Agricultural use suitability assessment and characterization of municipal liquid sludge: Based on South Africa survey

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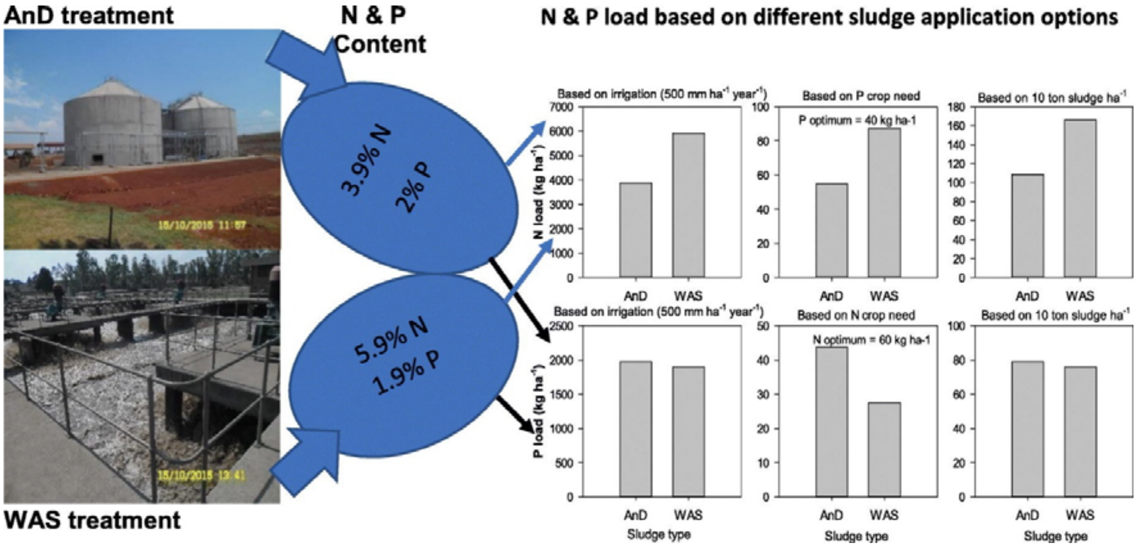
Highlights

- Sludge is a unique, complex and dynamic product.
- Municipal wastewaters from 18 WWTPs were characterized.
- Chemical properties were the basis of characterization and agricultural suitability assessment.
- Characterization must precede any sludge agricultural use.
- Crop nutrient needs are the sustainable sludge application option.

Abstract

Sludge recycling as an agricultural resource has gained great attention worldwide. This is exacerbated by the ever-rising municipal wastewater production and the realization of its potential as a soil amendment resource. Sludge suitability assessment and characterization is crucial to prompt informed decisions regarding its use on agricultural lands. Liquid sludge samples were collected from eighteen wastewater treatment plants (WWTPs) employing three different treatment processes in South Africa. Samples were analysed for physical and chemical parameters. Sludges' pH ranged from 4.5–9.5. Heavy metals concentrations were below the threshold level except for two waste activated sludge (WAS) which were downgraded to class B due to high Lead (Pb) content. Two anaerobically digested (AnD) sludges were downgraded to classes B and C because of high Pb and Cadmium (Cd) concentrations respectively. Electrical conductivity (EC) was above the 200 $m\mathrm{S\ m^{-1}}$ threshold in AnD and in one of aerobically digested (AeD) sludges whilst WAS had $\leq$100 $m\mathrm{S\ m^{-1}}$. Nitrogen (N): Phosphorus (P) ratios of the sludges were <8. Application of biosolids with low N:P ratio based on crop N requirements would lead to P pollution. Sustainable sludge application options were either to apply dry sludge based on crop N or P requirements and supplement the nutrient deficit with other fertilizer sources. The use of current liquid sludge as irrigation water to meet crop water needs and or applying dry sludge at 10 tons $\mathrm{ha^{-1}}$ options showed that such options are unsustainable and would add excess nutrients above crop need which would result in agroecosystems pollution. The study findings suggest that, supposedly these liquid sludges are used for irrigation, they should be diluted with fresh water or deficit irrigation should be implemented to limit nutrient load.

Graphical abstract



Keywords: Anaerobic digestion; Waste activated sludge; Characterization; Wastewater; Sludge use suitability; Biosolids

1. Introduction

Sludge recycling as an agricultural resource has gained greater attention around the world. This is not only due to sludge disposal challenges, but also because of the unprecedented increase in water demand for agricultural production across the globe, shortage of fresh water especially in arid and semi-arid regions (Feigin et al., 2012) and its potential for use as a soil amendment resource. Agricultural use of sludge is being driven by ever-rising world population (Hanjra et al., 2012) and the need to feed every additional individual from the current and yet unreliable agricultural production systems. The world population is expected to reach 8.9 billion by 2050, up from the current population size of 7.6 billion (United Nations, 2017). The growing world population is exerting pressure on the already limited available agricultural resources underpinning crop production. Every additional mouth will require food on daily basis, hence building pressure world – wide to improve on sustainable food production systems towards meeting the ever-rising demand.

However, the effort of raising agricultural productivity is being thwarted by the dwindling agricultural resources facing most parts of the world today. In the sub – Saharan Africa, soil fertility losses are critical and have been reported to be the limiting factors of crop production (Sanchez, 2002; Vågen et al., 2016; Wolka et al., 2018). Soil degradation and particularly phosphorus (P) decline (Reijnders, 2014), a non – renewable and finite resource (Chowdhury et al., 2017; Magnone et al., 2017), is fingered as the major culprit for reduced crop productivity (Wolka et al., 2018). P is an essential element for living organisms (plants and animals) (Chen and Graedel, 2016). It cannot be substituted by any other nutrient for crop sustenance, hence playing a crucial role in the world food security status (Magnone et al., 2017). It is because of this reason that P and phosphate rock decline are a cause for concern world – wide.

In addition, fresh water resources shortage is another challenge for the agricultural sector. In arid and semi – arid regions of the world, this is a major contributing factor to low and unreliable crop yields (Galvis et al., 2018; Ibekwe et al., 2018). The increase in population size, urbanization and the quest for improved standard of living coupled with climate change have caused a tremendous growth in demand for fresh waters (Falkenberg et al., 2018). Global climate change has caused long and lasting droughts around the world that have seen disappearance of some previously existing water bodies. This, in turn, has affected the size and availability of water channelled towards agricultural production.

Among other factors, the challenges cited above strongly pressure the world community to come up with innovations and alternative ideas towards improving agricultural production to meet the rising food and water demands. These cited challenges are derailing the efforts by world entities in addressing and achieving the United Nations Sustainable Development Goals (UN-SDGs). Resource shortages like water for supplementing erratic rains, nutrient losses, and climate change have a large bearing on agricultural production. Such shortages contribute negatively on reducing hunger, thus, negatively affecting zero hunger (Goal 2) campaign, hence increasing chances of poverty among individuals (affecting efforts targeting poverty reduction – UN-SD Goal 1) and erase confidence towards ensuring sustainable production and consumption patterns – UN-SD-Goal 12.

In view of these challenges, municipal wastewater and sludge recycling as a nutrient and or water resource for agricultural purposes is one tool to help mitigate the production challenges facing the world today. The use of municipal sludge on agricultural lands is beneficial and is seen as an alternative sludge disposal option (Feigin et al., 2012). Wastewater recycling presents dual benefits to the agro-ecosystems. It can be used either as a nutrient source (dried or dewatered biosolids) and or supplementary water for irrigation (liquid wastewater). When applied as irrigation water it would meet both crop-water requirements and crop-nutrients needs (Tesfamariam et al., 2015).

Generally, recycling municipal sludge for agricultural purposes bears multiple benefits (Du et al., 2012; Khajanchi-Lal et al., 2015; Seleiman et al., 2012). Some are economic benefits, like minimum transport costs for sludge disposal (Bedbabis et al., 2015) which could be incurred by the wastewater treatment plants (WWTPs), reduced costs for fertilizers purchases (Gil and Ulloa, 1997) for farmers, and agronomic benefits such as water for irrigation (Khajanchi-Lal et al., 2015) and ready supply of nutrients (Tunc and Sahin, 2015) required for crop growth have been reported. Municipal sludge is rich in macro and micro plant nutrients (Pu et al., 2012; Singh and Agrawal, 2010; Weggler-Beaton et al., 2003). Largely, sludge is used as a source of nitrogen (N) and phosphorus (P) and organic matter (OM) (Bell et al., 2004; Eriksen et al., 1999; Leifeld et al., 2002). Availability of organic matter in municipal sludge makes it a favorable soil conditioner and plays a significant role in improving soils' physco-chemical and biological properties (Jakubus and Czekała, 2001; Wei and Liu, 2005; Pan et al., 2017; Cogger et al., 2013) hence improving profitability of previously low fertile soils. Taking in municipal sludge as an agricultural resource to address water and soil fertility challenges can contribute to increasing resilience to drought around the world. As such, this will partially contribute towards achieving the UN-SDGs through enhancing crop productivity which in turn support the zero hunger and poverty reduction campaigns.

Among the macronutrients found in sludge, N typically exists in higher levels (Henry et al., 1999) relative to other nutrients. Wastewater management options that keep nitrate N (NO_3^-–N) on the check are vital for sludge production targeting agricultural use. The primary concern is to minimize excess $NO_3 - N$ application that would end up polluting the environment when leached and eroded into water bodies. Municipal sludge use on agricultural lands is largely applied based on agronomic rate, that is, the agronomic N required to meet the demands of a particular crop (Garau et al., 1991; Rowell et al., 2001; Serna and Pomares, 1992). The agronomic rate is determined based on various factors including; sludge characteristics, edaphic properties and climatic factors (Brady and Weil, 2013; Garau et al., 1986).

Overwhelming evidence exists world-wide with regards to benefits of sludge recycling in the agricultural sector. And as such, sludge must meet certain regulatory quality requirements before it can be applied on agricultural lands. Such quality checks are fundamental towards minimizing environmental contamination and health hazards to humans and animals (Parnaudeau et al., 2004; Plaza et al., 2003) that could emanate from the use of low quality sludges. Potential elements of concern from low quality sludge include organic pollutants, pathogens, and heavy metals content that would jeopardize health and safety of individuals in and around environments receiving sludge application. In view of such risks associated with the use of low – quality sludge, countries around the globe have set directives and restrictions for monitoring and regulating use of sludge on agricultural lands. Guidelines have been developed such that sludge classification can be done to determine how fit sludge is for agricultural use. In South Africa, sludge is classified for its agricultural use based on guidelines outlined by (Snyman and Herselman, 2006) and is applied within the parameters stipulated in the National Water Act (Republic of South Africa, 1998). In the Americas, US EPA (1984) provided a clear and detailed document to be followed when using sludge for agriculture production, whilst the European Union has produced a directive underlining the expected requirements for and how sludge should be used in the agricultural lands (Directive Council, 1986).

Sludge quality is born out of treatment and stabilization processes employed by WWTPs. To ensure sludge of acceptable quality, municipal wastewater is subjected to various treatment and stabilization processes. Existing wastewater treatment and sludge stabilization processes enhance sludge quality (Qin Lu and Stoffella, 2012) and these processes include primary, secondary and tertiary treatment and aerobic, anaerobic, and waste activated digestion, dewatering and sludge drying processes (Ramalho, 2012; Tchobanoglous and Burton, 1991; US EPA, 1984) and compositing among others. Globally, these processes vary from nation to nation and from one WWTP to another. Due to the intensity of particular treatment process (Feigin et al., 2012) in stabilizing sludge at WWTPs, the resultant sludge quality may vary regardless of its sources. Thus, differences in sources/origin of wastewater and wastewater treatment processes (Feigin et al., 2012) result in significant variation in sludge characteristics.

Because of this dynamic nature in quality, sludge can be perceived as a complex and unique product. Thus, it is varied in composition, quality, and characteristics which tend to change due to several factors, chiefly, the source of its feedstock. However, the type and degree of the wastewater treatment process is equally critical, as is the climate where the sludge is applied. It is therefore imperative that sludge use as a beneficial agricultural resource be not generalized.

For example, application rates based on sludge type should not be a blanket application rate across regions of different climatic and edaphic characteristics. In South Africa, the current maximum sludge application rate is set at ten (10) tonnes biosolids hectare^{-1} year^{-1} across the country despite differences in climatic conditions. However, having a single upper limit as a blanket application rate across various agroecological zones or soils across sludge type could not be a sustainable strategy for agricultural purposes due to the complex nature of sludge itself. Furthermore, the currently available and clearly set application rate is only for biosolids, leaving liquid sludge that could be applied as irrigation water unclarified. Therefore, this may result in over or under application of sludge which in turn could compromise the availability and uptake of target nutrients whenever it is applied as water resource for irrigation. Thus, exclusive and critical characterization of specific sludge type(s) from different WWTPs is necessary. Previous studies (Snyman et al., 2004) focused extensively on treatment processes' effect on physical and chemical properties of sludge. However, there is still scarce information, on the impact of feedstock sources composition on the final sludge composition, quality, and its general characteristics. Also, lacking is a specific clarity on how particular sludge from certain sources would be applied if one wants to use liquid sludge as irrigation water. A comprehensive understanding of different sludge types is necessary in determining the feasibility of applying sludge either as irrigation water, as biosolids or both.

The current study, therefore, intended to fulfill the following objectives; to characterize eighteen municipal liquid sludges and to assess the agricultural use suitability of municipal liquid sludge from selected wastewater treatment plants in South Africa. Parameters like physical and chemical characteristics of the eighteen liquid sludge samples were analyzed to avail a comprehensive understanding of the effect of sludge feedstock sources composition and wastewater treatment processes on sludge characteristics and agricultural use suitability. The combined output of this study was to determine the best possible option to which particular sludge, either based on its source composition or treatment process, could sustainably be used on agricultural lands.

2. Materials and methods

Agricultural use suitability assessment and characterization of liquid municipal sludge was conducted to trace back wastewater sources/origin composition and assess their implications on the final by-product (sludge). An exploration of the origin of the wastewater was done to establish the magnitude of domestic/household and industrial contribution to the wastewater flows to WWTPs. In cases of significant industrial contribution, further appraisals were done to establish the types of industries and products produced by such industries since these factors have a strong bearing on the final composition of wastewater. This was conducted through combining liquid sludge analysis data collected currently and some secondary data compiled by WWTPs. Secondary information was studied towards unraveling the descriptive information that could influence the municipal sludge's physical and chemical characteristics. The combined information of sludge from a particular WWTP was then assessed in relation to the requirements for wastewater targeted for agricultural use as stated in the South Africa National Water ACT 36 of 1998 (Republic of South Africa, 1998), and the Guidelines for the utilization and disposal of wastewater sludge, Volume 2 – Requirements for the agricultural use of wastewater sludge (Snyman and Herselman, 2006). Municipal wastewater liquid sludge was collected from eighteen (18) WWTPs. Wastewater treatment processes that are being employed vary from one WWTP to another. Of these WWTPs whose sludge was under investigation, 50% of them produce anaerobically digested sludge, 39% - waste activated sludge and 11% - aerobically digested sludge.

Briefly, AnD sludge was as a result of the traditionally conventional anaerobic technology (Tchobanoglous et al., 2003). The process produces a well stabilized sludge through mesophilic and or thermophilic and liming stabilization processes as highlighted by Chan et al. (2009) with the product containing >95% of water content. Alternatively, AeD sludge was processed through two stages. Wastewater from the primary settling tank (PST) is pumped to an open aerobic digester in which oxidation takes place. From the digesters, sludge is channelled to drying beds or to irrigate dedicated lands or lawn. Whilst WAS is produced through a typically aerobic biological treatment (Han et al., 2017) that passed through primary settling tank to the aeration tank (reactor) from which the sludge is channelled to the secondary clarifier. A portion of the sludge from the clarifier is returned to the reactor as return activated sludge whilst the rest is wasted.

2.1. Sampling

Bulk sample sizes of 20 litres (L) of digested municipal liquid sludge were collected from eighteen (18) selected WWTPs around Gauteng province in South Africa in September – November 2015 for physical and chemical properties characterization. Sampling points were at digesters' outlets for AnD and AeD sludge once the sludge was due for drying process (average of 21 days in digesters) or from sampling boxes for WAS. Soon after sampling, samples were transported in cooler boxes and stored under a controlled temperature of approximately four degrees celsius (4 °C) in cold rooms at the University of Pretoria Experimental Farm until laboratory analyses were done.

2.2. Sample preparation

Analyses were done on both liquid and solids portions of the sludge samples. Sub – samples of approximately 1 L were taken for analyses from the collected 20 L samples. The sub – samples were then separated into liquid and wet solid portions, that is, the liquid part of the sub – samples was decanted from the wet solid portion. Inorganic N, total suspended solids (TSS), electrical conductivity (EC) and pH were analyzed from the decanted liquid portions, whilst all other analyses were done from the dried solid portions. Total solids (TS) were calculated from the whole sample fraction before the liquid and wet solid fractions were separated. Before conducting the analyses from the solids portion, wet solids were oven dried at 50 °C over night (24 h) to evaporate excess water and allowed the samples to air dry to a constant mass before they were ground to pass through a 2 mm sieve. The wet solids sample portions were not completely dried in the oven to the required moisture level in order to minimize N losses that could happen in form of ammonia (NH_3) during drying especially when N rich samples are dried at such high temperatures.

2.3. Analytical procedure

sEC, pH, inorganic N (Nitrate N (NO_3 - N), Ammonium N (NH_4 - N) and Nitrite N (NO_2 - N)) and TSS were determined from the liquid portion of the samples. EC was measured by the EC meter, and pH reading using a pH meter, NH_4 – N was through the colorimetric method with Lachat Auto-analyzer (Lachat Quick Chem Systems, Milwaukee, MI) USA. NO_3 - N, and NO_2 - N were analyzed by Ion Chromatography. TS & TSS were determined by the gravimetric method. Total C (TC), N, and S were analyzed from dried sludge by total combustion using a Carlo Erba Na1500 C/N analyzer (Carlo Erba Strumentazione, Millan, Italy). Inductively Coupled Plasma – Optical Emission Spectrometer (ICP - OES) was used for total Ca, Na, Mg, Mn, S, Fe, Al, K, Cu, Zn, B, & P and heavy metals analysis after microwave-assisted nitric acid – perchloric acid mixture digestion. Extractable P was determined by Bray-1 P method. Organic carbon and organic matter (OM) were determined through loss of ignition (LOI) method as described by (Heiri et al., 2001) in which samples were combusted at 550 °C and all combustible compounds were lost. OM was then determined as the difference between the initial sample weight and the sample ash weight. C from the ash of the sample was also determined after-which the organic carbon was calculated as the difference between TC and inorganic carbon (C obtained from ash).

2.4. Computation of nutrient loads that could be potentially applied when using liquid sludge as water for irrigation or dried sludge application as a nutrient source

In assessing the potentially sustainable utilization option of sludge use with limited nutrient pollution to the receiving environment, a simple nutrient computation was done. The assessment was done for nutrient loads of three major nutrient elements; N, P and K (kg ha^{-1} $season^{-1}$). N, P and K nutrient application were based on semi-arid regions of South Africa rates as stated by Ogbazghi (2016) with maize chosen as the reference crop. The nutrient computations where done based on four possible sludge utilization options, that is, based on; (a) liquid sludge use as irrigation water, (b) dry sludge application based on maize N requirements, (c) dry sludge application based on maize P requirement and (d) dry sludge application based on the currently regulated upper limit of 10 t sludge per hectare per year.

Assumptions made on liquid sludge utilization as irrigation water (Scenario 1)

a) Maize crop will be receiving full irrigation from liquid sludge for its full season.

b) An average of 500 mm irrigation water need will be required for the full season of the crop from planting to maturity as is in the semi – arid rainfall range (Ogbazghi, 2016).

c) The liquid sludge used for the irrigation is constituted of ≤2% total solids.

d) The liquid sludge density is equivalent to the ordinary water density of 1000 kg m^{-3} just below that stated in literature (Andreoli et al., 2007).

e) Nutrient load will be calculated from only the ≤2% (AnD) and 0.3% (WAS) of total solids fraction of the sludge.

Assumptions when dry sludge is applied based on maize N requirements (Scenario 2)

a) The N mineralization rate of applied sludge per season will be 28% for semi-arid region as found by (Ogbazghi, 2016).

b) The sludge N application rate should supply 60 kg N ha^{-1} (FAO, 2005) and no excess.

c) Nutrient loads of P and K will be computed in this sludge utilization option applied targeting to meet 60 kg N ha^{-1}.

Assumptions when dry sludge is applied based on maize P requirements (Scenario 3)

a) The P mineralization rate of applied sludge per season will be 40% (Sullivan, 2015).

b) The sludge application rate should supply 40 kg P ha^{-1} and no excess.

c) Nutrient loads of N and K will be computed in this sludge utilization option applied targeting to meet 40 kg P ha^{-1}.

Assumptions when dry sludge is applied based on the currently regulated upper limit of 10 t per hectare per year (Scenario 4)

a) The sludge will supply N, P and K nutrients based on the mean concentration percentages observed for sludges collected and analyzed in this current study.

b) The data will be computed based on the nutrient concentrations identified for each sludge in this study.

c) Mineralization rate of 28% and 40% per year for N and P shall be used respectively.

3. Results and discussion

Sludge samples were collected from 18 WWTPs which are presented in Table 1. The WWTPs involved in here employ various treatment processes which include anaerobic and aerobic digestion, and waste activated sludge treatment. After-which the sludges are dewatered or used in various ways depending on the infrastructure available at each WWTP. The feedstocks flowing into these treatment plants originate from two major sources; that is, industrial and domestic origins. However, for most of the treatment plants, domestic sources are dominating whilst industrial origins contribute small percentages except for two plants that have had >50% industrial source contribution. Based on the information provided during the sampling in collaboration with a mini survey to the WWTPs and the associated physical and chemical analyses, the sludge classification based on Snyman and Herselman (2006), and European commission directive council and US EPA pollutants threshold limits, most of the sludges in this study do fit for agricultural use. However, currently, not all sludges are being used for agricultural purposes due to various reasons across WWTPs. Some are channelled and deposed off in lagoons whilst some plants resort to irrigate to non-cropped dedicated lands. This low uptake of sludge into agriculture could not be attributed entirely to contaminants and low sludge quality but there are no or few farmers around such locations to take up and use the sludges even though the quality could be good.

Table 1. Sources of wastewater composition percentages, treatment processes practized, sludge classification and the current uses of sludge from the surveyed wastewater treatment plants (WWTPs).

WWTP name	Source of wastewater composition %		Treatment and dewatering Processes involved at WWTPs[a]	Types of industries within the sources' catchment area	Sludge class[b]	Current use of sludge
	Industrial	Domestic				
WV	10	90	AnD and AeD, belt press, stockpiles	Starch, glass, tissue paper, plastics and beer production	A1b	Field crops and lawn application
VP	4	96	AnD, drying beds	Dairy products, beverages and food manufacturing	A2a	Lawn application
HF	60	40	AnD, AcT	‡	B3c	Maize and lawn irrigation
OF[c]	40	60	AnD, AeD, AcT, drying beds	Food, beverages, abattoirs products, grease trap chemicals	B3a	Application on field crops
RF	–	100	AnD, AcT, drying beds, stockpiles	‡	B1a	Field crops and lawn application
BN	30	70	AnD, drying beds	Dairy and battery products	B1b	Dedicated land
AC	40	60	AnD, lagoons	Food, beverages, abattoir, pulp and paper	–	Field crops
JS	2	98	AnD, drying beds, stockpiles	Tiles and plastics	A1a	Stockpiles
RB	30	70	AnD, AcT, lagoons	Food industries	B2b	Ploughing in dedicated land
DK	70	30	AnD, drying in paddies	Food and beverages	A1a	Ploughing in dedicated land
WD	15	85	AnD, lagoons	Steel polishing and paints	B2b	Irrigated to dedicated lands
RT	–	100	AeD, AcT, drying beds, stockpiles	–	B2a	Stockpiles

WWTP name	Source of wastewater composition %		Treatment and dewatering Processes involved at WWTPs[a]	Types of industries within the sources' catchment area	Sludge class[b]	Current use of sludge
	Industrial	Domestic				
TK	–	100	AeD, AcT, lagoons	–	–	Lagoons
HD	15	85	AeD, AcT, drying beds	‡	B1a	Irrigated to dedicated non - cropped land
HB	40	60	AeD, AcT,	Tannery and other	B1b	Lawn irrigation
CG	–	100	AeD, AcT	–	A1a	Irrigated to dedicated non - cropped lands
DT	–	100	AeD, AcT, lagoons	–	B1a	Lagoons
JM	2	98	AeD AcT	‡	B2b	Transferred to WWTP WD

‡No information was provided by the WWTP.

[a] Treatment processes practised at WWTP; AnD = Anaerobically digested, AcT = Activated, AeD = Aerobically digested sludge. Drying beds, belt pressing, paddies, and lagoons are sludge dewatering and drying techniques, whilst stockpiles are short and long-term storage and management options.

[b] Classification followed the South Africa sludge classification system (Snyman and Herselman, 2006) based on the information provided by the WWTPs (microbiological class data) and chemical properties results obtained after the samples analyses.

[c] During the time of sampling from this WWTP, the anaerobic digesters were non-functional hence activated sludge samples were collected.

3.1. Physicochemical properties of sludge

3.1.1. Moisture content, total solids, pH and EC

Total solids, pH and EC values of sludges in this study are presented in Table 2. Generally, there was a small variation observed in pH values for sludges under WAS and AeD processes which ranged from 6.21–6.9 and 7.11–7.91 respectively. A closer look onto AnD sludges showed that a greater variation existed among the sludges produced under this process with their pH ranging from 5.72 to 7.77. Sludge pH is a critical factor to consider for irrigation water as it influences soil pH in the long run. Plant nutrients availability for crop uptake and solubility of toxic metals also depend on pH. Under acidic conditions ($pH \leq 4.5$), plants would show signs of macronutrients (N, P, K, Ca and Mg) shortages whilst in alkaline soil status, micronutrients like Fe, Mn and B would be limited for plant access. However, the analysis showed that all of the sampled sludges in this study had their pH values falling within the acceptable range of between 4.5 and 9 which support nutrients availability (Peterson, 1982) and positive crop productivity.

Table 2. Total solids, total suspended solids, pH and EC of the studied sludge.

Names of WWTPs	**pH**	**EC** ***m*S m^{-1}**	**TS** **%**	**TSS** **mg L^{-1}**
	Anaerobically digested sludge			
RB	7.73	611	2.38	165
DK	7.42	510	0.72	27
VP	5.83	284	2.84	108
WV	7.77	821	0.93	254
AC	7.40	447	0.40	215
BN	6.87	213	0.16	56
JS	7.36	441	1.81	20
RF	5.72	598	0.67	558
HF	7.00	318	1.24	164
WD	6.42	239	2.11	261
	Aerobically digested sludge			
HD	7.91	365	16.21	ND
CG	7.11	111	0.16	4
	Waste activated sludge			
OF	6.90	91	0.29	ND

Names of WWTPs	pH	EC mS m^{-1}	TS %	TSS mg L^{-1}
RT	6.70	58	0.26	ND
HB	6.62	69	0.36	2
TK	6.66	44	0.30	ND
DT	6.80	61	0.28	ND
JM	6.21	95	0.25	9

ND = Not detectable.

EC = Electrical conductivity.

TS = total solids.

TSS = total suspended solids

The sludges' EC varied from 44 to 821 mS m^{-1} (Table 2). Wastewater treatment processes have exhibited an influence on salts concentration during sludge treatment. Largely, WAS processed sludges had EC ≤ 95 mS m^{-1}. However, AeD and AnD sludges' EC values were above 100 mS m^{-1}. EC is an indicator of dissolved salts concentration in a solution. Whenever municipal sludges are used as supplementary water for irrigation, critical irrigation management needs to be observed and adhered to. Following the use of liquid sludge for irrigation, an increase in salts concentration in the soil could show in the long run (Mohammad Rusan et al., 2007) and this may lead to crop damage and destruction of soil structure especially in hot regions where high and fast evaporation could be experienced (Becerra-Castro et al., 2015). Therefore, high EC generally limits the sludge irrigation application rates to reduce soil quality loss and yield loss resulting from salts addition.

WAS processed sludges investigated in this study could be used freely without fear of salts accumulation and salinity problems since their EC falls below the critical limit of 200 mS m^{-1} (2 dS m^{-1}) that suits irrigation water. Salinity has been known to be a major challenge reducing crop yield (Patel et al., 2002; Rogers, 2002) and such a challenge could be observed on soils irrigated with municipal liquid sludge. For all WWTPs employing anaerobic and one for aerobic digestion processes, their sludge EC values were above the threshold level. These high values in EC could be attributed to some chemicals used during treatment, some detergents from the industrial feedstock and washing materials from the domestic sources especially considering that most of the WWTPs in this study receive 50% or more of their feedstock from the domestic origin (Table 1). In addition, digested sludges exhibited high solids content (TS and TSS) which could be organic and inorganic and likely to have fractions that dissolve in water, releasing salts and lead to high EC. The use of water with high EC above 200 mS m^{-1} have been seen to cause salinity and reduce yields in grain crops like rice (Asch et al., 2000). Application of sludge with high levels of salts could lead to ion toxicity, oxidative stress and hyperosmotic thereby reducing plant growth and productivity (Levy and Tai, 2013; Ngara et al., 2012). To minimize soil structure destruction when irrigating with municipal sludge, periodic monitoring of soil quality parameters is always crucial.

Moisture content (MC) of the sludges is not presented in this study, however, for each WWTP (Table 2), MC it is regaded as 100% less TS percentage. Almost all analyzed sludges have shown MC of 97% and above with a single sludge sample recording 83.3% MC and 16.2% of TS (HD plant) during sampling period. However, all other sludges' total solids ranged between 0.16 and 2.84%, with activated sludge recording solids of ≤0.36% relative to aerobic and anaerobic sludges which had ≥0.4% TS (Table 2) except for BN (AnD) and CG (AeD) that had 0.16% TS. TSS were high in AnD processed sludges with most of the sludges having >20 mg L^{-1}.

3.1.2. Organic matter, ash and carbon content

Fig. 1A and B presents organic matter (OM), ash, total and organic carbon (C) content of the sludges. All (except one) of the sludges in this study showed high OM content ranging between 52% and 79%. WAS processed sludge recorded the highest OM in range of 66% to a maximum of 78%. For anaerobic sludges, VP and HF plants had 76%, WD 71% whilst the rest of plants recorded between 52 and 66% OM. An exceptionally high variation of OM content was observed between the aerobically processed sludges. HD sludge had 33%, whereas CG had 79% OM. It is highly possible that industrial wastes channelled to HD are non-combustible and are largely of non-organic material status hence strongly influencing the final sludge product's organic materials.

This was clearly observed after the oxidation of the material in high temperatures of 550 °C (ashing) in a furnace that resulted in 67% ash content (Fig. 1A) and it is likely associated with lime addition used for stabilization at the plant. The HD WWTP uses lime as part of its sludge stabilization processes and it is strongly evident that this contributed to high ash content in the sludge material. However, the ash content fractions for the other sludges under this study were <50% and fall between 21% and 47.6% range. Generally, municipal sludge is known to be a reliable source of OM (Wijesekara et al., 2017) and almost all sludges (except for HD sludge) had over 50% OM. The presence of high OM content makes sludges good soil conditioner materials (Bell et al., 2004). As such, they can be used to rejuvenate fertility of degraded soils because their application would make a substantial increase in soil organic carbon and other required nutrients (Burducea et al., 2019; Cogger et al., 2013).

Carbon fractions were also assessed, and it was observed that C lies between 24.4% and 43.8% (Fig. 1B). There was no significant difference (only ≤0.1%) between organic C and total C for most sludges except for HD sludge that showed a 6% variation. The high percentage variation in C observed in HD sludge is related to its high ash and low OM content and possibly indicating non – combustible material of this sludge. As reiterated earlier, this is likely as a result of lime stabilization. This can be observed by the high level of Ca in this individual sludge (Table 3).

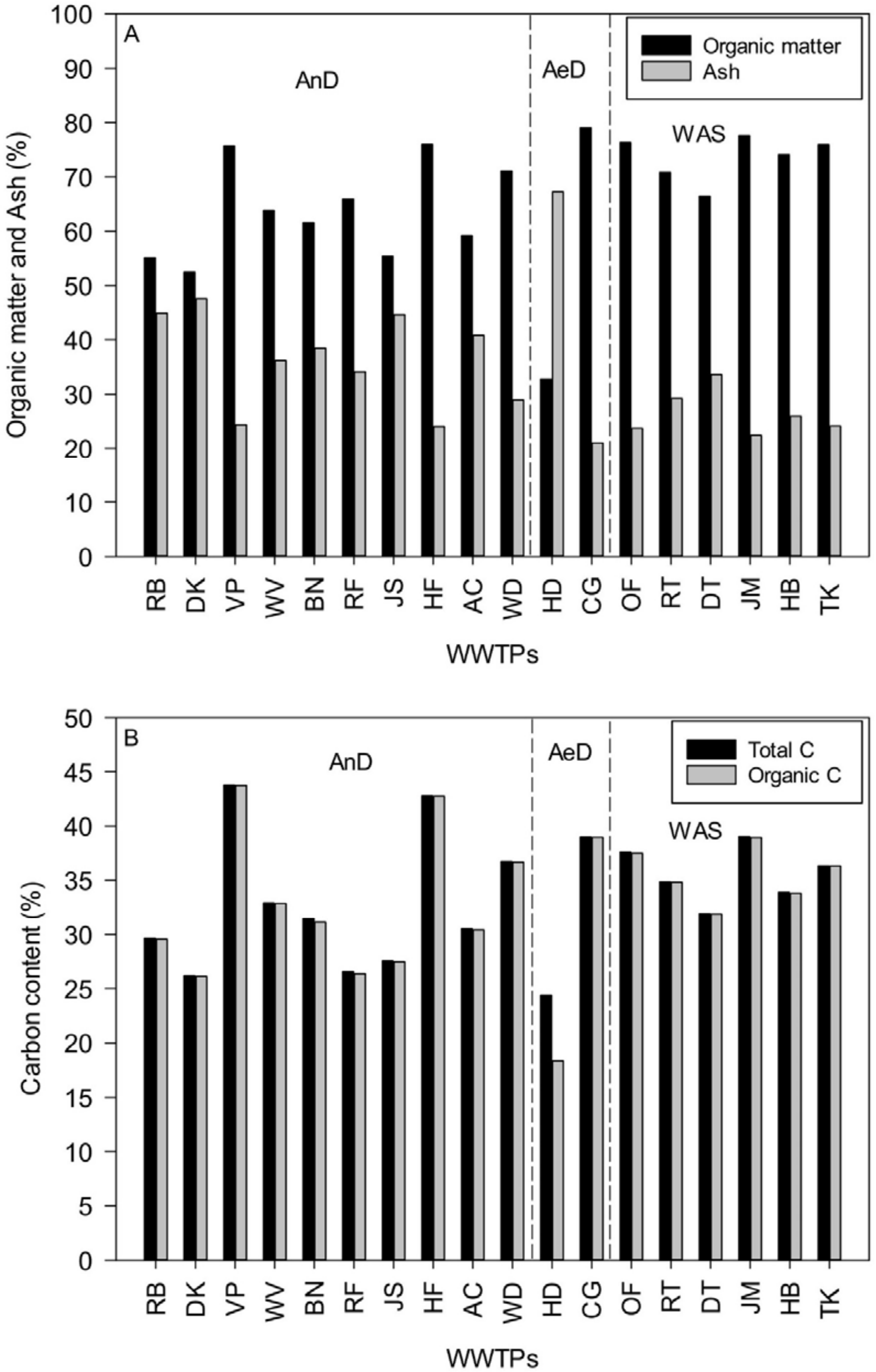


Fig. 1. Organic matter, ash (A) and carbon (B) content (%) of the sludge involved in the study. The first ten (RB – WD) are AnD sludge plants, followed by two (HD and CG) AeD sludge plants and the last six (OF – TK) are WAS producing plants. AnD – anaerobic digestion, AeD – aerobic digestion and WAS – waste activated sludge.

Table 3. Macro and micronutrients concentrations for the 18 WWTPs sludge under investigation against the threshold limits set for sludge classification.

WWTPs name codes	Ca	Mg	Na	B[a]	Fe	Al	Mn	S	Mo[a]
	g kg^{-1}								mg kg^{-1}
Anaerobically digested sludge									
RB	27	4	3	0.03	52	16	1.76	21	19
DK	34	4	5	0.03	51	30	0.6	19	10
VP	23	2	3	0.01	41	12	1.17	29	6
WV	27	6	5	0.04	28	18	0.76	17	8
BN	30	5	10	0.06	109	8	1.96	18	8
RF	32	3	3	0.02	38	17	0.44	11	5
JS	33	4	5	0.04	109	12	0.85	14	3109
HF	20	6	6	0.02	21	8	0.49	18	8
AC	31	4	5	0.04	51	19	0.84	21	7
WD	17	5	6	0.03	17	11	0.46	16	28
Aerobically digested sludge									
HD	228	5	1	0.01	5	10	0.14	5	3
CG	25	5	24	0.03	1	4	0.16	9	3
Waste activated sludge									
OF	15	6	10	0.06	9	11	0.23	9	4
RT	16	8	10	0.05	9	15	0.29	10	4
DT	14	6	4	0.04	24	21	0.39	9	2
JM	14	5	9	0.04	8	10	0.44	9	601
HB	19	9	17	0.08	9	10	0.48	7	4
TK	14	6	7	0.05	8	12	0.14	9	4
South Africa limits[b]	–	–	–	<0.02, 0.02–0.07, >0.07		≤20	≤1.5	–	<4, 4–12, >12

[a] Thresholds are based on South Africa guidelines limits with lower, middle and higher ranges denoting pollutant classes a, b, and c respectively.

[b] Adapted from Snyman and Herselman (2006).

3.1.3. Total N, inorganic N, total and extractable P content

Fig. 2A presents total nitrogen content of the analyzed sludges in this study. Nitrogen is an essential soil nutrient to support agricultural productivity. It is limited in its accessibility especially to many smallholder farmers in the developing world. When sludge is used, it is applied largely based on crop N requirements (Cogger et al., 2004). However, the larger percentage of sludge N is in organic form (Gilmour et al., 2003), and unavailable for crop uptake especially in the early days of its application. With relatively low inorganic N associated with sludge materials, N must be initially mineralized to be available for plant uptake. The analytical outcomes in this study revealed a generally varied total N depending on sludge source and treatment process.

Higher total N percentages were observed on waste activated sludge (WAS) than digested sludges from the other two treatment processes (Fig. 2A). Total N ranged from 4.9–6.5% for WAS, and 2.9–5.6% for AnD sludge. AeD sludge showed larger variation in total N percentage between the two WWTPs employing this treatment system with HD recording 1.5% whilst CG had 6.8% total N. The wide variation and low N content in HD sludge is closely related to low OM recorded at this WWTP and such scenario is related to high lime treatment. More so, HD's wastewater has some industrial input, which could further reduce organic material and associated N content compared to CG plant. Mean total N was 3.9% for anaerobically digested, 4.2% for aerobically digested and 5.9% for waste activated sludge. The low total N observed on anaerobically digested sludge is likely due to the treatment process that involves biological nitrogen removal. Although HF and WD WWTPs employ the same treatment processes, their total N was highest with 5.5 and 5.6% N respectively (Fig. 2A). The higher N concentration levels of these two plants over and above the other WWTPs employing the same process could be attributed to the origin of the wastewater. Larger fractions of wastewaters treated at HF and WD were highly of domestic origin. Basically, wastewaters from domestic sources are rich in biodegradable matter thereby slowly releasing N during the treatment process. Such N could then be retained in the sludge relative to wastewaters that contain more of non-degradable materials.

Fig. 2B presents inorganic N species of the sludges under investigation. Of the three inorganic N species ($NH_4 – N$, $NO_3 – N$ and $NO_2 – N$) presented in this study, the observed dominating N fraction was $NH_4 – N$ followed by $NO_3 – N$ whilst $NO_2 – N$ was very low (Fig. 2B). AnD sludge showed higher $NH_4 – N$ ranging from 94 to 751 mg L^{-1} with an average of 344 mg L^{-1}. Under this AnD group of WWTPs, BN sludge recorded the lowest $NH_4 – N$ level. For AeD sludge, $NH_4 – N$ was highly variable between HD and CG WWTPs recording 144 and 0.57 mg L^{-1} respectively. For WAS, $NH_4 – N$ was much lower than for the AnD sludges. Digested sludge had a high N fraction in the form of $NH_4 – N$ relative to WAS in the order of AnD > AeD > WAS. Ammonium N is typically the highest inorganic N fraction in anaerobically digested sludge (Mtshali et al., 2014). This is attributed to the stabilization process that takes place in digesters. During digestion process, OM is decomposed and stabilized, thereby releasing N from nitrogen-rich proteins (Yang et al., 2018). Sludges with high $NH_4 – N$ and $NO_3 – N$ species are suitable for supplying the much needed and readily available N for plant uptake at the time of application than those high in organic N. In the other hand, the order of $NH_4 – N$ content between the processes concur strongly with the previous studies that AnD is poor in ammonium N removal especially if the process is not in combination with AeD process (Chan et al., 2009; Tchobanoglous et al., 2003). AeD processes can effectively remove nutrients during treatment since it includes biological nutrient removal stages in their treatment configurations. However, WAS is mostly

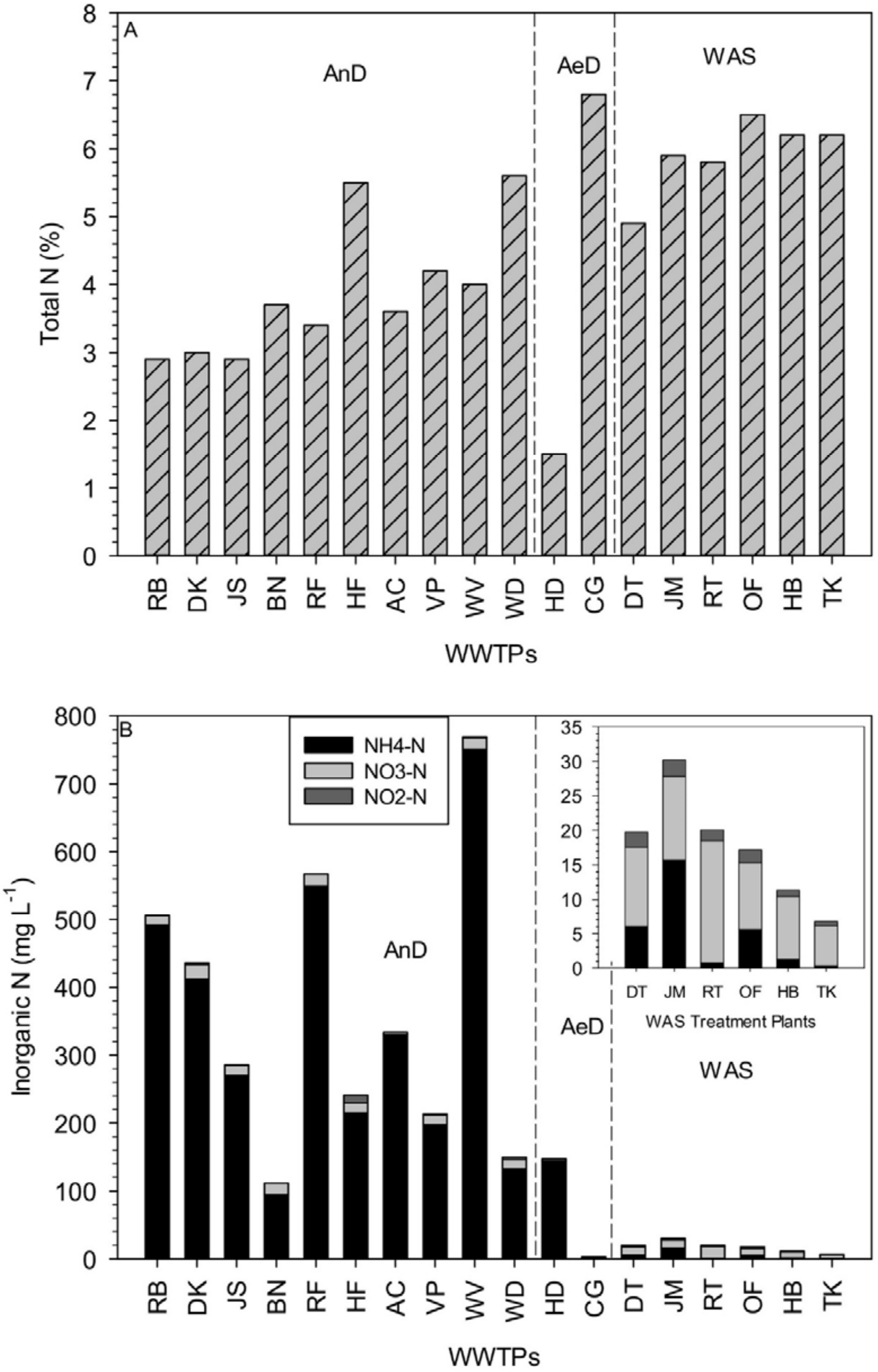


Fig. 2. Total nitrogen (%) (A) and inorganic N (B) ($NH_4 - N$, $NO_3 - N$ and $NO_2 - N$) concentration (mg L^{-1}) for liquid sludge collected from 18 WWTPs under the study and their respective wastewater treatment processes. The insert shows the rescaling of the WAS WWTPs' inorganic N for clear vision of $NO_3 - N$ and $NO_2 - N$ fractions AnD = anaerobically digested sludge, AeD = aerobically digested sludge, WAS = waste activated sludge.

unstabilized resulting in high total N content retention (Fig. 2A) and low inorganic N release (Fig. 2B) compared to digested sludges. With a greater number of WWTPs' sludge in the current study high in $NH_4 – N$, strategic options are required especially when using liquid sludge for irrigation purposes to minimize N losses through $NH_4 – N$ volatilization. Mean $NO_3 – N$ was generally low for all sludges, ranging from 2.4 mg L^{-1} for AeD sludge to 11 mg L^{-1} for WAS and 15 mg L^{-1} for AnD sludge.

Fig. 3A presents total and extractable P concentrations of the studied sludges. Phosphorus is among the most essential and yet often limiting nutrients for crop production, especially on soils in the developing countries (Graham and Vance, 2000; McLaughlin et al., 2008). Sludge use in agricultural lands would help address P shortages in degraded agricultural soils. Sludge products have substantial amounts of P, and its use for agricultural productivity could bring in some favorable benefits in supplying P and improving soil fertility status. In the current study, P content varied among WWTPs within each treatment process, but the ranges were similar across treatment processes. Total P content ranged from 13 to 28, 23–30 and 15–30 g kg^{-1} for AnD, AeD sludge and WAS respectively (Fig. 3A). HB (WAS) and CG (AeD) WWTPs had sludge with highest total P relative to other WWTPs.

Although these sludges have shown substantially high amounts of total P, their Bray-1 extractable P was very low in all AnD and AeD sludge sources. AnD WWTPs had the lowest extractable P ranging from almost 0.1–0.9 g kg^{-1} with WV, WD and HF recording the highest amounts of 0.6, 0.8 and 0.9 g kg^{-1} respectively, followed by AeD WWTPs with an average of 1.33 g kg^{-1}, whilst the highest extractable P was observed from WAS processed sludges that ranged from 1.8–6.2 g kg^{-1} (Fig. 3A). The sludges under investigation had total P levels within the range of 1.5–3.5% and they fall in previously reported (Sullivan, 2015) range. However, the extractable P was very low against the 50% of the total P expected to be available for crop uptake within the first year of application as stated by Antille et al. (2014). Sullivan (2015) posit that about 20 to 60% of the total sludge P applied is available through mineralization per year. This agrees with the 50% average mineralization rate reported by Antille et al. (2014). This suggests that the Bray-1 P extraction may not be the most appropriate method to estimate available P in sludges.

Fig. 3B presents the observed K content of the sludges in the current study. Generally, there was no systematic pattern in K content between and across WWTPs employing particular treatment process. K content varied significantly within and across treatment processes. In this instance, it can be deduced that the major cause of such variation was originating from the feedstock sources for each WWTP.

On average, sludges from the WAS processing plants showed superior K content over AeD and AnD (Fig. 3B). The lowest levels of K were observed in sludges that underwent anaerobic digestion in which K ranged from 1.6–8.0 g kg^{-1} with WV WWTP recording the highest K concentration, AeD sludge had 1.5 (HD) and 12 g kg^{-1} (CG) whilst K in WAS sludges was between 6.8 and 14.8 g kg^{-1}. Reports state that, in dewatered sludges, K concentration is generally low probably because K can be easily lost in effluent (Wen et al., 1996). Although K is one of the major nutrient elements required for agricultural production, its content was very low in the sludges studied. This is however not surprising because sludge and its by-products are generally known to have low K (Sullivan, 2015). There is a strong indication that, application of organic materials like sludge may even result in low available K in soil suggesting that there might be a negative correlation of soil K availability with soil organic matter (Wen et al., 1996). Therefore, in most instances, when sludge materials are used for agriculture, there might be need for K source supplements from chemical fertilizers.

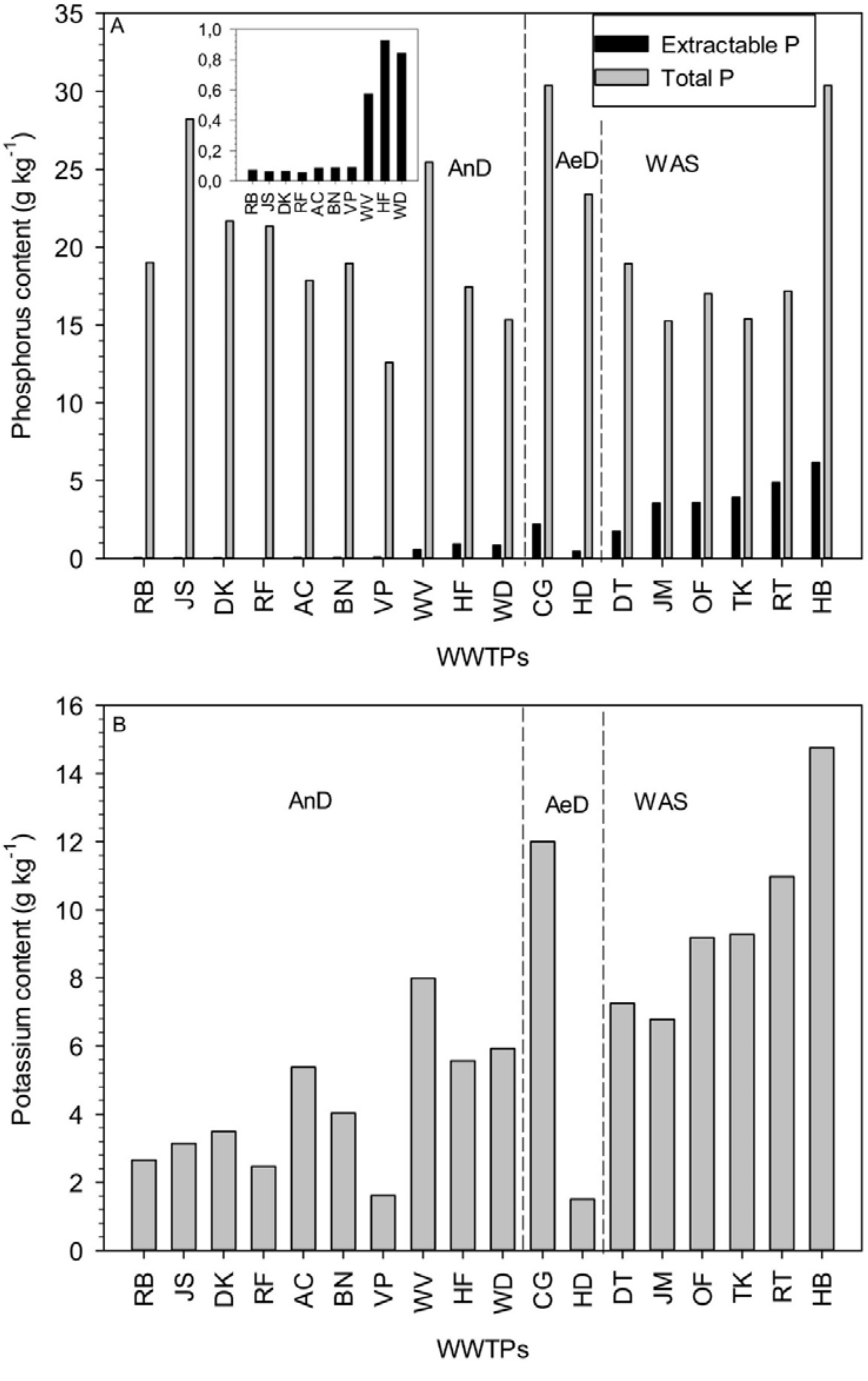


Fig. 3. Total P and extractable P (A) and Potassium (B) concentration (g kg^{-1}) for liquid sludge collected from 18 WWTPs under the study and their respective wastewater treatment processes. The insert shows re-scaled of extractable P for AnD (RB – WD) WWTPs. AnD = anaerobically digested sludge, AeD = aerobically digested sludge, WAS = waste activated sludge.

3.1.4. Micronutrients and non - toxic metals concentrations

The current sludges were tested for micronutrients and low risk metals needed for crop growth (Table 3). The sludges have shown substantial amounts of required micronutrients for plant support. Anaerobically digested sludges had generally high Ca content ranging from 17 to 34 g kg^{-1} relative to waste activated sludge where the Ca was between 14 and 19 g kg^{-1}. Aerobically digested sludge had exceptionally high Ca content especially HD WWTP that recorded 228 g kg^{-1}. The observed high Ca level in HD plant could be likely associated with calcium carbonate (CaCO3) lime treatment done for sludge stabilization at this WWTP. The use of lime at this plant can also be connected to the high pH level (7.91) recorded for its sludge and this was basically the highest of all sludges in the study. Lime stabilization is handy in wastewater treatment as it raises the wastewater pH which in turn reduces the availability of such heavy metals as Cd (Ma et al., 2018). For other micronutrients like Mg and Na, WAS processed sludges had higher concentrations relative to AnD sludges. According to South Africa sludge utilization guidelines for agricultural use, sludge should meet certain criteria in terms of its metal content. Threshold levels have been established above which sludge should not be applied onto agricultural lands or can be applied coupled with other management options (Snyman and Herselman, 2006).

For low risk metals (Fe, Al, Cu, Mn and Mo), except for WD, all other sludges from AnD process had higher Fe content, whilst for waste activated sludge, only one plant (DT), had sludge with Fe and Al content above other WWTPs under this process. DK (AnD) also recorded Al content of 30 g kg^{-1} that is 10 g above the limit. Two of the AnD plants (RB and BN) had sludge Mn (Table 3) levels above the critical limit whilst other plants' Mn falls within the limit. The AnD plants from which the sludges were collected for this study do use ferric chloride ($FeCl_3$) as a coagulant and subsequently P removal chemical. $FeCl_3$ use is evidenced by high Fe concentrations recorded in these WWTPs than WAS sludges. The use of $FeCl_3$ in municipal sludge process is another useful option and its use have shown some evidence that Fe oxides can reduce availability and enhance removal of toxic metals such as Cd, Cr, Ni, Zn and others from wastewater (Patoczka et al., 1998; Terashima et al., 1986). As for Cu, all WWTPs under the three processes except for BN recorded sludge Cu concentration within the threshold level (Table 4). BN recorded Cu concentration of 2080 mg kg^{-1} and that pushed this sludge to pollutant class b category. Additionally, Mo concentration was exorbitantly high in JS and JM WWTPs. These plants receive most of their influent from households however there are some mining activities and tiling material production around these places which are likely to be the greater contributing sources of Mo.

Table 4. Toxic elements concentrations for the 18 WWTPs sludges under investigation against the set threshold limits.

WWTP name	Pb	Cr	V	Cd	As	Hg	Se	Ni	Co	Zn	Cu
	mg kg^{-1}										
Anaerobically digested sludge											
RB	240	732	53	15	21	1.8	8	351	60	4520	740
DK	261	481	33	4	6	0.8	1	51	13	1570	300
VP	38	420	15	8	3	0.6	1	232	24	1460	310
WV	117	296	26	5	8	0.8	5	111	13	4280	310
BN	1371	1092	21	3	8	0.9	6	139	46	1610	2080
RF	69	133	29	4	6	1.9	1	43	10	1510	460
JS	117	122	783	4	35	1	10	104	377	1910	460
HF	234	133	17	167	3	1	1	112	7	1920	270
AC	141	837	32	5	14	0.8	1	77	45	10,450	290
WD	634	710	20	1	24	2.9	192	162	26	710	310
Aerobically digested sludge											
HD	11	30	5	0.3	1	0.3	13.76	12	3	310	120
CG	64	88	10	3	2	0.3	0.58	18	3	250	120
Waste activated sludge											
OF	99	39	31	1	2	0.5	1.45	28	3	560	100
RT	22	33	18	1	4	0.4	1.07	26	3	680	90
DT	34	56	29	1	5	1.7	1.45	34	6	1370	140
JM	807	506	15	1	8	4.6	1.27	39	6	590	250
HB	26	550	13	1	3	0.4	1.17	75	9	2820	170
TK	29	29	20	1	4	1.5	1.09	26	4	640	200
Pollutant class a[a]	<300	<1200	–	<40	<40	<15	–	<420	–	>2800	<1500
Pollutant class b[a]	300–840	1200–3000		40-85	40–75	15–55	–	420	–	2800–7500	1500–4300
Pollutant class c[a]	>840	>3000	–	>85	>75	>55	–	>420	–	>7500	>4300

[a] South Africa's pollutant classification as stated in Snyman and Herselman (2006).

Table 4 also presents an array of toxic and low risk metal species concentrations for the analyzed sludges. In relation to the pollutant classification of these sludges, South Africa guidelines for agricultural utilization and disposal of municipal wastewater sludge by Snyman and Herselman (2006) was used. The analyses showed that except for a few WWTPs, most plants had sludge falling within the pollutant class A threshold. WD, JM and BN treatment plants were high in Pb (634, 807 and 1372 mg kg^{-1} respectively) with the two former WWTPs' sludge classified under pollutant class B and the later under class C. HF was high in Cd (167 mg kg^{-1}) placing the sludge in class C. Zn was also above the threshold limit for RB, WV and AC plants and pulled the former two plants into class B and the latter's sludge downgraded to class C (Table 4). Application of sludge in agricultural lands is largely limited by toxic metals concentrations. Sludges falling within pollutant class A are suitable for agricultural use without additional restrictions and requirements, whilst class B sludge could be used but with some restrictions to be observed.

For example, the receiving soil for Class B sludge must be thoroughly analyzed before application to ascertain that the metals load can be accommodated without the receiving soil reaching the minimum limit of class C upon sludge application. However, class C sludge should never be put into agriculture use (Snyman and Herselman, 2006). Although it does not form part of sludge classification component, it is also important to note that besides the nutrient content, other sludge properties like salts level would limit individual sludge application.

3.2. Implication of N and P concentrations and the nutrient loads to agricultural land based on sludge application options/scenarios

AeD sludges were drawn from only two WWTPs of which HD had TS of around 16% (Table 2) hence it was considered non – liquid and unfit for irrigation use. Therefore, to use only CG for the nutrient loading computations was inferred to be inadequate to give a true representation of the AeD sludges. As such, AeD was entirely excluded in the comparative nutrient loading analyses and discussion in this study. Different sludge application options presented various nutrient loading rates on agricultural lands (Table 5). With reference to the nutrients concentrations (%) identified for the studied sludges, and the target N of 60, P of 40 and K of 35 kg ha^{-1} $season^{-1}$ for a maize crop supposedly grown under semi – arid region area and expected to receive an average total rainfall of 500 mm, the computed nutrient loading rates varied strongly with sludge application option and sludge type. Two application options showed nutrient loading rate quantities much higher than the recommended crop nutrient needs. The nutrient loading rate followed the order of; as irrigation water >10 tons ha^{-1} dry sludge > N or P based application. This order of nutrient loading was observed in all three major nutrients estimated in this study.

Table 5. Available N and P, and total K nutrient loads (kg ha^{-1} season^{-1}) that would be applied under maize production based on sludge application options.

		Nutrient supply through specific application option		
Sludge application option	**Sludge type**	**Available N**	**Available P**	**Total K**
		kg ha^{-1}		
Target nutrient rates[a]	–	60	40	35
As Irrigation at 500 mm water ha^{-1} year^{-1}	AnD	3800	1980	420
	WAS	5920	1900	970
Based on N requirement	AnD	60[a]	44	23
	WAS	60[a]	28	35
Based on P requirement	AnD	55	40[a]	21
	WAS	87	40[a]	51
Based on 10 tons ha^{-1} year^{-1}	AnD	109	79	42
	WAS	166	76	97

[a] Target application rate as assumed to be optimum fertilizer requirement for maize grown under dryland production.

Application of liquid sludge as a water source for irrigation has shown that it presents nutrient loads much higher compared to other options. This option could potentially load N quantities that are 60 and 97 times higher for AnD and WAS sludge respectively above the required 60 kg N ha^{-1} season^{-1}. Almost 4000–6800 kg N ha^{-1} season^{-1} (Table 5) could be potentially applied when liquid sludge is used for irrigation. In the other hand, N loads in the range of 108–165 kg ha^{-1} from sludge application could be observed from a single rate of 10 tons ha^{-1} whilst when sludge is applied based on crop P need, the load of about 43–87 kg N ha^{-1} would be observed (Table 5). Similar to N trends, P loading onto the receiving land was observed to be over and above the crop P requirements across all sludge types assuming the current sludges are applied either as irrigation water or at 10 tons ha^{-1} season^{-1} (Table 5). The AnD and WAS showed P loads of almost 2000 kg ha^{-1} when irrigation option is used. However, if crop N need based application is chosen, it was seen that AnD sludge would supply P at rates similar to the crop requirements. Under such scenario, AnD would oversupply P by just 4 kg whilst WAS would undersupply the same nutrient with 12 kg less. About 44 and 28 kg P ha^{-1} could be potentially loaded from AnD and WAS sludges respectively when sludge is applied based on crop N requirements. In contrary, at 10 tons sludge ha^{-1} scenario, approximately 79 kg from AnD, and 76 kg P ha^{-1} from WAS would be loaded.

Additionally, the use of current sludges as water for irrigation would see K supply following the same trend as on N and P. This irrigation option would result in highest K loads relative to the other options. About 420 from AnD and 970 kg K ha^{-1} from WAS (Table 5) would be loaded through the irrigation option against 23 (AnD) and 35 (WAS) kg K ha^{-1} if sludge is applied based on crop N requirement, whilst 21 (AnD) and 51 (WAS) kg K ha^{-1} could be added to the land when the application is made based on crop P requirements. Sludge application based on 10 tons ha^{-1} would potentially add about 42 (AnD) and 97 (WAS) kg K ha^{-1} to the receiving soils. WAS sludge showed a greater K loading rate over AnD sludge in all three of the proposed sludge application scenarios. Ultimately, the nutrient supply of N, P and K was excessively high when liquid sludge application is proposed to be used as irrigation towards meeting crop water needs. However, supposedly liquid sludge is applied targeting to meet the crop N requirements of 60 kg N ha^{-1} for the maize crop, it was observed that a very small fraction of crop water requirements would be met. Based on the crop water requirement of 500 mm for a maize crop per season as suggested in this study, only about 1% and 1.5% of the crop water requirements would be achieved through irrigating with WAS and AnD sludge respectively.

Although vast literature posits that sludge be applied based on crop N requirements (Binder et al., 2002; Cogger et al., 2001), the basis applies largely to sludge materials assumed to have much of N relative to other nutrients. It is however a different case when a sludge material has P content that is as equally high as its N content. In such cases, P accumulation and its pollution could be detrimental to the environment. In the current study, the sludges exhibited N content between 1.5 and 6.8% and 1.3–2.5% P for most of the sludge sources, whilst only three out of the eighteen sludges had >2.5% P. Sludge is a good external source of P supply and with its substantial P content, it is potentially capable of altering N:P ratio of agroecosystems. N:P ratio is an important indicator for measuring nutrient status (Han et al., 2005) in both soil and plant tissues. Although the N:P supporting plant growth is highly varied in literature (Wang and Wang, 2009), many crops and other terrestrial plants do well in their total biomass accumulation in an environment of N:P ratio between the range of 10 and 20 (Güsewell, 2004). It is under such environmental conditions that P pollution risk is seemingly low. Looking at the nutrient status of the sludges in this study, their P values are equally high as their N content hence very low N:P ratios were observed which ranged between 0.6:1 and 4:1. Although the magnitude of P built-up into the soil profile depends on various factors, (Güsewell, 2004; Maltais-Landry et al., 2016), application of sludge material with P content status equivalent to the sludges assessed in this study, multiple applications through irrigation option towards meeting crop water requirements, or application based on 10 tons sludge ha^{-1} $season^{-1}$ would lead to P accumulation in the soil. In the long run, this could pose detrimental effects to the agroecosystems repeatedly receiving such sludge materials. Basically, it would be logical to apply sludges based on crop N or P requirements to minimize long term environmental pollution from nutrient accumulation. These applications scenarios could be more sustainable if the material has high N:P ratio, or application rates are reduced or stopped when soil P reaches high or target levels.

3.3. How best should these sludge materials be applied to agricultural lands?

Municipal sludge application to agricultural lands has been and still largely done in two ways, that is, either as irrigation water towards mitigating agricultural water shortages especially in arid regions or as biosolids and biosolids products upon post – treatment dewatering and drying processes applied to meet crop nutrient requirements. Using sludge materials as those observed in this study either as water for irrigation or biosolids for nutrients supply would require well scheduled nutrient management options. Two sludge application scenarios (as irrigation water and biosolids applied at 10 tons ha^{-1}) presented herein have shown that they could result in over application of major nutrients in excess of the crop requirements. Alternately, if liquid sludge be applied as irrigation targeting meeting crop N needs without overapplication of such, only about 1–1.5% of the crop water requirements could be met through such option. In contrast, application of dry sludge based on crop N and or P have shown to be better options that could be applicable in a sustainable manner. Based on crop N needs scenario, the AnD sludges would supply P slightly above average with 9% whilst WAS would undersupply P by 32%. AnD would undersupply K by 34% lower than the crop requirements, however, under similar conditions, WAS would be capable of meeting the specific K crop needs. Apparently, a single application of AnD sludge based on crop N needs would supply enough P without environmental risks, whilst WAS application would underapply P by 13 kg ha^{-1}. Therefore, this option would need a supplementary P and K sources to bring up these nutrients to the crop requirement levels. However, if the option of applying sludge based on crop P could be chosen, AnD would undersupply N and K whilst WAS would supply 45 and 46% in excess of N and K respectively.

When sludge material is to be used as water for irrigation, minimization of nutrients loading into the agroecosystem and application trade – offs should be the options to consider. Their application should focus on balancing the nutrient load and crop water needs. Another interesting option when irrigating with such sludge could be to apply it under scheduled deficit irrigation where the nutrients content will be the controlling factor determining how much water to be applied per season. Alternatively, in places where some sources of fresh water do exist, it would be proper to dilute municipal wastewater with fresh waters during irrigation. As such, the applied nutrients would be reduced and curtailed from exceeding crop requirements whilst the crop water needs are met. In cases where dried biosolids are being used as sources of nutrients, the nutrients concentration per unit mass of sludge should be considered and be the guiding factor. This should be the basis of sludge application rate calculations where parts of the nutrients required are met by sludge application whilst the balance would be applied through other means. This is handy especially when the sludge material's N:P ratio is low such that accumulation of N and or P in the soil profile is limited. In the interest of reducing the on-site and non-point pollution to the generality of the receiving environments, it is therefore suggested that application of the current sludges as irrigation water is unsustainable. Based on the analyses done for this study, the best option could be applying sludge as biosolids based on crop nutrient requirements (either based on N or P crop needs) at specific and predetermined application rates after taking the nutrients concentration into cognisance.

3.4. The study-to-UN-sustainable development goals linkage

The use of municipal wastewater sludge as a resource in agroecosystems can be a tool in supporting several of the UN-SDGs, including Goal 2 – Zero Hunger, Goal 3 – Health and Well-Being, Goal 6 – Clean Water and Sanitation, Goal 11 – Sustainable Cities and Communities, Goal 12 – Sustainable Production and Consumption, Goal 13 – Climate Action, and Goal 15 – Life on Land. Recycling sludge would mean reduced accumulation of waste on land, fewer nutrients and pollutants leaching and running off into underground and surface water bodies, hence reduced environmental contamination, improved sanitation and thus improved health. Taking wastewater sludge into agricultural land reuses otherwise what could have been wasted water and soil nutrients. This could lead to improved soil fertility, giving rise to enhanced agricultural productivity and reducing food insecurity. This would help achieve the zero-hunger goal in communities with access to wastewater sludge recycling. Additionally, application of sludge into agroecosystems improves soil organic carbon build-up. This increases C sequestration, which would reduce net CO_2 emission, hence helping to mitigate the worldwide challenge of global warming and climate change

(Soriano-Disla et al., 2010; Torri et al., 2014; Pitombo et al., 2015; Antonelli et al., 2018). This also helps reverse land degradation through addition of organic matter and increased fertility. Although recycling wastewater sludge through land application is only one of many actions needed to achieve the SDGs, it is nonetheless a valuable action and should not be neglected.

However, achieving these potential benefits towards sustainable goals could be possibly challenging without proper sludge characterization and critical use suitability assessment. Critical characterization influences proper classification of individual wastewater sludges which in turn helps in drawing up decisions towards use and management practices befitting specific sludge type. Sludge characterization and its use(s) suitability assessment are linked aspects which are required to address a common goal – cost effective management and sustainable utilization of wastewater sludge.

The current study highlighted the strengths and importance of municipal sludge characterization and the need for proper use suitability assessment whenever sludge is to be selected for agricultural purposes. It also highlights the potential challenges associated with specific sludge application options as they exist in the day-to-day activities involving wastewater recycling in the agriculture. As well, it presents expected properties of sludges that have undergone different treatment processes, and potential application options in line with reduced environmental contamination.

4. Conclusion

Sludge is a unique, complex and dynamic product. Proper characterization of this type of organic material is crucial to prompt proper decision making regarding its use and application options on agricultural lands. In this study, sludge pH levels were within the acceptable range (4.5–9.5) required in supporting plant growth and production. In addition, the sludges' high-risk metals concentrations were below threshold levels with the exception of JM (WAS) sludge which was downgraded to class b due Pb above threshold level and three AnD processed sludges from BN and WD sources taken down to class b because of high levels of Pb and HF to class c due high Cd concentration. Zn was one of the pollutant elements that pushed some sludges into class c with respect to pollutants classification. Application of biosolids based on crop N or P requirements showed to be the better options. Basically, it would be logical to apply the current sludges based on crop nutrient requirements and minimize long term environmental pollution from nitrogen and phosphates accumulation. Such options would suggest fractions of the under applied nutrients from sludge application be met through other external nutrient sources. Application of liquid sludge on agricultural lands as irrigation water towards meeting the supplementary water needs would add nutrients in excess of plant demands and would be detrimental to the agroecosystems as surplus nutrients would cause agro-ecosystems pollution, therefore, it is an unsustainable option. Interestingly, if liquid sludge is applied to meet the targeted 60 kg N ha^{-1} requirement for maize, only a merger 1 and 1.5% of the water requirements would be met from WAS and AnD sludges.

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CRediT authorship contribution statement

T. Badza: Writing - original draft, Methodology, Investigation, Formal analysis, Validation, Data curation. **E.H. Tesfamariam:** Conceptualization, Resources, Writing - review & editing, Supervision, Validation, Project administration, Funding acquisition. **C.G. Cogger:** Writing - review & editing, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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