settlement, Percolating filter and anaerobic digester.	Sludge sample taken after anaerobic digestion. Dried sludge and fresh sludge from sludge drying bed.
4	Nhlangano	Waste stabilization pond	Anaerobic pond
5	Piggspeak	Waste stabilization pond	Anaerobic pond
6	Siteki	Settlement, Percolating filter and anaerobic digester.	Sludge sample after secondary settlement tank
7	Ezulwini	Settlement, Percolating filter and anaerobic digester.	Sludge sample taken after anaerobic digestion. Dried sludge and fresh sludge from sludge drying bed.

Table 2. Physico-chemical characteristics of sludge samples collected from waste treatment plants in Swaziland

Parameter	Unit	Value	Hlathu- kulu	Matsa- pha	Nhlam- beni	Nhlan- gano	Piggs Peak	Siteki	Ezulwini
Cation Exchange Capacity	(meq/ 100 gm)	Median average	88	123	253	138	159	153	105
		Range	71 -151	65 - 205	144 - 259	106 - 173	103 - 615	138 - 244	81 - 112
Electrical Conductivity	(µS /Cm)	Median average	1775	2840	3130	2220	939	2780	983
		Range	1014 -2090	1062 -7220	2530 - 3720	1181 - 2460	611 - 1087	2640 - 2920	648 - 1646
pH	(pH Units)	Median average	5.93	6.025	6.96	6.81	6.43	7.08	6.72
		Range	5.35 - 6.27	5.77 - 6.21	6.58 - 7.02	6.21 - 7.84	6.00 -6.75	7.04 - 7.45	6.50 - 6.90
Organic carbon	(%)	Median average	10	15	23	27	30	19	29
		Range	5 - 25	12 - 22	21 - 25	25 - 29	6 - 31	18 - 22	28 - 30
Organic matter	(%)	Median average	20	30	46	53	60	38	57
		Range	11 - 51	24 - 43	43 - 49	49 - 57	12 - 61	37 - 43	55 - 59
Volatile solids	(%)	Median average	14	33	52	47	83	35	51
		Range	9 - 45	28 - 42	45 - 84	47 - 48	9 - 85	35 - 48	43 - 55
Nitrogen	(%)	Median average	1.7	1.6	3.7	1.8	2.3	2.3	3.9
		Range	0.8 - 1.9	1.3 - 2.6	3.3 - 4.5	1.6 - 2.4	0.5 - 3.2	2.2 - 2.9	3.1 - 4.1
C/N ratio		Median average	5.9	9.4	6.2	15.0	13.0	8.3	7.4
		Range	2-31	4-16	4-7	10-18	2-62	6-10	7-10
Phosphorous	(%)	Median average	1.2	2.1	2.2	1.5	1.0	1.4	2.4
		Range	1.1 - 1.3	2.1 - 2.2	2.1 - 2.3	1.4 - 1.5	0.7 - 1.5	1.4 - 1.6	2.4 - 2.5

Table 3. Macro and trace element concentrations characteristics of sludge samples collected from waste treatment plants in Swaziland

		Hlathukulu		**Matsapha**		**Nhlambeni**		**Nhlangano**	
Parameter	Unit	Median	Range	Median	Range	Median	Range	Median	Range
As	mg/kg	67	45 - 134	139	115 - 169	102	100 - 106	115	107 - 118
Co	mg/kg	79	57 - 163	92	80 - 107	98	88 - 99	109	104 - 110
B	mg/kg	93	75 - 135	70	45 - 137	79	65 - 95	77	64 - 83
Cr	mg/kg	452	317 - 543	943	642 - 1396	561	493 - 579	472	462 - 507
Cu	mg/kg	208	103 - 696	528	405 - 606	501	491 - 518	239	227 - 251
Mo	mg/kg	5	1 - 6	18	10 - 25	6	4 - 7	6	5 - 7
Ni	mg/kg	48	24 - 1242	233	128 - 327	74	57 - 115	15	0 - 75
Pb	mg/kg	14	12 - 65	83	65 - 96	90	80 - 96	28	28 - 32
Sn	mg/kg	292	210 - 324	434	294 - 601	372	323 - 382	307	280 - 310
Zn	mg/kg	729	553 - 1046	1402	478 - 2311	1357	1238 - 1400	1577	1549 - 1659
Ca	(%)	0.67	0.38 - 0.85	0.89	0.53 - 1.51	1.07	0.93 - 1.36	1.22	1.12 - 1.27
K	(%)	0.05	0.04 - 0.13	0.12	0.09 - 0.18	0.14	0.13 - 0.14	0.16	0.15 - 0.16
Mg	(%)	0.06	0.04 - 0.10	0.21	0.14 - 0.30	0.31	0.28 - 0.33	0.22	0.21 - 0.23
Na	(%)	0.07	0.07 - 0.09	0.18	0.11 - 0.53	0.10	0.08 - 0.10	0.14	0.12 - 0.14
Si	(%)	0.02	0.01 - 0.05	0.07	0.03 - 0.12	0.05	0.03 - 0.07	0.07	0.05 - 0.10
Al	(%)	0.00	0.00 - 1.42	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00 - 0.00
Fe	(%)	2.15	1.66 - 3.62	2.46	1.85 - 3.16	2.49	2.28 - 2.54	2.81	2.74 - 2.86

Table 4. Macro and trace element concentrations characteristics of sludge samples collected from waste treatment plants in Swaziland

		PiggsPeak		**Siteki**		**Ezulwini**	
Parameter	Unit	Median	Range	Median	Range	Median	Range
As	mg/kg	12	5 - 139	149	137 - 151	150	141 - 169
Co	mg/kg	21	19 - 100	114	-7142 - 120	104	103 - 118
B	mg/kg	50	30 - 72	85	72 - 94	88	59 - 101
Cr	mg/kg	429	409 - 648	435	403 - 453	528	468 - 542
Cu	mg/kg	32	8 - 146	241	215 - 328	479	417 - 536
Mo	mg/kg	2	0 - 4	5	4 - 524	5	4 - 7
Ni	mg/kg	4	0 - 131	60	25 - 65	54	48 - 65
Pb	mg/kg	7	0 - 35	23	21 - 92	71	64 - 76
Sn	mg/kg	290	277 - 303	169	159 - 248	203	141 - 207
Zn	mg/kg	93	69 - 882	1182	1082 - 1216	1441	1331 - 1610
Ca	(%)	0.51	0.12 - 0.60	1.33	1.22 - 1.59	0.77	0.63 - 0.92
K	(%)	0.28	0.07 - 0.49	0.18	0.17 - 0.19	0.12	0.12 - 0.13
Mg	(%)	0.14	0.12 - 0.19	0.41	0.38 - 0.43	0.22	0.20 - 0.23
Na	(%)	0.07	0.06 - 0.08	0.14	0.11 - 0.14	0.04	0.02 - 0.05
Si	(%)	0.08	0.05 - 0.10	0.04	0.03 - 0.04	0.05	0.04 - 0.06
Al	(%)	0.45	0.00 - 0.54	0.00	0.00 - 0.00	0.00	0.00 - 0.00
Fe	(%)	0.91	0.86 - 2.56	2.96	2.85 - 3.01	2.89	2.30 - 2.95

The pH of the sludge samples varied between 5.9 and 7 with an overall median average of 6.7. pH controls the bioavailability of metals particularly those metals that exist largely in the labile form. Sludge applied to low pH soils (soil pH less than 5) may decrease soil pH further and as such is not recommended for application unless it is stabilized with lime. Agricultural crops grow well when the soil pH is between 6 and 7 because nutrients are available more at pH of around 6 [27]. Since the pH values of most of the sewage samples analyzed fall in the desired range (between 6 and 7) further stabilization may not be necessary for application on soils that are not too acidic or too alkaline. Further stabilization should only be considered if future pilot trials on particular soils suggest otherwise. The available phosphorous content is high in most of the sewage samples analyzed with the anaerobically digested sludges having higher phosphorous contents compared with the other sewage sludge samples. Phosphorus availability partly depends on the extent of treatment the sludge underwent. For the analyzed sludge samples, except for anaerobic digestion no further treatment was made. Treatment of sewage sludge to a higher pH is known to reduce phosphorus availability and because binding of phosphorous occurs in the inorganic form, organic decomposition has little effect in making phosphorous available as is normally the case with nitrogen.

The heavy metal analysis was carried out with the objective of identifying potential toxicity as a result of application of sewage sludge to agriculture. It is known that heavy metals such as cadmium, mercury and lead carry high level of toxicity to humans and animals while being less toxic to plants. By contrast zinc, nickel and copper are more damaging to pants when they are found in higher concentrations. Heavy metals such as molybdenum and selenium can also cause toxicities in animals and humans. However, they are often present at low concentration in sludge and do not, therefore, limit the rate of sludge application to agricultural lands. Higher concentrations of heavy metals are also known to affect soil biological properties as well as soil microbial population and as such can reduce or entirely inhibit soil fertility. The total metal concentrations present in the sludge samples taken from the seven waste water treatment plants in Swaziland were analyzed by the ICP-OES and are presented in Table 4. The concentrations show ranges of variations that reflect the characteristics of the wastewaters generated from the respective cities and the level of industrial establishments present in the cities. Sludge samples from the Matsapha wastewater treatment plant generally showed higher heavy metal concentrations compared to the sludge samples taken from the other wastewater treatment plants. This is apparent as Matsapha is an industrial area and several of the effluents generated from the industries have minimal treatments, such as equalization basins, before being discharged to the municipal sewer. The heavy metals concentrations in the sludge were also compared with existing regulatory limits from countries such as South Africa, China, USA and the European Union. The concentrations were mostly within the regulatory limits of the standards considered. The copper concentration is exceeded in the case of Chinese limit which is considered very high compared to other regulatory limits. The chromium, lead, zinc and nickel concentrations were all below the regulatory limits considered for all sludge samples. The results of the experiments in this research generally showed low risk of heavy metal toxicity of the sludge samples (in terms of the regulatory limits specified) and therefore a reasonably good potential for the sludges from the treatment plants to be used for agricultural purposes. This positive outcome of the research result can be good news to the waste water treatment plants in Swaziland that currently keep large piles of sludge in their respective wastewater treatment plants premises with the possible future option of using sludge for agricultural application. Considering the nutrient and soil condition values of the sludges, reusing them for agriculture is an economically attractive option and should be given greater attention.

4. Conclusions

Characterization of sewage sludge is important before application sewage sludge to soil for agricultural purposes. Such characterization is helps determine the potential of sewage sludge for nutrient supplementation and for increasing plant yields. In addition the information will be useful for determining suitable rate of application of sewage sludge and for investigating pollutant risks that may be associated with the use of sewage sludge. The sludge samples taken from seven wastewater treatment plants in Swaziland were analyzed for a range of physico-chemical characteristics including nutrients, organic matter and trace elements. The organic matter contents were high in all of the sludge samples despite the fact that some of the dried sludge samples were stored over a period of ten years. Sludge samples that were kept for a long period of storage under wet conditions, such as the waste stabilization ponds, showed relatively lower contents of organic matter. The nutrient contents (nitrogen and phosphorous) were high in all of the sludge samples with the samples from the anaerobically digested sewage sludge containing the highest concentrations. Generally higher C/N ratios were recorded in the sludge samples which is an indication that there is limited mobilization of nitrogen by incorporation into cell mass which make the nitrogen contents available at a later period when it is needed most for plants during the period of growth. The high cation exchange capacities of the sludge samples were also evident with the nitrogen contents showing strong correlation with the sludge cation exchange capacities. This result is one positive outcome for application of sludge for agricultural purposes because such association of nitrogen with cation exchange capacity means slow release of nutrients (greater period of availability). In addition increase in cation exchange capacity results in reduced mobility of potentially toxic and inhibitory heavy metals. The pH of the sludge samples mostly fell in the range between 6 and 7. Further stabilization of the sludges may not be necessary for application to soils that are not too acidic or too alkaline, or unless it is indicated by further plant trials. The major trace metal concentrations were largely found to be below the regulatory limits specified in the South African, USA, EU regulations. The sludge samples, therefore, carry low risk of potential heavy metal toxicity with respect to agricultural uses. This positive result shall be examined further with future pilot trials of plants grown on sludge amended soils under different soil and plant conditions in Swaziland.

Appendix (Characteristics of Sewage Sludge from a Number of Countries)

Table A1. Selected Physico-chemical properties of sewage sludge [59, 61, 9, 7, 39, 26, 3, 33, 25, 35]

	Ireland	Turkey		USA	Spain		Spain	Russia	Poland	Spain
Parameter	Average value	Mean Sample 1	Mean Sample 2	Median	Mean Sample 1	Mean Mean (Anaerobically digested)	Mean			
pH	7.39	7.6		7.34	7.62	6.94	6.60	7.1	7.07	6.65
Electrical conductivity (μs.cm^{-1})	412	658							1001	7100
Total salt (%)			3.64							
Moisture content (%)	87.3						8.79			
Dry matter content (%)					25.45	25	91.21			
Fixed solids (%)							43.95			69.2
Volatile solids (%)							47.26			30.8
Organic matter (%)	27.8	74.2	46.39	48		44		38		25.04
Organic carbon (%)							26.26		27.24	15.74
Nitrogen (%)	7.03	6.3	3.06	3.3	2.42	3.2	2.63	2.1	3.87	1.5
Phosphorous (%)	1.95	1.045	1.33	2.3	1.64	1.03	1.81	1.8		
C/N ratio						7.3				

Table A2. Selected macro and trace element properties of sewage sludge [59, 61, 9, 7, 39, 26, 3, 33, 25, 35]

	Ireland	Turkey		USA	Spain		Spain	Russia	Poland	Spain
Parameter	Average value	Mean Sample 1	Mean Sample 2	Median	Mean Sample 1	Mean Mean (Anaerobically digested)	Mean			
Calcium (%)	1.26		3.74	3.9	4.75	0.68				
Sodium (%)				0.2	0.1	0.08				
Magnesium (%)	0.35		0.68	0.4	1.58	0.43				
Potassium (%)	0.23	0.561	0.68	0.3	0.2	0.25		0.3		
Aluminum (%)				0.4						
Iron (%)				1.1	1.03		2.37			
Boron(mg/kg)	242			33						
Cadmium (mg/kg)	13.7			16	<0.01			9		5.6
Copper(mg/kg)	979			850	205			21	284	375
Chromium(mg/kg)					75.3					
Lead(mg/kg)					144.4			31	102	84
Manganese(mg/kg)	386			260	105.1					
Nickel(mg/kg)					22.6			81	270	56
Zinc(mg/kg)	1268			1740	1808.6			238	593	1179

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