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ASSESSMENT OF THE BENEFITS AND RISKS OF SEWAGE SLUDGE APPLICATION AS SOIL AMENDMENT FOR AGRICULTURE IN ESWATINI

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ABSTRACT

Sewage sludge is an important soil conditioner, and source of nutrients with a potential for use in agriculture. However, such benefit needs to be weighed against the risks due to the presence of heavy metals, and other substances that may endanger human health, plants, soil and the ecosystem. This research had the objective of evaluating the agricultural potential of sewage sludge together with the risks that may be present in use. Samples of sewage sludge from seven wastewater treatment plants in Eswatini were analyzed for selected physical and chemical parameters, and heavy metal concentrations using commonly established laboratory procedures. The analysis results indicated that, sludge samples exhibited high organic matter content, cation exchange capacity, macro nutrients such as nitrogen and phosphorus and micro nutrients (trace metal elements) needed for plant growth. Anaerobically digested sludge samples showed higher carbon to nitrogen ratio because of biomass loss in the form of methane and carbon dioxide. The heavy metal concentrations are all within safe limits except the sludge from Matsapha area that had levels of chromium, and nickel above regulatory limits. With respect to their heavy metal contents, most of the sludge samples would qualify as Class A sludge ready to be used as organic fertilizer for agriculture without regular monitoring of heavy metals in the soil to which they are applied. The study results indicated the importance of sewage sludge for their agricultural potential through supplementation of both micro and macro nutrients needed for plant growth, for improving the soil properties such as water holding capacity and permeability, through the increase of organic matter content, and retention of nutrients due to the high cation exchange capacity. All these benefits are realized with sewage sludge being a lower cost alternative to commercial fertilizers. Moreover, the low concentration of heavy metals present in the sludge presents lower risk that may arise in the course of utilizing the sludge as agricultural supplement.

Key words: Agriculture, fertilizer, heavy metals, nutrient, sewage, sludge, nitrogen, phosphorous

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INTRODUCTION

Sewage sludge is known to contain nutrients and trace elements that are required for growing plants. It is also a good soil conditioner that offers comparative advantages over mineral fertilizers [1, 2, 3]. Mineral fertilizers containing phosphorus and nitrogen are based on limited phosphorus resources, and nitrogen that is expensive, and energy intensive during its production [4, 5]. Mineral fertilizers also reduce the soil pH and increase soil acidity as well as aluminum saturation [6, 7]. However, sewage sludge is reported to increase the organic carbon in soil three times when compared with mineral fertilizers [8, 9].

Even though the nutrient ratio in sewage sludge may not be optimum for plant growth, it significantly improves soil properties, and mends its physical condition, increasing the humus content, porosity, field capacity, and wilting point [10, 11, 12]. According to Manyatsi *et al.* [13], the yield and moisture retention capacity of a sewage sludge amended soil increased significantly when used for growing spinach. A combination of sewage sludge and mineral fertilizer applied in a 1:10 ratio reportedly gave optimum conditions for plant growth and reduction of toxicity effects due to application of sewage sludge [14]. Sewage sludge also increases the needed macro elements such as nitrogen, phosphorus and potassium which create nutritional balance in plants [15, 16, 17]. Acidic soils show deficiency in macronutrients as well as increased aluminum toxicity [10]. Alkaline soils reduce manganese uptake due to precipitation of manganese at pH greater than 6.2 [18, 19]. Specifically, the organic matter in sewage sludge decreases bulk density, increases water holding capacity, grain stability, and water infiltration of the soil to which it is applied [20]. As a result of the application of sewage sludge, soil biota increases in diversity, nutrients become stable in the soil, and erosion is reduced [21]. In fine soils there will be greater infiltration and air circulation following sewage sludge application [22, 23, 24]. According to Diana *et al.* [25], a dose of 25 t/ha sewage sludge application provided highest wheat crop productivity, while cadmium (Cd) and lead (Pb) concentration levels in soil and wheat grain were under the maximum values allowed by the local regulation. On the other hand, other authors have reported that sodic soils lack zinc and manganese [26] and attributed limited growth in tomato and maize to exchangeable calcium deficiency while magnesium and potassium below 40 mg/kg of soil can also limit plant growth [27, 28].

Sewage sludge increases the cation exchange capacity (CEC) of soils that provides a site for nutrient adsorption as well as reducing heavy metal bioavailability [13, 29, 30]. Compared to chemical fertilizers, sewage sludge increases soil biota, enzymatic activity, evolution of C, N and CO_2. All these contribute to better biomass yield [31]. The effect is long term in soils except in sandy soils that degrade the organics fast [10]. The pH of sludge varies between acidic and alkaline ranges based on the treatment it receives [32]. Crops grow well at pH between 6 and 7 that make nutrients more available and, for sludge amended soil, pH above 6.5 is recommended [33, 34, 35]. Although humic acid release from sewage sludge reduces pH, soils amended with sewage show increase in pH due to the exchangeable cations such as calcium as well as reducing soil aluminum saturation [36, 37, 38, 39, 40].

Sewage contains nitrogen as much as 40 – 50 kg/ton which is an essential element found in plant proteins and nucleic acids [10, 41]. Nitrogen is often the limiting factor in plant growth. Anaerobic digestion increases nitrogen content by concentration due to release of biomass in the form of methane and carbon dioxide [42]. It requires about a month for sludge to decompose and mineralize and thus making nitrogen available for uptake by plants [10, 43]. With a high C/N ratio, sludge mineralizes slower. Composting also immobilizes nitrogen. Nitrate leaching to groundwater from sludge application is low due to immobilization and the nitrogen loss is due to ammonia and denitrification. An inorganic fertilizer increases mineralization and nitrate leaching. Phosphorous, another essential element, though immobile can be as high as 50% available within a year of sludge application. Sludge amendment increases phosphorus from 3 mg/kg up to 114 mg/kg [9]. Poor yield may result in acidic soils which attract phosphorus to soil and immobilize it [38].

The recycling of sewage sludge is widespread in countries such as the United States, Australia, France, Belgium, Norway, the United Kingdom, and Spain whereby some areas in these countries recycle as much as 90% of the sludge generated in their region as soil amendment [44]. In Europe, overall 37% of sewage sludge is recycled as soil amendment for agriculture. The percentage varies between countries. For example, Norway applies 90% of sludge for soil amendment, France 60%, Belgium 57% and Poland 19% [45].

As much as there are benefits, there are also potential risks posed by the application of sewage sludge as soil amendment. With growing environmental awareness, the reuse of sewage sludge is being scrutinized against potential health, and environmental risks [44]. High salinity in sewage sludge can inhibit plant growth [3]. According to Prakash *et al.* [46], the grain yield of pearl millet and wheat reduced by an average of 31.2% and 32.6%, respectively because of the application of sewage sludge that contained salinity at a level of 10 dS/m. Sewage sludge, depending on the extent of treatment, may contain harmful pathogens that pose health risk if applied as soil amendment for growing crops [47]. Sewage sludge may also contain persistent organic compounds such as polychlorinated biphenyls and dioxins that may be harmful to health [48]. The presence of heavy

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metals in sewage sludge is another health and environmental concern. Heavy metals, if present in excess concentrations, can cause toxicity to the soil microorganisms, the crops grown, and to humans consuming such crops. Heavy metal elements that are classified as toxic include: Cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) [49]. Heavy metals such as lead and cadmium have been reported to be a concern in the application of sewage sludge for agriculture use in the European Union [48]. Heavy metals availability in soil is influenced by soil pH, organic matter, clay content, and cation exchange capacity that influence metal speciation. Cation exchange capacity (CEC) and redox potential also affect heavy metal uptake by plants [29]. Lime amendment reduces soil acidity as well as plant metal uptake [40]. The mobility of some heavy metals can also be decreased by lime amendment whereas for some metals such as chromium and copper limited change in mobility were observed with lime amendment in the form of calcium oxide [50].

Per capita food production in Eswatini and other parts of sub-Saharan Africa will continue to decline unless soil fertility depletion is addressed [51]. Soil fertility depletion in smallholder farms is recognized as the basic cause of declining *per capita* food production in Africa. In Eswatini, Maize is a staple food and is grown in all four agro-ecological zones, that is, Highveld, Middleveld, Lowveld and Lubombo Plateau. The crop is grown as a household staple by small scale famers who sell some of it if they have produced a surplus [52]. The average yield per hectare of maize 1.5 mt. ha^{-1} compared to more than 8.0 $mt.ha^{-1}$ in research trials whereas some favorable agro-ecological zones such as in Highveld and Middleveld have higher potential for greater yield, the yield is restricted to 3.0 $mt.ha^{-1}$ [52] The reason for poor yield is low or no fertilizer application which is worsened by the fact that fertilizer costs are high which most small scale farmers cannot afford with their limited financial resources. Past trends in Maize *per capita* consumption in Eswatini showed decreasing trends while the *per capita* output for other food crops namely potato and sweet potatoes remained constant [53]. The declining trend in *per capita* crop production in Eswatini in general indicated that Eswatini has been unable to meet its maize consumption from domestic production and imports of maize and other food crops, especially rice is required to bridge this gap. Therefore, there is a challenge for Eswatini in meeting its food security and poverty reduction objectives.

The trend of fertilizer usage in Eswatini has shown consistent increase over the years. According to the report by the Regional Strategic Analysis and Knowledge Support System for Sothern Africa (ReSAKSS-SA), fertilizer use has increased substantially and far surpasses the SADC-RISDP target [52]. However, even though the fertilizer usage has improved substantially, this has not translated into

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crop yield improvement. This has the implication that the fertilizer use is not uniformly distributed across major crops and farmer types. The fertilizer use is mainly by large scale farmers, and some smallholder irrigation farms especially the sugar cane production which is the major agricultural crop of Eswatini. According to the report by Dlamini and Masuku [54], small holder farmers fail to meet the recommended fertilizer application rates due to the constraints of operational costs, mainly credit.

MATERIALS AND METHODS

The research work followed a quantitative evaluation of the nutrient potential as well as risks to application of sludge to agriculture. Experimental technique has been used to quantify the physical and chemical characteristics of sludge samples using commonly adopted laboratory standard operating procedures for each parameter. For the experimental evaluation purposes, samples of dried and stored wastewater sludge were collected from seven wastewater treatment plants in Eswatini located at different regions within the country. The methods of determination for the physical and chemical parameters are specified in the sampling and laboratory analysis section.

The study area

According to the agro ecological zone classification of Eswatini [51], the Highveld is a mountainous region on the western side of Eswatini with a temperate climate of warm wet summers and dry winters. The Middleveld is a hilly grassland region with a warm, subtropical climate ideal for cultivating various crops. It is the main agricultural area of Eswatini. The Lowveld is a rolling lowland region further east, covering about 40% of the country. It has a near tropical climate and is prone to drought, but sugarcane, cotton and cattle are found in this region.

Highveld and Middleveld soils are characterized by intense weathering and leaching and with very deep soil formation (Ferrisols and Ferralitic soils). They have low Cation Exchange Capacity (CEC) clay and low base saturation of the exchange complex. The Middleveld and Lowveld soils are characterized by moderate weathering (Pseudopodzolic soils, Brown soils, vertisols, and Halomorphic soils) [55]. They have a moderately high to high CEC clay and generally high base saturation.

According to Haque and Lupway [51, 62], soils in the Lowveld have higher calcium and magnesium than other soils. The Highveld contains significantly more organic matter and total and extractable aluminum, while the Lowveld region has significantly higher pH and cation exchange capacity. The Middleveld contained significantly less total nitrogen and phosphorus than soils in the other regions, implying that nitrogen-based fertilizers would be needed in this region.

The Lowveld had a significantly lower carbon to nitrogen C: N ratio than other soils. The Ca: Mg ratios ranged from 1:1 to 3:1 and soils in the Lowveld had significantly higher ratios than soils in the other regions. A Ca: Mg ratio of 3:1 to 4:1 is considered to be the optimum range of Ca:Mg ratios for most crops with lower ratios inhibiting phosphorus uptake and 1:1 as the lowest acceptable limit as calcium availability is reduced at lower rates.

Potassium deficiency is also anticipated in some low cation exchange capacity soils in the Highveld. The Highveld soils also contain less water extractable phosphorus than other soils. The exchangeable potassium reserves in the heavy soils of the sugarcane growing areas of Lowveld are reportedly lower, and less able to sustain potassium supply to plants on a long- term basis. In the Middleveld, native forage has been reportedly deficient in crude protein, and magnesium contents implying that the soil contents were low in magnesium and nitrogen. In general, most soils in Eswatini were deficient in phosphorus nutrient. Soils in the Highveld contain significantly more iron than other soils. Copper and zinc are generally highest in the Lowveld.

Sampling Sites

Figure 1 shows the location of the seven wastewater treatment plants within the kingdom of Eswatini from which samples of wastewater sludge were collected to determine the physical and chemical characteristics of sludge. The seven wastewater treatment plants range from traditional waste stabilization ponds to plants employing conventional treatment in the form of trickling filters and anaerobic digestion.

The Ezulwini - the wastewater treatment plant - is located in the lower area between Mbabane and Matsapha areas, and is receiving wastewater flows from the settlement areas in Mbabane. The treatment plant consists of settlement, trickling filter and anaerobic digester. The Matsapha waste water treatment plant receives wastewater flows from Matsapha area that includes the industrial site where several industries discharge their effluents into the receiving municipal sewer system that drains to the treatment plant sites. The old wastewater treatment plant at Matsapha was a series of waste stabilization ponds consisting of anaerobic, facultative, and maturation ponds. Recently a new treatment plant has been built that is in the form of an activated sludge plant, and is already operational.

The wastewater treatment plant at Nhlambeni receives wastewater flows mainly from Manzini areas and like the Ezulwini wastewater treatment plant consists of Settlement tank, trickling filter and anaerobic digester. The Hlathukulu wastewater treatment plant is regionally established to treat the wastewater in the less

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urbanized settlement of the area, and consists of settlement tank, waste stabilization pond, constructed wetland. Similarly, the wastewater treatment plants in Nhlangano and Piggs Peak consist of waste stabilization pond treatment system. The wastewater treatment plant at the town of Siteki consists of a treatment system based on percolating filter biological treatment similar to the Ezulwini and Nhlambeni treatment plants, and has settlement tank, trickling filter and anaerobic digester. However, the treatment plant has a larger capacity and seems to operate below capacity.

Table 1 shows the types of wastewater treatment processes existing in each of the seven wastewater treatment plants from which sampling was carried out.

The dried and stored wastewater sludge was available from Ezulwini, Matsapha, Nhlambeni, Nhlangano and Siteki sites. Samples were collected from these stored sludge piles. The Ezulwini and Matsapha sites sludge samples include: sludge that were stored over a 10 years period while the Siteki and Nhlambeni sludge samples were from piles that were stored over a period less than 10 years. Since dried and stored sludge samples were not available from the Piggs Peak, and Hlatikulu sites, samples were collected from within the anaerobic pond where most of the sludge is collected.

Sampling and laboratory analysis

Sampling

The locations of sampling within the piles were selected randomly while sampling was carried out from the surface, as well as the inner depths of the pile. Later in the laboratory, composite samples were prepared to get representative samples from the different pile depths.

The sludge samples were collected with plastic bags that were treated first with acid and then rinsed with distilled-deionized water. After collection, the sludge samples were dried at room temperature. The dried sludge samples were passed through 2 mm sieve to discard stones and roots, and then powdered to find sizes with mortar and pestle. The sludge samples were then stored in a refrigerator at 4˚C until they were analyzed.

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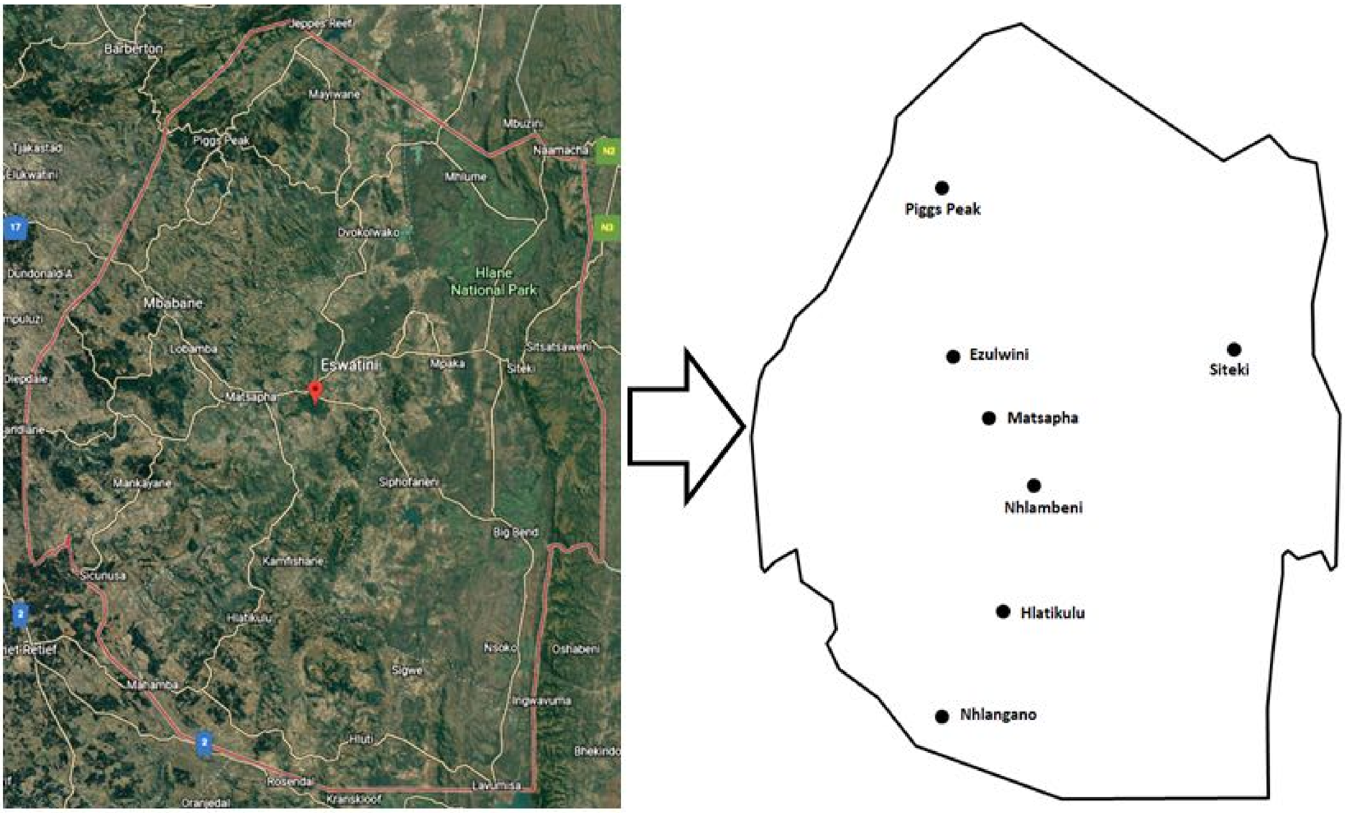

Figure 1: Wastewater treatment plant locations in Eswatini from which samples were collected

Laboratory analysis

The parameters determined by laboratory analysis included: pH, electrical conductivity, moisture content, dry solids percentage, volatile and fixed solids, organic matter, organic carbon, available nitrogen, available phosphorus, cation exchange capacity and metals. Table 2 shows the methods of determination used for each of the parameters analyzed. The physico-chemical characteristics of sludge samples were determined taking a minimum of three repetitions for each sample. The pH of the sludge was determined using a calibrated pH meter after mixing the sludge sample in a 1:2.5 (W/V) solution of distilled water and stirring the solution for 30 minutes using a glass rod [56]. The electrical conductivity of the sludge sample was measured using the sample solution prepared for pH [57]. 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 ˚C. Cation exchange capacity was determined using the USEPA method 9081 using sodium and ammonium acetate extractions [58]. Total fixed and volatile solids were determined using the gravimetric method according to Method 1684 of USEPA [59]. Organic carbon was determined by

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the Walkey and Black method [60]. Available nitrogen was determined by the Alkaline-Permanganate method [56]. The available phosphorus was determined using the Bray and Kurtz method [56]. The total metal determinations were carried out using two methods for comparison and quality assurance purposes. The methods used were atomic absorption spectrometer (Varian–AAS) and Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-OES) [61]. Sample digestion was carried out according to METHOD 3050B of the USEPA: Acid Digestion of Sediments, Sludge and Soils [62].

Data Analysis

The data obtained from the laboratory analyses were analyzed for ranges of variation, mean and standard deviation. Correlation between cation exchange capacity and available nitrogen as well as correlation among heavy metal elements was carried out using Pearson's correlation test. Significance tests of differences among average values of parameters such as organics, cation exchange capacity, etcetera, was carried out using the Analysis of Variance (ANOVA) for groups of samples from all treatment plants. For statistical analysis, the IBM Statistical Package for Social Sciences, SPSS, was used.

RESULTS AND DISCUSSION

Agricultural potential of sewage sludge

Table 3-5 shows the physico-chemical analysis results of the sludge samples. The organic matter content (Table 3) varies between 20% and 60%. Sludge samples from the Matsapha wastewater treatment plant (a waste stabilization pond) show low values of organic matter because the sludge underwent prolonged anaerobic decomposition within the waste stabilization pond before it was desludged (Figure 2). By contrast, the organic matter contents of the sludge from the Ezulwini, Siteki and Nhlambeni plants only underwent anaerobic digestion through a digester, and hence have greater content of organic matter.

The sludge from Ezulwini treatment plant may have comparable storage period of the sludge as the Matsapha sludge, and the effect of sludge storage is low on the Ezulwini treatment plant sludge as is evidenced by the high content of organic matter in the sludge. Despite the loss of organic matter in the anaerobic digestion, sludge samples from anaerobically digested processes still show up to 50% organic matter. The high content of organic matter in the sludge samples is evidence of the greater value of the sludge for agricultural application to soils.

According to the ANOVA test results using the F test criteria, there was quite a significant difference in the percentages of organic matter among the different sludge samples with p=0.003 (Table 6). Similar F-tests for sludge samples from wastewater treatment plants, namely, Nhlambeni, Siteki and Ezulwini show there is

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significant difference among the samples from the three stations with respect to their organic matter contents (p=0001).

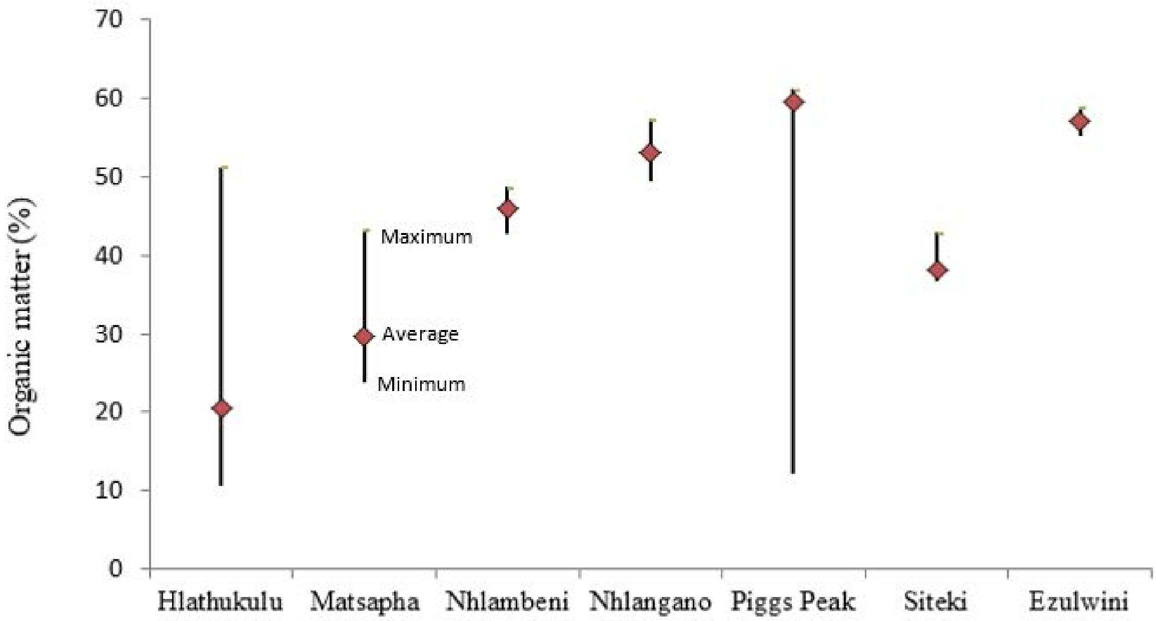

Figure 2: Organic matter content in sewage sludge samples collected from different wastewater treatment plants in Eswatini

The cation exchange capacity (CEC) shown in Figure 3 is high, particularly for sludge samples collected from wastewater treatment plants that subject the sludge to anaerobic digestion process and that are relatively of recent age. The cation exchange capacities for Matsapha and Ezulwini treatment plants are relatively low, probably due to the combined effect of prolonged storage with leaching effects from rain. However, the level of statistical significance of differences in variation among samples from the different wastewater treatment plants is low. According to the ANOVA results using the F-test, the differences are insignificant (with p=.155 and Table 7). This implies that the sludge CEC characteristics seem to be common, largely unaffected by the nature of wastewater treatment processes.

A plot of the cation exchange capacity was made against the percentage nitrogen using pooled data from the analyzed sludge samples. The bounded nitrogen is strongly correlated with cation exchange capacity as shown in Figure 4 (Pearson's correlation coefficient of over 0.74 at p= 0.01 significance level (SPSS version 20). It is worth noting from Figure 4 that anaerobically digested samples behave differently in the CEC vs. nitrogen relationship probably due to more concentration of nitrogen as a result of the biomass loss. High CEC affects speciation in favor of ammonium as well as increasing struvite precipitation.

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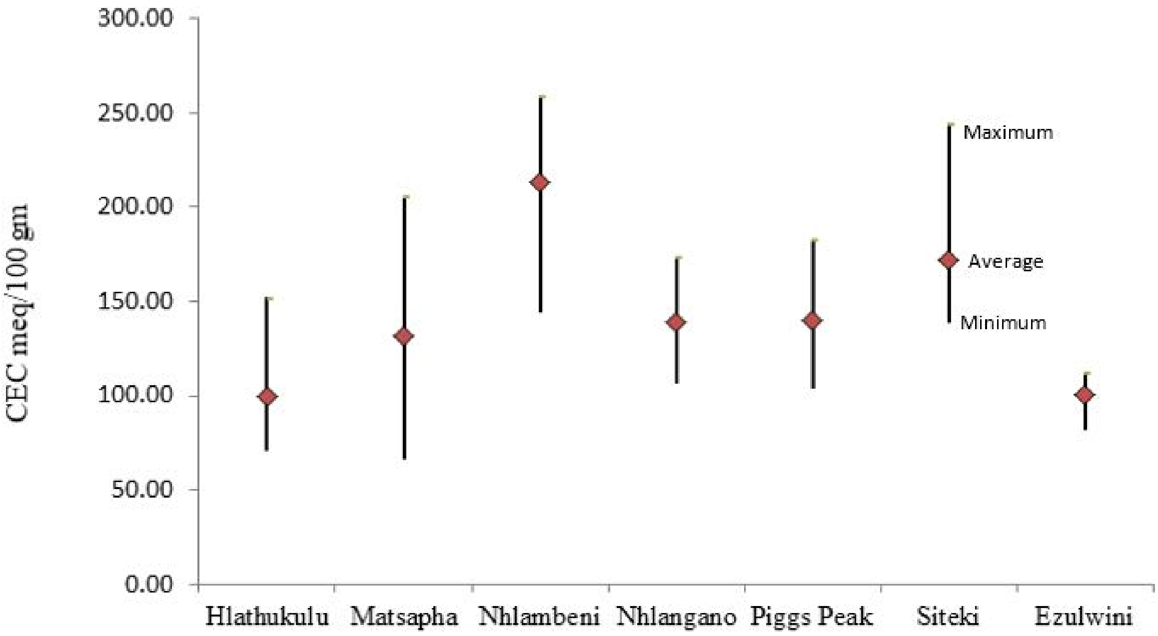

Figure 3: Cation exchange capacity (CEC) in sewage sludge samples

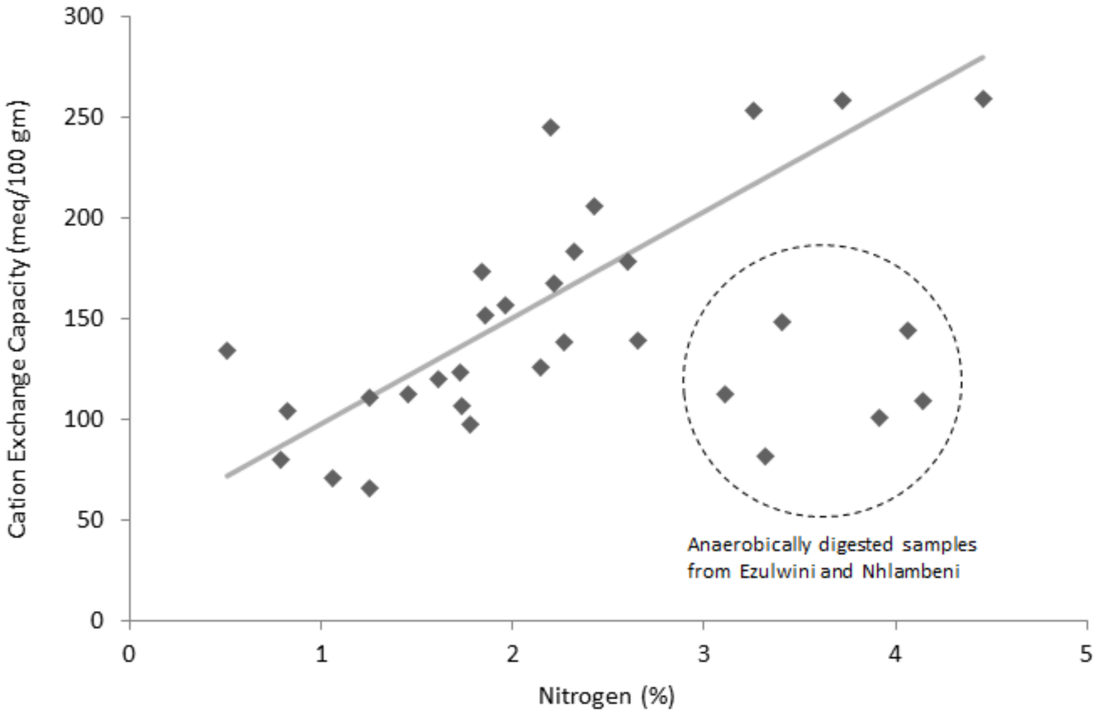

Figure 4: Variation of available nitrogen with cation exchange capacity in sludge samples

Because of biomass loss, the C/N ratios of sludge samples taken from waste stabilization ponds (Nhlangano and Piggs Peak in Figure 5) are greater than those

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from anaerobically digested samples (Ezulwini and Nhlambeni). The greater storage time of the Matsapha sludge in the anaerobic pond may have resulted in low C/N ratio. Higher C/N ratio limits nitrogen mobility and loss, making nitrogen available later during the growing period. The anaerobically digested samples, besides showing high percentage of nitrogen due to biomass loss in the form of methane and carbon dioxide, also have greater content of ammonium because of anaerobic conversion from organic nitrogen. It is also to be noted that despite the longer period of storage of the sludge samples such as the ones at Ezulwini, there is limited amount of nitrogen loss in the samples indicating there is a high extent of nitrogen immobilization.

The pH of the sludge samples (Figure 6) generally varies within a narrow range between 5 and 7 with a mean of 6.7. This pH is close to the recommended pH of sludge-amended soils that make nutrients available [31]. However, if the sewage sludge is to be applied to low pH and acidic soils, it is recommended to amend them with lime since humus production may further decrease the pH. It is also to be noted that this pH range can also increase the bioavailability of heavy metals. The sludge that underwent anaerobic digestion process such as those obtained from Nhlambeni, Ezulwini, and Siteki show relatively higher pH (and hence better nutrient retaining properties and less mobility of elements) compared to other samples.

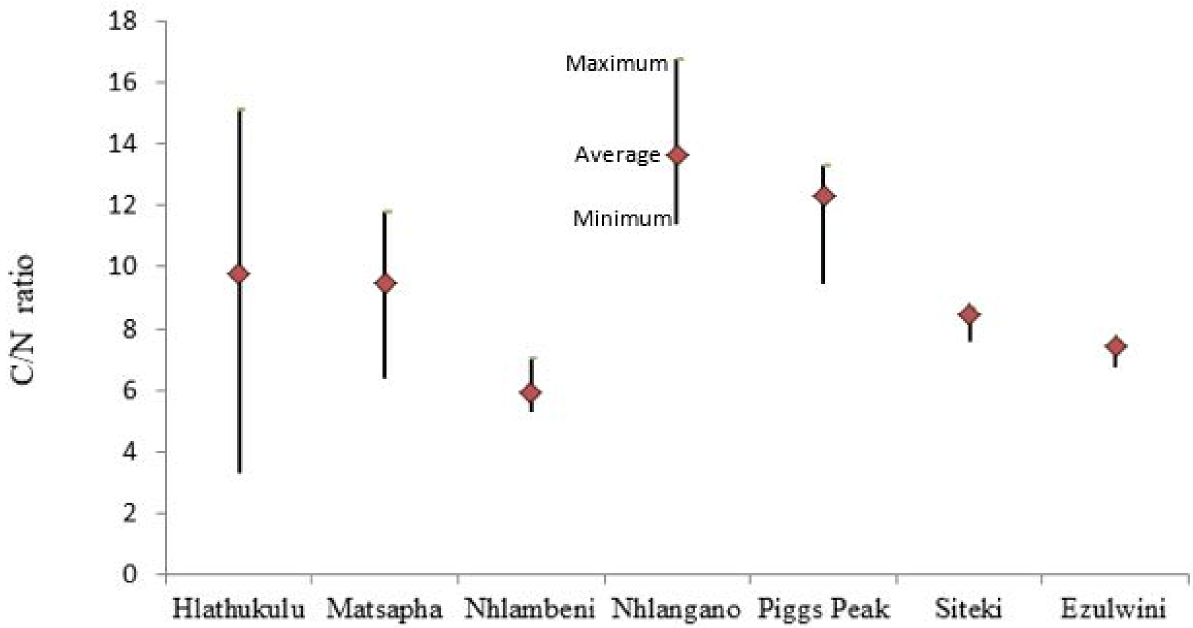

Figure 5: Carbon to available Nitrogen ratio in sewage sludge samples

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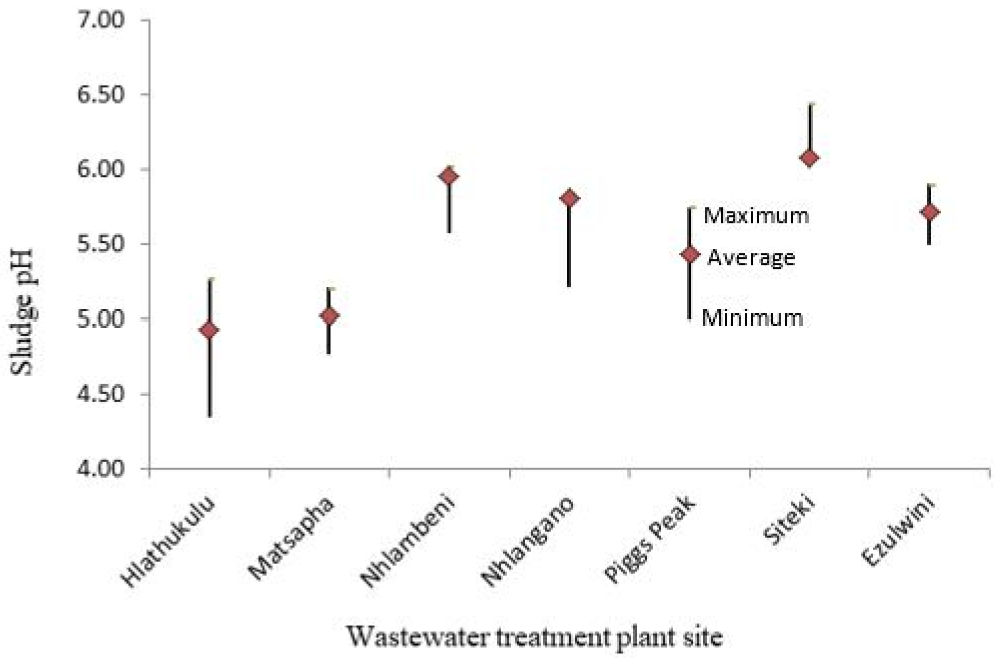

Figure 6: Variation of pH among sewage sludge samples from different treatment plants

The available phosphorus (Table 3) was determined to be high for most of the sewage samples analyzed. This level of phosphorus present, coupled with the fact that the pH of the sewage sludge is between 6 and 7, should make most of the phosphorus available for uptake by plants. Availability of phosphorus is affected less by organic matter decomposition because phosphorus also binds with inorganic matter.

Heavy Metal Concentrations

The data on heavy metals are given in Table 4 and 5. Figure 7, 8, 9, 10, and11 show variations of copper, chromium, nickel, lead and zinc concentrations, respectively among the seven wastewater treatment plant sites. From the tabulated data and the figures, it can be noted that the Matsapha wastewater treatment plant sludge produced high content of heavy metals compared with sludge samples taken from other treatment plants. This is because of the high concentration of metals in general from the industry effluents discharging into the wastewater treatment around the Matsapha area. In addition, samples from Nhlambeni and Ezulwini wastewater treatment plants also show relatively higher concentrations of heavy metals. The reasons could be because of the greater level of urbanization in these areas compared to the other sites and/or the increased mineralization as a result of anaerobic digestion processes employed in these two treatment plants.

The effect of the wastewater treatment process on the concentration of heavy metals can be observed from the sum of the absolute values of Pearson's correlation coefficients for each heavy metal against other metals shown in Table 8. The first-row values show the values where all treatment plants are included. The second row is only for treatment plants that employ anaerobic digestion, namely, Nhlamebni. Ezulwini and Siteki treatment plants. The high correlation present in both rows (such as for arsenic) may represent heavy metals with similar sources whereas differences in correlation among the treatment plants may indicate the influence of the treatment process on metal concentrations [63]. As is apparent from the data in Table 8, the second row exhibits a high sum of correlation coefficients indicating a strong influence of wastewater treatment processes, such as anaerobic digestion in the concentration of heavy metals in sludge.

Evaluation of heavy metal risks based on national standards
The risks due to heavy metals were evaluated by comparing the measured concentration of heavy metals against known standards, and regulatory limits such as those from South Africa, China, USA and the European Union. It should be noted that national standards specify minimum standards and the effect of heavy metals in soils is influenced by the rate of application of sewage sludge to soils [23]. It will be noted from Figures 7-11 that the heavy metals concentrations were below the limits for most of the sludge samples. The concentrations of copper shown in Figure 7 are generally low, and below the regulatory limits mentioned. Copper is mostly bound with organic matter and its bio availability may increase as the organic matter is mineralized with time. In addition, higher chloride content increases copper mobility because of greater solubility.

The chromium and nickel concentrations are shown in Figures 8 and 9, respectively. Except the wastewater sludge samples from Matsapha, these metal concentrations are shown to be within the regulatory limits specified. This is an indication that, except for the Matsapha sludge, sludge samples from the other wastewater treatment plants carry lower risk of toxicity due to chromium and nickel. The lead concentration shown in Figure 10, indicates that for all of the sludge samples, the lead concentrations are well below the regulatory limits. Lead is known to be highly immobile and its translocation in plants is limited. The zinc concentration shown in Figure 11 indicates that the concentrations are below the limits stipulated by South Africa, The United States Environmental Protection Agency, USEPA and The European Union, EU guidelines. This implies that all of the wastewater sludge samples are safe with respect to zinc toxicity. Zinc is a useful trace element but high concentrations are toxic to both plants and animals.

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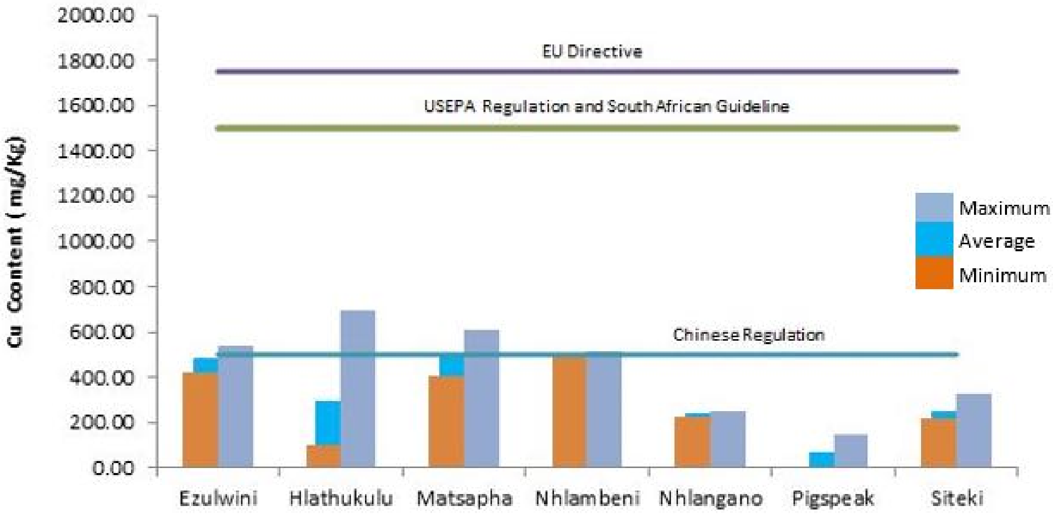

Figure 7: Copper contents of sludge from wastewater treatment plants in Eswatini (graph showing minimum, average and maximum values against national standards)

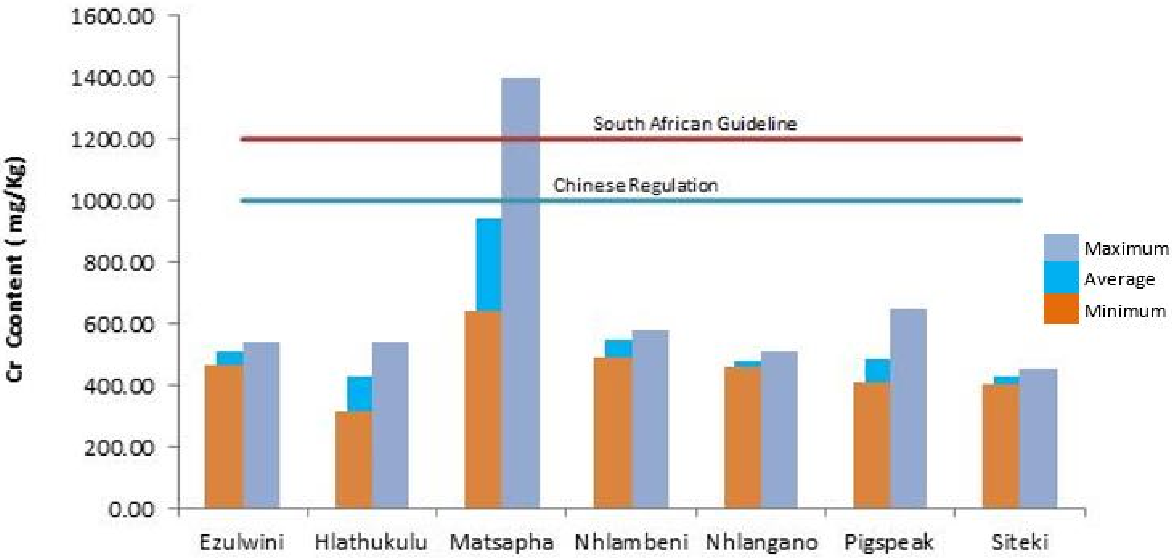

Figure 8: Chromium contents of sludge from wastewater treatment plants in Eswatini (graph showing minimum, average and maximum values against national standards)

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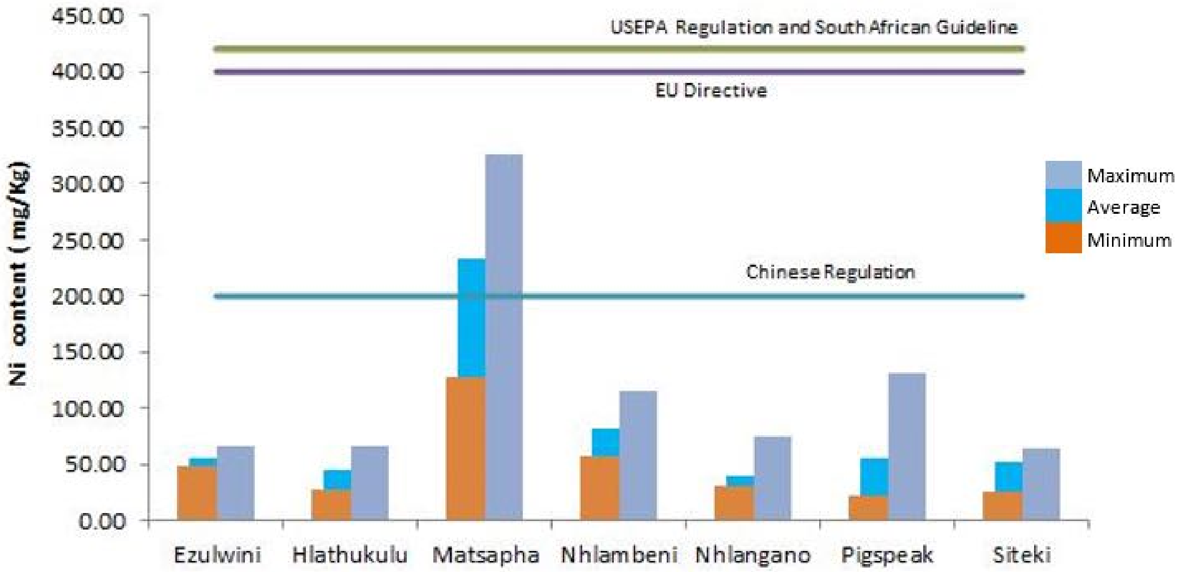

Figure 9: Nickel contents of sludge from wastewater treatment plants in Eswatini (graph showing minimum, average and maximum values against national standards)

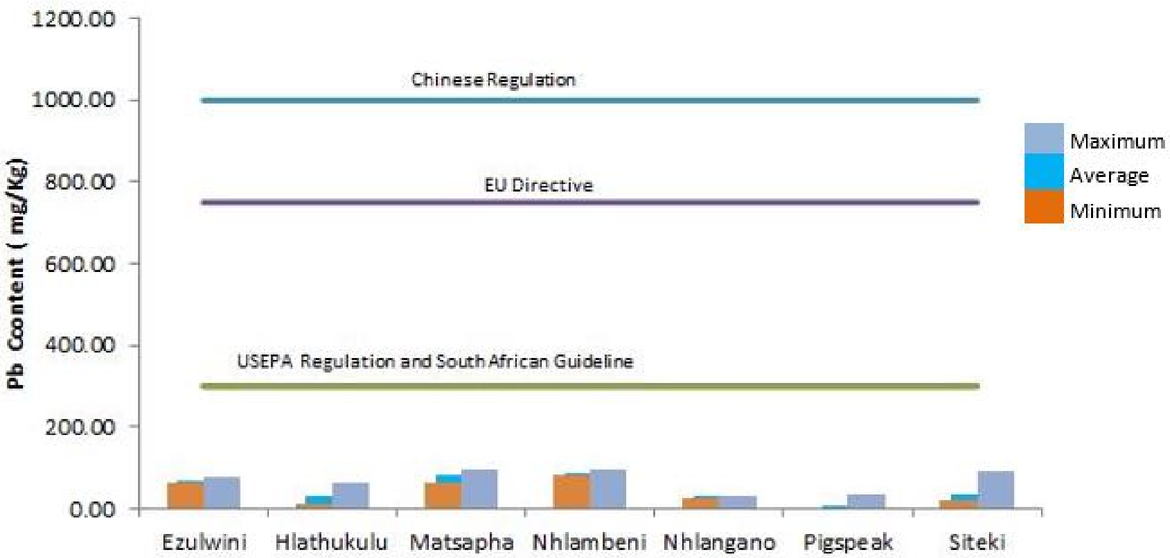

Figure 10: Lead contents of sludge from wastewater treatment plants in Eswatini (graph showing minimum, average and maximum values against national standards)

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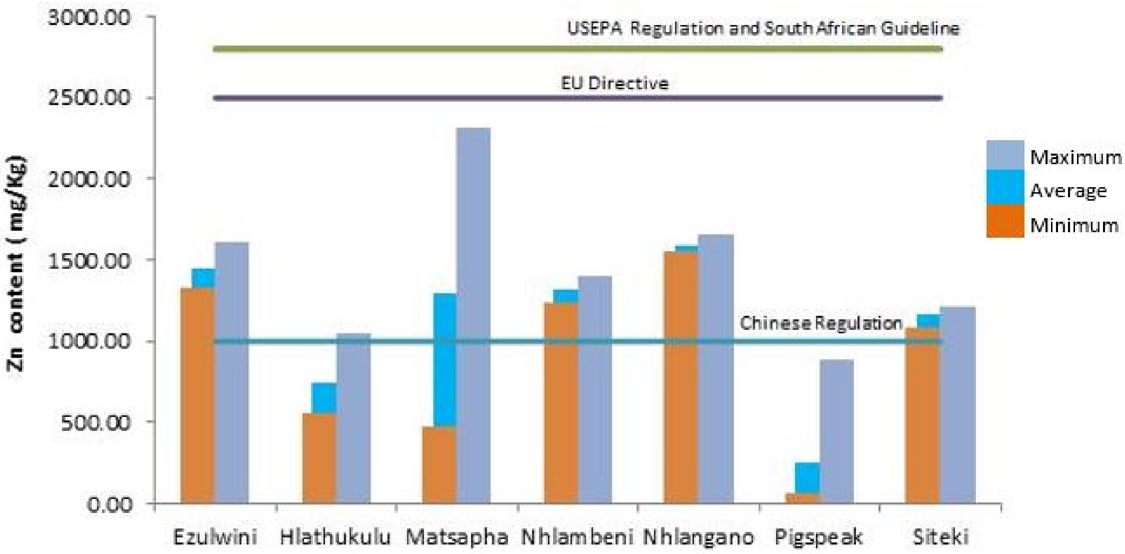

Figure 11: Zinc contents of sludge from wastewater treatment plants in Eswatini (graph showing minimum, average and maximum values against national standards)

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

Sewage sludge is known for its potential to supplement soils with nutrients as well as modifying the soils' physical, chemical and biological properties making them conducive to better plant growth and yields. On the other hand, the constituents of sewage sludge and the toxicities that may be present may also pose risks to the soil, plants and humans. Moreover, the rate of application of sewage sludge and the determination of whether the sludge requires further amendment such as with lime to increase the pH depends on the quality of the sludge as established. It is, therefore, necessary to characterize the quality of processed sludge before application of the sludge to agricultural lands.

With all the observed benefits of dried sewage sludge in the form of nutrients, trace elements and characteristics that improves the soil fertility, the value of sewage sludge as soil conditioner is apparent, and its use should be given greater attention. Moreover, the economic benefits are apparent as mineral fertilizers are costly and their production is energy intensive. In addition, some fertilizers such as phosphorus have limited resource availability. The current rate of fertilizer use in Eswatini particularly by individual and small scale farmers is hampered by the high cost of mineral fertilizers. Sewage sludge can provide a low cost locally available alternative to such farmers for use.

However, the potential for the use of sludge as soil amendment has to be supported by a proper policy and regulatory provision in order to encourage the use as well as limit the potential side effects due to the presence of harmful heavy metals, and in the case where sludge is not adequately treated from pathogenic organisms. Currently, there is no national regulation regarding the safe limits of heavy metals in sludge for agricultural application, and reference has to be made to standards developed by other countries including USA, the EU, South Africa and China. There is a need for developing national guidelines and standards for the safe use of sewage sludge in Eswatini as informed by experience from other countries, and local evidence of the use of sewage sludge. According to the comparison of the different countries' standards of heavy metals in sludge, it is recommended that the USEPA regulation be used as a less stringent standard, and more applicable to the situation in Eswatini. Moreover, the experience of USEPA in developing heavy metal standards is longer and wider which increases the reliability of using such standards.

The trace heavy metal concentrations are mostly low for all the sludge samples. Comparison of trace heavy metal concentrations with regulatory limits from South Africa, USA, European Union and China were made. It was found out that only the sewage sludge sample from the Matsapha wastewater treatment plant showed nickel and chromium concentrations above the regulatory limits. This is not surprising as Matsapha is an industrial area where many of the industries release wastewater to the centralized sewer system after minimal treatment. Sludge samples from Nhlamebni and Ezulwini treatment plants also show higher concentration probably due to increasing urbanization and the mineralization effect of anaerobic digestion processes existing in these two treatment plants. Except the Matsapha sludge, all the sludge samples from the other six wastewater treatment plants are safe for agricultural application with respect to heavy metal toxicity.

Further research is recommended using pilot experimental plantation studies to evaluate the results of application of sewage sludge as soil amendment for agriculture under different soil environments, as well as study the mobility of heavy metals into plants, and the risks that may be posed by application of sewage sludge as soil amendment. This is important due to the fact that application of sewage sludge to soil at an increasing rate has the incentive of providing more nutrients to the soil, whereas on the opposite side the risk due to heavy metals and other substances can increase. It is, therefore, necessary to evaluate through such experimental studies both the positive and negative benefits of sludge application both in the short and long term.

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Table 1: Wastewater treatment processes existing in the sites from which sludge samples were collected

#	Treatment plant Location	Type of wastewater treatment processes
1	Ezulwini	Conventional wastewater treatment process involving screening, grit removal, primary settlement tanks, two stage percolation filter, secondary settlement tank, chlorination, sludge thickening, anaerobic digestion and sludge drying beds.
2	Matsapha	Wastewater treatment process involving screening, grit removal, waste stabilization pond consisting of anaerobic, facultative and maturation ponds followed by disinfection using chlorine.
3	Hlatikulu	Wastewater treatment process involving screening, grit removal, waste stabilization pond system consisting of anaerobic, facultative and maturation ponds followed by wetland treatment process.
4	Nhlangano	Wastewater treatment process involving screening, waste stabilization pond system consisting of anaerobic, facultative and maturation ponds.
5	Siteki	Conventional wastewater treatment process involving screening, grit removal, primary settlement tanks, two stage percolation filter, secondary settlement tank, chlorination, sludge thickening, anaerobic digestion and sludge drying beds.
6	Piggs peak	Wastewater treatment process involving screening, grit removal, waste stabilization pond system consisting of anaerobic, facultative and maturation ponds.
7	Nhlambeni	Conventional wastewater treatment process involving screening, grit removal, primary settlement tanks, two stage percolation filter, secondary settlement tank, chlorination, sludge thickening, anaerobic digestion and sludge drying beds.

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Table 2: Laboratory analysis methods for the sludge physico-chemical parameters analyzed

Parameter	Method of determination
pH	Potentiometric method with glass electrode
Electrical conductivity	Resistivity method using conductivity meter
Cation exchange capacity (CEC)	Extraction with sodium acetate (USEPA method 9081)
Total, fixed and volatile solids	Gravimetric method
Moisture and dry solids percentage	Gravimetric method
Organic carbon	Walkey and Black method
Available nitrogen	Alkaline Permanganate method
Available phosphorus	Bray and Kurtz method
Heavy metals	Atomic absorption spectrometer (Varian–AAS) and inductively coupled plasma atomic emission spectrometry (ICP-OES)

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Table 3: Physico-chemical characteristics of sludge samples collected from waste treatment plants in Eswatini

Parameter	Unit	Value	Hlatikulu	Matsapha	Nhlambeni	Nhlan-gano	Piggs Peak	Siteki	Ezulwini
Cation Exchange Capacity	(meq/ 100 gm)	Median	88	123	253	138	159	153	105
		Range	71 -151	65 - 205	144 - 259	106 - 173	103 - 615	138 - 244	81 - 112
		Stdev	36	46	63	31	239	50	13
Electrical Conductivity	(µS /Cm)	Median	1775	2840	3130	2220	939	2780	983
		Range	1014 - 2090	1062 - 7220	2530 - 3720	1181 - 2460	611 - 1087	2640 - 2920	648 - 1646
		Stdev	436	1819	483	507	186	106	440
pH	(pH Units)	Median	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
		Stdev	0.44	0.15	0.18	0.27	0.30	0.17	0.17
Organic carbon	(%)	Median	10	15	23	27	30	19	29
		Range	5 - 25	12 - 22	21 - 25	25 - 29	6 - 31	18 - 22	28 - 30
		Stdev	9	3	1	2	1	1	1
Organic matter	(%)	Median	20	30	46	53	60	38	57
		Range	11 - 51	24 - 43	43 - 49	49 - 57	12 - 61	37 - 43	55 - 59
		Stdev	18	6	3	3	1	3	2
Volatile solids	(%)	Median	14	33	52	47	83	35	51
		Range	9 - 45	28 - 42	45 - 84	47 - 48	9 - 85	35 - 48	43 - 55
		Stdev	17	5	16	1	1	5	5
Nitrogen	(%)	Median	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
		Stdev	0.5	0.5	0.5	0.3	1.1	0.3	0.4
C/N ratio		Median	10	9	6	14	12	8	7
		Range	3-15	6-12	5-7	11-17	9-13	8-9	7-8
		Stdev	4,5	1,5	0,8	2,2	1,7	0,5	0,5
Phosphorous	(%)	Median	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
		Stdev	0.17	0,12	0,11	0,06	0,43	0,12	0,04

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

Parameter	Unit	Hlatikulu			Matsapha		
		Median	Standard deviation	Range	Median	Standard deviation	Range
As	mg/kg	67	39	45 - 134	139	18	115 - 169
Co	mg/kg	79	45	57 - 163	92	9	80 - 107
B	mg/kg	93	24	75 - 135	70	26	45 - 137
Cr	mg/kg	452	99	317 - 543	943	242	642 - 1396
Cu	mg/kg	208	234	103 - 696	528	71	405 - 606
Mo	mg/kg	5	2	1 - 6	18	5	10 - 25
Ni	mg/kg	48	536	24 - 1242	233	61	128 - 327
Pb	mg/kg	14	26	12 - 65	83	12	65 - 96
Sn	mg/kg	292	45	210 - 324	434	113	294 - 601
Zn	mg/kg	729	186	553 - 1046	1402	575	478 - 2311
Ca	(%)	0.67	0.17	0.38 - 0.85	0.89	0.31	0.53 - 1.51
K	(%)	0.05	0.04	0.04 - 0.13	0.12	0.04	0.09 - 0.18
Mg	(%)	0.06	0.03	0.04 - 0.10	0.21	0.05	0.14 - 0.30
Na	(%)	0.07	0.01	0.07 - 0.09	0.18	0.13	0.11 - 0.53
Si	(%)	0.02	0.02	0.01 - 0.05	0.07	0.03	0.03 - 0.12
Al	(%)	0.00	0.64	0.00 - 1.42	0.00	0.00	0.00 - 0.00
Fe	(%)	2.15	0.90	1.66 - 3.62	2.46	0.39	1.85 - 3.16
As	mg/kg	102	2	100 - 106	115	4	107 - 118
B	mg/kg	79	12	65 - 95	77	9	64 - 83
Cr	mg/kg	561	34	493 - 579	472	18	462 - 507
Cu	mg/kg	501	12	491 - 518	239	10	227 - 251
Mo	mg/kg	6	1	4 - 7	6	1	5 - 7
Ni	mg/kg	74	23	57 - 115	15	19	0 - 75
Pb	mg/kg	90	6	80 - 96	28	2	28 - 32
Sn	mg/kg	372	23	323 - 382	307	13	280 - 310
Zn	mg/kg	1357	69	1238 - 1400	1577	42	1549 - 1659
Ca	(%)	1.07	0.16	0.93 - 1.36	1.22	0.06	1.12 - 1.27
K	(%)	0.14	0.00	0.13 - 0.14	0.16	0.01	0.15 - 0.16
Mg	(%)	0.31	0.02	0.28 - 0.33	0.22	0.01	0.21 - 0.23
Na	(%)	0.10	0.01	0.08 - 0.10	0.14	0.01	0.12 - 0.14
Si	(%)	0.05	0.02	0.03 - 0.07	0.07	0.02	0.05 - 0.10
Al	(%)	0.00	0.00	0.00 - 0.00	0.00	0.00	0.00 - 0.00
Fe	(%)	2.49	0.10	2.28 - 2.54	2.81	0.05	2.74 - 2.86

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Table 5: Macro and trace element concentrations characteristics of sludge samples collected from waste treatment plants in Eswatini

Parameter	Unit	PiggsPeak			Siteki			Ezulwini		
		Median	Standard deviation	Range	Median	Standard deviation	Range	Median	Standard deviation	Range
As	mg/kg	12	69	5 - 139	149	6	137 - 151	150	11.41	141 - 169
Co	mg/kg	21	43	19 - 100	114	52	-7142 - 120	104	6.32	103 - 118
B	mg/kg	50	15	30 - 72	85	8	72 - 94	88	15.65	59 - 101
Cr	mg/kg	429	102	409 - 648	435	25	403 - 453	528	34.88	468 - 542
Cu	mg/kg	32	62	8 - 146	241	44	215 - 328	479	46.74	417 - 536
Mo	mg/kg	2	1	0 - 4	5	232	4 - 524	5	1.24	4 - 7
Ni	mg/kg	4	49	0 - 131	60	16	25 - 65	54	6.36	48 - 65
Pb	mg/kg	7	15	0 - 35	23	31	21 - 92	71	5.35	64 - 76
Sn	mg/kg	290	9	277 - 303	169	47	159 - 248	203	30.98	141 - 207
Zn	mg/kg	93	356	69 - 882	1182	57	1082 - 1216	1441	122.89	1331 - 1610
Ca	(%)	0.51	0.19	0.12 - 0.60	1.33	0.14	1.22 - 1.59	0.77	0.11	0.63 - 0.92
K	(%)	0.28	0.18	0.07 - 0.49	0.18	0.01	0.17 - 0.19	0.12	0.00	0.12 - 0.13
Mg	(%)	0.14	0.03	0.12 - 0.19	0.41	0.02	0.38 - 0.43	0.22	0.01	0.20 - 0.23
Na	(%)	0.07	0.01	0.06 - 0.08	0.14	0.02	0.11 - 0.14	0.04	0.01	0.02 - 0.05
Si	(%)	0.08	0.02	0.05 - 0.10	0.04	0.01	0.03 - 0.04	0.05	0.01	0.04 - 0.06
Al	(%)	0.45	0.28	0.00 - 0.54	0.00	0.00	0.00 - 0.00	0.00	0.00	0.00 - 0.00
Fe	(%)	0.91	0.90	0.86 - 2.56	2.96	0.07	2.85 - 3.01	2.89	0.27	2.30 - 2.95

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Table 6: ANOVA test results for organic matter among the seven wastewater treatment plants

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3429.059	6	571.510	4.504	.003
Within Groups	3426.000	27	126.889		
Total	6855.059	33			

Table 7: ANOVA test results for CEC among the seven-wastewater treatment plants

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	89263.461	6	14877.243	1.731	.155
Within Groups	214894.414	25	8595.777		
Total	304157.875	31			

Table 8: Sum of correlation coefficients of heavy metal elements

Treatment plant	As	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Sn	Ti	V	Zn
All treatment pants	6.6	4.2	4.4	5.2	5.7	4.6	4.2	4.3	5.1	4.2	4.9	5.0	5.5
Anaerobically digested plants	6.7	5.9	10.0	9.8	8.9	9.7	9.6	8.0	9.9	7.1	9.6	9.7	7.4

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