CHARACTERIZATION OF ANAEROBIC DIGESTATES FROM BIOGAS PLANTS FOR THEIR PLANTS NUTRIENTS VALUE

Emmanuel Baffoe Tanor[a], Sibusisiwe Magama[b]

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Abstract: The application of digestate from biogas production could be a cost-saving and eco- friendly method of disposal of biodegradable organic waste and recycling nutrients for sustainable agricultural production. The aim of this study is to characterize solid digestates from eight small-scale fixed dome digesters fed with mixed organic wastes and operated on the semi-continuous feeding method. The physico-chemical characteristics, plant nutrients and heavy metals were investigated. The nutrients content and the physico-chemical characteristics of the digestates indicate that they contained significant amounts readily available forms of essential major plant nutrients (N, P, S, Ca and Mg) that can enhance plant growth when applied to soils. The digestates contained some micronutrients (Co, Cu, Fe, Mn, Mo, Ni and Zn) as well. However, these digestates may only be applied as partial replacement for mineral fertilizers due to the low concentrations of some of the nutrients. The heavy metals (As, Cd, Hg, Pb) were also present, but in concentrations many times lower than the recommended maximum guideline limits

Keywords: Biodigester, Digestate, Biofertiliser, Nutrients, Manure, Food waste, Macronutrients, Micronutrients

[a]. National University of Lesotho, Department of Chemistry and Chemical Technology, P.O. Roma 180, LESOTHO
[b]. National University of Lesotho, Department of Biology, P.O. Roma 180, LESOTHO

***Corresponding Author**

E-mail: eb.tanor@gmail.com

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INTRODUCTION

The challenge of providing enough food to feed the growing population of the world at the minimum environmental impact and to ensure long-term agricultural production without compromising the goals of sustainable development requires good and improved farming practices (Eyhorn et al, 2019). These include the adoption of innovative and cost effective systems of primary production and the application of non-conventional environmentally friendly soil amendment and conditioning materials as alternatives to the intensive application of synthetic chemical fertilizers. This is essential to mitigate or eliminate, if possible, the environmental and health impacts of these chemical fertilizers (Sanchez, 2020, Kumar, et al, 2019, Xu et al, 2019).

Any natural material that maintains or improves the properties of the soil and boost crop yield when applied to the soil could be used as a soil amendment resource. Anaerobic digestates are a good alternative source to fertilizer (Makádi, Tomócsik and Orosz 2012), because they are rich in essential plant nutrients like nitrogen; N, organic matter; OM, phosphorus; P, potassium; K, calcium; Ca, magnesium; Mg), and sulphur; S (Insam, Gómez-Brandón, & Ascher, 2015; Nkoa, 2014) and micronutrients (Makádi, Tomócsik and Orosz 2012). The use of anaerobic digestates in agricultural production is well documented (Lee, Steinman and Angelo 2021) and have been demonstrated to have an excellent fertilizer potential. Crops fertilized with anaerobic digestates have shown either similar or higher yields compared to those fertilized with synthetic inorganic fertilizer or undigested animal manures or slurries (Nkoa, 2014). Though anaerobic digestates provide many benefits as a substitute for synthetic inorganic chemical fertilizers, their application to agricultural soil must be done with caution as it comes with challenges, such as nutrient imbalances, contamination with toxic metals and pathogenic microorganisms (WHO, 2005). Their over-application may lead to other problems like leaching of nutrients and accumulation of heavy metals, which are usually present in digestate in varying degrees (Insam, Gómez-Brandón and Ascher 2015; Alburquerque et al, 2012; and their uptake by plants, and eventually end up in the food chain (Antonious & Kochhar, 2009). Moreover, increasing concentrations of these heavy metals in soils may disturb the natural balance of chemicals in the soil, which can negative impact on soil microbiota and eventually affect soil health and fertility because of the vital role microorganisms play in soils. The common heavy metals such as, As, Cd, Cr, Pb, and Hg have no established biochemical and physiological functions in humans, animals or plants and are considered as undesirable substances or contaminants. A potential source of heavy metals in anaerobic digestates is from the feedstock of the biodigesters and impurities in the minerals added as supplements to animal feed (Nicholson et al, 2013). Although these metals are highly toxic, even at low concentrations in water and food, the physiological role of arsenic in poultry has been confirmed (Živkov et al, 2019) and also organic arsenic has been used for the control of diseases in pig and poultry production for decades, though banned in some countries, but it is still used in other countries (Li et al, 2005). There is no literature reference to suggest that Cd is added to livestock feed, therefore, any contamination is due to impurities from mineral supplements such as zinc salts (Li et al, 2010).

The anaerobic digestion of organic waste for biogas production is an emerging technology in Lesotho and is slowly being adopted, especially by households (Lebofa, 2012). The common biodigesters in Lesotho are the fixed dome plants, because of the low cost in design, low maintenance requirements, and long life span (Kranert et al, 2012). The solid digestate from these small-scale household biodigesters is applied on backyard vegetable gardens as a biofertilizer as a cheaper and beneficial option for its disposal. However, there is limited study on the fertilizer value, environmental impact and health effects of the application of the digestate on soil. The few studies done focused on the liquid fraction of the digestates (Tanor et al, 2021; Amoah et al, 2018). There is a sustained increase in the number of these small-scale bioreactors because of the numerous economic and environmental benefits (Bhatt & Tao, 2020, Zaks et al, 2011) with the corresponding increase in the volume of the digestate generated. The potential end use of the digestate as a fertilizer depends on the chemical composition, a better knowledge and understanding of the agronomic value and the environmental and human health impacts associated with their application on agricultural land. Therefore, prior to application, the composition is vital to ensure that other components like potential and toxic metals are within the acceptable limits.

The aim of the current study is to characterise the solid anaerobic digestates from 8 selected small-scale fixed dome biodigesters in Maseru, Lesotho for their potential for application as biofertiliser. The biodigesters are assumed to be operating under psychrophilic conditions, because the annual temperature range in Maseru is 5.1o C to 32o C with a mean of 15.2o C and there is no control of the operating temperature of these digesters.

EXPERIMENTAL

MATERIALS AND METHODS

The study was carried out on the solid digestates from eight selected small-scale fixed dome biodigesters (BD) for the production of biogas for households, mainly for cooking and heating. The biodigesters are denoted as BD1 to BD8. All the biodigesters were single stage digestion and operating under the semi-continuous feeding method and the feedstock was a mixture of different organic waste waste;food waste (FW), domestic wastewater (DW) and green garden waste (GW), which were common to all the 8 biodigesters. In addition some for the feedstock contained pig slurry (PS), chicken manure (ChM) or cow manure (CwM). The composition of the feedstock for the biodigesters is shown in Table 1.

The study focused on the physicochemical characteristics, plant nutrients, and toxic metals. The selection of the parameters for analysis was guided by the National Wastewater Discharge Standards (NES, 1997) the WHO guidelines for use of wastewater and its treatment products in agriculture (Aryes & Westcot, 1994) and South African guidelines for the utilisation and disposal of wastewater sludge, (DWAF, 2006). The composition of the feedstock for the bio-digesters is shown in Table 1 below. The proportions of the various components of the feedstock were unknown, because such data was not kept by the various households. The biodigeseters operated under psychrophilic conditions (mean annual temperature range is 5.1o to 32o C) and the secondary treatment of the effluent from the bio- digesters was achieved by gravel filter beds, because low cost operation and maintenance requirements and requires minimum skill labour (Carr et al, 2004).

Table 1. Feedstock of the biodigesters

Digester		*Treatment units	§Feedstock					
ID	Size, m3		PS	ChM	CwM	FW	DW	GW
BD1	6.0	AD → PGF	x	x		x	x	x
BD2	5.0	AD → PGF		x		x	x	x
BD3	4.0	AD → ST →PGFB	x	x	x	x	x	x
BD4	6.0	AD → PGF		x		x	x	x
BD5	9.0	AD → PGF	x		x	x	x	x
BD6	9.0	AD → PGF	x			x	x	x
BD7	18.0	AD → PGF	x	x		x	x	x
BD8	4.0	AD → PGF		x		x	x	x

*PGFB – AD – Anaerobic digestion, Planted gravel filter bed, PGF - planted filter bed, ST - Septic tank
§PS – Pig slurry, ChW – chicken manure, CwM – cow manure, FW – food waste, DW – domestic wastewater, GW – green garden waste

Sample Preparation and Analysis

The samples were transported to the laboratory within 12 hours of collection and stored at 4oC before the chemical analyses. The samples were separated into solid and liquor fractions by passing through a 75μm sieve. The separated solid fractions were further separated by centrifugation at 2050G for 30 sec (Beckman J2-MC Centrifuge) (Moller, Hansen and Sorensen 2007). The separated samples were filtered through a <0.45μm sieve. The final solid fractions were air-dried at room temperature for 7 days. A set of the samples were acidified to pH 5.5 before the separation process to reduce the loss of nitrogen through NH3 volatilization during the sample drying process.

The moisture content; MC of the samples was determined by oven-drying at 105OC for 24 hours according to standard methods salts in the soil. 10 g of the dry sample was put into a conical flask and 10 mL 0.01 M CaCl2 solution added, mixed thoroughly and allowed to stand for 1 hour and the pH was measures using Hanna 8314 Membrane pH meter. The electrical conductivity; EC was measured in a digestate to water suspension in the ratio 1:5 by weighing 50g of the air dried digestate into a conical flask, added 250 mL deionised water and shaken for 1 hour on a mechanical shaker and then allowed to stand still for 20 min (Loveday, 1974). The conductivity of the suspension was measured at 25oC with conductivity meter (Condi-330i, WTW).

The total solids; TS, volatile solids; VS, total nitrogen; TN, ammonium nitrogen (NH4+-N), total phosphorous (P) and chemical oxygen demand; COD were determined according to the Standard Methods for the Examination Water and Wastewater (Baird, Eaton and Rice 2017). Total organic carbon; TOC content was determined by wet dichromate oxidation method (Nelson & Sommers 1996). The digestion of samples for the determination of metals was according to method (U.S. EPA. 1996) and measured by ion-coupled plasma atomic emission spectrometry on a Varian ICP-AES. The determination of As and Hg incorporated hydride generation using Varian AAS FS220 spectrometer with a VGA77 unit (Sneddon et al, 2006). All chemicals, reagents and the standard solutions for AAS analysis were analytical grade (Merck Laboratory Supplies, Johannesburg, South Africa). A 1.0 g portion of the air-dried digestate sample was prepared for analysis by wet acid digestion (U.S. EPA. 1996).

Statistical Analysis

The data for the solid digestates were statistically analysed by the Tukey multiple comparisons test using one-way analysis of variance; ANOVA to determine if the mean values for the parameters for each of the digestate samples were significantly different from each other at significance level of $p<0.05$.

RESULTS AND DISCUSSION

The composition and characteristics of the solid digestate as a biofertilizer should be able to sustain the three closely inter-related components of soil, i.e. physical fertility, chemical fertility and biological fertility and the wide range of soil microorganisms and their highly complex and dynamic interactions with the physical and chemical components of soil (Möller & Müller 2012; Doran 2002).

Physico-chemical parameters

The physico-chemical characteristics of the digestates are shown Table 2. The digestates, though have very high moisture content (53.50 % to 90.33 %), they can be considered as solid digestates because the dry matter content was above 15% (Makadi et al, 2012) except for the digestate from biodigester BD3 whose TS content is 9.62%, because the values were within the reported range of moisture. The values are within the reported range of moisture, which is referred to as the non- dried solid fraction of digestate (Möller, 2016; Teglia, Tremier and Martel 2011). This means that the digestates had a low content of total solids – 9.62 – 46.56 %, of which the total organic carbon was in the range of 24.14 – 34.29 %.

The pH values of the digestates were weakly acidic to weakly alkaline and showed very little variation (6.95 - 8.27) among them because the feedstock had very little variations and were all fixed dome biodigesters and operated in the mesophilic range. The pH values were within the range recommended for land application, i.e. pH 5.50 to 9.50 (Tesfamariam et al, 2018), thus made them potential good soil amendment material.

The pH of the digestates is critical as it influences its potential applicability in acidic or alkaline soils. pH affects the bioavailability of plant nutrients because it largely determines the form in which these nutrients would exist in the soil. The ideal range for soil pH is between 6.5 and 7.5 because most plant nutrients are readily bioavailable (Jensen, 2018). However, for most crops, except for acid-loving plants, soil pH values up to 8.0 rarely cause any problems, pH above 8.0 will result in some severe deficiencies of micronutrients such as iron, zinc, and manganese (Clark and Baligar, 2000) as they form insoluble precipitates and therefore not available to plants. In acidic soils with pH < 5 the bioavailability of N, P, and K is often low while micronutrients tend to be more available except for molybdenum which appears to be more available in moderately alkaline soils. In highly acid soils(pH<5), at the same time, metals such as aluminium an iron become so soluble and may be toxic to plants.

In alkaline soils, ammonium, NH4+ is lost as ammonia, NH3 through volatilization, while acid soils helps to maintain NH4+ levels. In alkaline soils with pH above 6.5 phosphorous in the form of phosphate ions readily form less soluble compounds with calcium and magnesium and becomes less available. The plant available form of sulphur, the sulphate; SO42- is less affected directly by soil pH. The availability of all the known micronutrient, except for molybdenum, decreases as soil pH increases (Jensen, 2018). The pH values of most of the digestate samples analysed were below

8.0 and therefore stabilization may not be necessary for application on most soils, but might require further treatment if they are applied to too alkaline soils. It would also depend upon the type of crops grown, since crops vary greatly in terms of preferred soil pH. Soil acidity also adversely affects the activity of microbes, bacteria become less active and the growth of beneficial nitrogen-fixing bacteria is usually inhibited in highly acid soils.

Table 2: Physicochemical characteristics* of solid digestates from small-scale biodigesters

Biodigester	pH	EC, dS/m	Moisture %	COD, g/kg	TS, % ww	VS, %TS	TOC, % TS	Ash, % TS
BD1	7.22 ±0.64a	1.04 ±0.04a	64.97 ±3.66a	25.30 ±3.05a	35.09 ±4.30a	61.62 ±1.06a	26.78 ±0.80a	12.39 ±2.10a
BD2	8.27 ±0.21b	0.52 ±0.09bk	85.20 ±2.65b	21.53 ±0.92ae	14.75 ±0.52bf	52.67 ±12.0bh	24.57 ±12.0ae	17.76 ±12.0b
BD3	6.95 ±0.05ac	0.63 ±0.05a	90.33 ±1.39cb	26.67 ±2.84af	9.62 ±1.22cf	52.83 ±0.35ch	28.10 ±0.36af	18.07 ±4.52cb
BD4	7.55 ±0.31ab	0.62 ±0.21a	72.50 ±0.82dgh	19.90 ±0.63adg	27.34 ±5.21ak	56.27 ±2.12ak	25.65 ±2.29ad	18.73 ±1.15d
BD5	7.65 ±0.18ab	7.40 ±0.10cg	67.77 ±0.85agi	28.93 ±1.00ach	32.16 ±1.40agl	59.25 ±3.70dil	31.75 ±0.75ac	11.35 ±1.04ed
BD6	6.95 ±0.57ae	1.45 ±0.24eh	72.63 ±1.01egkm	26.90 ±1.61ai	27.28 ±9.70dm	66.25 ±1.86em	24.14 ±1.97ia	8.75 ±0.94a
BD7	7.02 ±0.25a	1.31 ±0.25ai	53.50 ±0.82fn	37.36 ±0.85bj	46.56 ±5.15en	52.53 ±5.02fhn	34.29 ±5.40bj	15.07 ±2.17fb
BD8	7.23 ±0.13a	0.89 ±0.25ak	69.03 ±2.16ahkp	24.43 ±2.98ak	30.85 ±0.15ajo	63.73 ±3.05gil	26.52 ±0.40ak	9.75 ±1.08gd

* Values of each parameter with the same letter are statistically not different at $p<0.05$

The measurement of electrical conductivity; EC was to estimate the total concentration of soluble ionic salts present in the digestates as EC is the standard for assessment of soil salinity. EC influences crop yields, availability of plant nutrients, activity of soil microorganisms and may also affect physical properties of soil and ion toxicity. Just as with pH, soils have varying degrees of salinity, and each crop has tolerance limit to soil salinity and a slight to moderate change in salinity can significantly impede crop growth and yield. The values of EC of the digestates were below 2.5 dS/m, which is the tolerance limit for most plants (Machado & Serralheiro, 2017). The application of the digestates on agricultural land may not hinder crops growth and no accumulation of salts would be expected.

The ash content of a digesate, which is a reflection of inorganic material content was found to be in the range from 8.75% TS for BD6 to 18.73% TS for BD5. The highest ash content was for BD5 (21.35% TS) and BD7 (20.07% TS). These two digestates BD5 and BD7 contained the largest sum of both macronutrients (244.05 mg/kg and 286.67 mg/kg) and micronutrients (92.43 mg/kg and 161.14 mg/kg) respectively. Generally the digestates from the biodigesters whose feedstock contained pig slurry had higher nutrients content.

The carbon content was estimated from the volatile solids content of a material. Volatile solids content; VS are the components, mainly carbon, oxygen and nitrogen that burn off from a sample in a laboratory furnace at 550oC leaving only the ash, which is largely calcium, magnesium, phosphorus, potassium and other mineral elements. The content of nutrients of anaerobic digestate depends primarily upon the type of feedstock and the digestion process (Alburquerque, et al 2012).

The total solid, TS content of the feedstock and the type of process occurring in the biodigester, i.e. either wet or dry fermentation, also affect the TS content of the digestate. The TS values for most of the digestates from the biodigesters vary within a narrow range because there was not much difference among the feedstock of the biodigesters (Table 1). The biodigester BD7 has the highest TS content of 47.2% wet weight, which reflected the feedstock cow dung, chicken manure and pig slurry. The highest TS content was found in BD7 (46.56 %) and the lowest in BD3 (9.8%) wet weight. Generally, the digestate with higher TS will contain more organic matter, which can sustain the soil microbial community and meet the requirements for crop growth, if the digestate is used as a fertilizer (Möller & Műller, 2012). Soil microorganisms play an important role in soil quality by degrading biodegradable organic matter, cycling nutrients and fertilising the soil. When microorganisms degradable organic matter, they use the carbon and nutrients in the organic matter for their growth and release excess nutrients into the soil, which become bioavailable to plants.

Organic carbon in organic matter is critical to soil fertility. The addition of organic matter to soil increases soil aggregation, permeability and water-holding capacity, The total organic carbon content of the digestates varies in a narrow range from 24.14% to 31.75% TS. Generally, the carbon content of digestate is lower than that in the substrate used as the feedstock because some is lost as carbon dioxide, CO2 and for the formation of methane, CH4 the main product of the fermentation process in the bioreactors.

Macronutrients

One critical property of a digestate as a biofertilizer is its potential to supply nitrogen, an indispensable plant nutrient.

Nitrogen in the feedstock is either in the organic form or ammonium, NH4+ form. During the digestion process much of the organic nitrogen is mineralized to ammonium, which raises the overall level of ammonium in the digestate. The ammonium nitrogen, NH +-N content in digestate is of great importance as it is the readily available form to plants. The total nitrogen content in the digestate was within the range of 5.1 g/kg to 15.2 g/kg (Fig. 3) and an appreciable amount of it is in the NH4+-N. Though NH4+-N is readily accessible to plants, however it can easily be lost as ammonia in alkaline soils. The content of NH4-N of the digestate as a percentage of the total nitrogen content was within the range of 11.35 % to 48.364 %, which is within the range reported by other authors (Akhiar et al, 2017).

Table 3. Macronutrients content of solid digestates from small-scale biodigesters

Bioigester	Tot N, g/kg	NH4+N, g/kg	$\frac{NH_4^+}{Total\ N}$ %	Tot P , g/kg	S, g/kg	Ca, g/kg	Mg, g/kg	K, g/kg
BD1	7.97 ±0.47a	5.17 ±0.35a	62.50 ±2.55a	3.47 ±0.65ac	0.88 ±0.10ag	12.63 ±0.60ah	5.70 ±0.56ah	13.13 ±0.45a
BD2	5.33 ±0.68b	2.93 ±0.21bf	61.50 ±2.70a	6.87 ±0.35b	0.72 ±0.08afh	12.73 ±0.65abh	6.60 ±0.80ai	10.87 ±0.50b
BD3	6.07 ±0.35cb	2.30 ±0.20cf	42.28 ±5.27b	12.53 ±1.02ah	1.07 ±0.06bi	16.30 ±0.60bh	9.00 ±0.46bj	7.23 ±0.55c
BD4	6.35 ±0.29ab	0.66 ±0.09d	11.90 ±0.58c	2.93 ±0.29c	0.72 ±0.04afjp	95.30 ±2.65c	5.87 ±0.21ak	4.43 ±0.71d
BD5	14.67 ±0.96d	5.53 ±0.67ag	36.84 ±1.16db	14.23 ±0.56dh	0.81 ±0.05afkp	147.97 ±29.70d	17.37 ±0.90clp	6.63 ±0.41ec
BD6	8.10 ±0.44a	6.40 ±0.62ah	73.50 ±2.26e	6.77 ±0.55eb	0.63 ±0.05cflp	55.00 ±1.08e	16.60 ±0.65dmp	4.30 ±0.53fd
BD7	15.80 ±0.65ed	12.07 ±0.60ei	76.53 ±1.43fe	21.80 ±0.65f	0.63 ±0.07dfmp	106.40 ±7.54f	42.63 ±0.81en	10.83 ±0.67gb
BD8	6.23 ±0.45fb	4.67 ±0.60aj	65.30 ±3.73a	7.23 ±0.81gb	0.62 ±0.06efnp	49.07 ±2.05g	35.53 ±1.54fo	6.77 ±0.45hc

* Values of each parameter with the same letter are statistically not different at $p<0.05$

P plays an important role in early plant development, as a component of nucleic acid structure, it regulates protein synthesis and, by extension, cell division and tissue formation. The levels of phosphorous in the digestate limits the amount that can be applied to agricultural land in a crop rotation cycle. Digestate may be applied to help meet the nitrogen needs of a crop growing in soils with concentrations up to 50 mg/kg of P. However, P applied should not to exceed the amount taken up by the crops over a rotation cycle as over-fertilization of phosphorous can lead to eutrophication of water bodies through leaching and run-off. If a field's P levels exceed 100 mg/kg, then no P additions in manure or fertilizer are permitted.

Micronutrients

Livestock manure is one of the major sources trace elements in agricultural soils (Luo et al, 2009). Some minerals are usually added to commercial animal feeds as micronutrients for various functions (Lu, et al, 2015). Cu and Zn salts are added to feed for weaning pigs to reduce post-weaning diarrhoea and as a growth-promoter in pigs and poultry (Debski, 2016; Poulsen, 1998). Generally, the large proportion of micronutrients ingested by farm animals in feed are excreted (Hays, 2013). The highest amount of the micronutrients was recorded for the digesates from the biodigesters, whose feedstock contained PS, CM and CwM as shown in Table 4 and Figure 3. There was no regular pattern in the concentrations of the micronutrients in the digestates. The digestate BD7 recorded the highest concentrations for Co (1.25 mg/kg), Cu (37.35 mg/kg), Mo (1.83 mg/kg) and Zn (64.13 mg/kg). The highest concentrations were recorded for Fe in digestate BD1 (51.90 mg/kg); Mn in digestate BD1 (21.43 mg/kg) and Ni in digestate DB6 (12.95 mg/kg). On the average higher concentrations for Cu, Fe, Mn and Zn was found for most of the digestates.

Table 4 Micronutrients in solid digestates from small-scale biodigesters

Biodigester	Co, mg/kg	Cu, mg/kg	Fe, mg/kg	Mn, mg/kg	Mo, mg/kg	Ni, mg/kg	Zn, mg/kg
BD1	0.31 ±0.06ah	19.37 ±0.70ah	51.90 ±3.61a	20.97 ±1.40a	0.96 ±0.14ah	11.54 ±0.86a	5.10 ±0.56ago
BD2	0.09 ±0.03afi	9.00 ±0.79b	18.07 ±1.50bi	17.40 ±0.96b	0.23 ±0.06bh	1.21 ±0.25b	3.43 ±0.65afho
BD3	0.52 ±0.06adj	9.27 ±1.20cb	16.52 ±2.50cbij	20.47 ±0.90a	0.53 ±0.13abh	5.66 ±0.76c	2.67 ±0.40ai
BD4	0.46 ±0.06aek	12.67 ±0.47d	13.20 ±1.02dil	21.43 ±0.91a	0.11 ±0.02cb	1.51 ±0.51db	15.70 ±0.60bj
BD5	0.76 ±0.08bel	16.14 ±0.67e	9.07 ±0.45ekl	16.07 ±1.75cb	2.12 ±0.18de	9.10 ±0.39e	25.87 ±0.83ck
BD6	0.39 ±0.10aem	18.67 ±0.47ah	10.57 ±0.85fjkl	10.36 ±1.93de	1.45 ±0.57afg	12.95 ±0.61ag	20.93 ±1.25dl
BD7	1.25 ±0.25cn	37.35 ±1.10fi	17.30 ±0.98gbi	11.63 ±0.75e	1.83 ±0.08efg	10.53 ±0.97ahe	64.13 ±1.82em

* Values of each parameter with the same letter are statistically not different at $p<0.05$

The digestates can be applied to supplement micronutrients in soils, which are deficient in these nutrients due to high leaching of nutrients and highly alkaline conditions (Deckers & Steinnes, 2004).

Heavy metals

The heavy metals analysed (As, Cd, Cr, Pb, Hg) have no established essential biochemical functions in plants and are considered as contaminants and are toxic even in low concentrations. The major source of exposure of these metals to plants is from soil and through their roots. These pollutants get into the soil through the use of pesticides, herbicides and micronutrient fertilizers, application of sewage sludge and digestate as biofertilisers, The concentrations of the heavy metals investigated are presented in Table 5 and Figure 4. The heavy metals were present at low concentrations in all the digestates and Hg was below the detection limit of the analytical method.

Table 5 : Heavy metals content of solid digestate from small-scale biodigesters

Biodigester	As, mg/kg	Cd, mg/kg	Cr, mg/kg	Hg, mg/kg	Pb, mg/kg
BD1	0.13±0.02a	0.35±0.07a	8.84±0.25a	0.06±0.02a	3.07±0.19af
BD2	0.05±0.01ab	0.21±0.04b	2.80±0.27b	nd	1.92±0.18bcf
BD3	0.17±0.06ac	0.16±0.05cb	6.75±0.48c	0.02±0.01a	1.79±0.45cf
BD4	0.03±0.02ae	0.14±0.03db	3.29±0.70db	nd	1.68±0.35dcf
BD5	0.14±0.02a	0.42±0.04a	13.30±0.85e	0.06±0.02a	2.65±0.47acg
BD6	0.09±0.06a	0.410.02a	14.86±0.34f	0.21±0.24a	4.81±0.28eh
BD7	0.18±0.08ad	0.66±0.05e	16.80±0.34g	0.09±0.01a	2.33±0.40ac
BD8	0.11±0.07a	0.11±0.07fb	4.34±0.46hd	nd	2.20±0.13ac
Maximum limitsa	<40	<40	<	<15	<300

nd – not detected; a – DWAF, 2006; *Values of each parameter with the same letter are statistically not different at $p<0.05$

There are no well validated benefits of these metals to plants, on the contrary, their uptake by plants from the soil has various harmful effects by causing physiological, biochemical, and structural changes in plantsThe probable source of these heavy metals in the digestates is the poultry manure, pig slurry because pig feed is often highly enrich in heavy metals due to the wide use of mineral additive (Lan et al, 2022) and cow manure because, the animal feed is supplemented with commercial feeds, which contain various essential elements to promote optimum nutrient supply and optimum growth rate. However, these supplements may also contain heavy metals as impurities (Adamse, Van der Fels-Klerx, and de Jong 2017; Demirel, Göl and Onay 2013). The toxic effects of most heavy metals in many plants is reduction in uptake and translocation of nutrients and water, increased oxidative damage, disruption of plant metabolism due to interference with enzymatic activities, These toxic effects are observed in the inhibition of seed germination, seedling development plant growth and induction of various morphological and physiological defects (El-Shehawi et al, 2022; Zulfiqar et al, 2019; Romero-Puertas et al, 2004; Haider et al, 2021).

The highest concentrations of the heavy metals were recorded for digestates from biodigesters whose feedstock contained pig slurry, chicken manure. The digestate BD7 has the highest levels of As (0.18 mg/kg) and Cd (0.66 mg/kg), BD6 has the highest Hg (0.21 mg/kg) and Pb (4.81 mg/kg), Hg was not detected in the digestates from the biodigesters BD2, BD4 and BD8 and also these digestates contained the lowest amounts of other heavy metals (As, Cd, Cr and Pb). This may be attributed to the fact that the feedstock of these biodigesters did not contain PS since the heavy metal content of animal manures are largely a reflection of their content in the feeds consumed by the animals. The contents of Cr also significantly reflected a similar pattern. The amounts were higher in digestates from biodigesters with pig slurry and chicken manure as components of the feedstock - BD7 (16.46 mg/kg) > BD6 (14.53 mg/kg) > BD5 (13.17 mg/kg) > BD1 (8.65 mg/kg).

The concentrations of these heavy metals were in the ranges from 60 to 200 times lower than the recommended maximum limits of the South African guidelines for the agricultural use of wastewater sludge (DWAF, 2006). The heavy metals in the digestates were below the maximum limits recommended for the agricultural use of wastewater sludge.

CONCLUSION

In this current study solid digestates from eight small-scale fixed dome biodigesters in Maseru, Lesotho, which operate under psychrophilic conditions were assessed to evaluate their potential for application as biofertilizers. All the digestates were characterized by their physico-chemical characteristics, nutrients and heavy metals concentration. The digestates contain considerable amounts of major plant nutrients (N, P, K, S, Ca, Mg) and micronutrients (Co, Cr, Fe, Mn, Ni, Zn). The digestates are a potential source of plant-available nitrogen with more than 60% of the total N in the form of ammonium nitrogen, NH4+-N. The content of micronutrients is adequate to consider the digesates as valuable sources of these minerals. However, the digestates might only be used as a supplement or partial replacement for mineral fertilizers because of the low concentrations of some of the nutrients. The concentrations of heavy metals in the digestates were much less (range of 60 to 200 times) than the maximum guideline limits of the South African standard requirements for the agricultural use of wastewater sludge. The concentration of Hg in three digestates (BD2, BD4, BD7) was below the detection of the analytical method. The variation in the concentrations of nutrients among the digestates may allow for customised application as different crops have different nutrient demands. It may be concluded that the use of the digestates material as a biofertilizer and may not cause an accumulation of heavy metals in soil to toxic levels.

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