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RESEARCH ARTICLE

In-field assessment of soil pH and mineralization of phosphorus and potassium following the application of composted winery solid waste in sandy loam Ferric Luvisol

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ABSTRACT

Special attention on the plant nutrients mineralization rates is often required when organic fertilizers are used on croplands. This study described the patterns of phosphorus (P) and exchangeable potassium (K) released from winery solid waste (WSW) compost in sandy loam soil. Treatments consisted of equivalent rates of 0, 5, 10, 20 and 40 t ha^{-1} of compost-soil mixture in Ziplock bags buried on the field at 30 cm soil depth. Destructive sampling of treatments was conducted at 0, 7, 21, 42, 63, 84, 105 and 126 days after incubation (DAI) for laboratory analysis. The 40 t ha^{-1} rate resulted in up to a 9.5% increase in soil pH while the contents of net mineralized P and K measured were significantly affected by compost rate and incubation period interaction. Over the 126 days of the incubation period that runs across summer and winter seasons, mineralized P ranged from -62 to 86 mg kg^{-1} whereas mineralized K varied between 41 and 2047 mg kg^{-1}. Cumulative mineralized P and K contents ranged from 62 to 207 mg kg^{-1} and 1272 to 9206 mg kg^{-1}, respectively with the highest amount obtained at the 40 t ha^{-1} compost rate. The high net P and K mineralized contents suggest that WSW compost may act as a P and K source. However, cautious use of WSW compost as a soil amendment is recommended to mitigate the potential risks of soil pH increases and other unintended consequences such as toxicity, nutrient imbalance, and possible P and K antagonistic effects.

Keywords: Compost; Nutrient mineralization; Phyto-toxicity; Soil amendments

INTRODUCTION

The use of excessive chemical fertilizers and pesticides in conventional agriculture comes at a great price with respect to soil health, which is a key component to achieve agricultural sustainability (Sihi et al., 2017). Organic farming is increasingly promoted worldwide as a sustainable management alternative to conventional farming (Condron et al., 2000). Long-term soil fertility and soil quality protection is one of the key characteristics of organic farming (Condron et al., 2000). Organic farming aims at closing the loop of nutrients by returning back the organic wastes to the field and at the same time incorporating perennial and leguminous plants into the soil without the addition of synthetic fertilizers (Lori et al., 2017). A review by de Araújo and de Melo (2010) revealed that the agricultural practices in organic farming system, such as addition of compost, straw and natural amendments, promote positive changes in the soil microbiological and biochemical processes, resulting in the increase of soil microbial biomass.

Grape growing and processing for winemaking often generate prodigious solid wastes. Winery solid organic waste materials include grapevine prunings and grape marc consisting of pressed skins, stalks, seeds, and pulps (Nerantzis et al., 2006; Oliveira and Duarte, 2016). The over-production and persistent increase in winemaking

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perpetuates inappropriate disposal of these waste materials on agricultural land (Van Schoor, 2005; Domínguez et al., 2014). Although the grape marc can be used as a nutrient-rich organic soil amendment (Domínguez et al., 2014; Sebaaly et al., 2017), its direct soil application can have negative effects on the environment due to its polluting characteristics such as low pH and phytotoxic and anti-bacterial phenolic substances (Raquel et al., 2018). Domínguez et al. (2014) suggested the use of vermicomposting waste treatment technology to minimize or eliminate the agronomic problems associated with soil application of the raw grape marc. Co-composting offers an alternative treatment strategy for WSW since most conventional waste treatments are becoming increasingly expensive and demanding significant amounts of effort, resources and energy for safe waste discharge into the environment (Zacharof, 2017). Co-composting refers to the controlled aerobic degradation of organics using more than one feedstock. The use of diversified material properties in composting enhances compost quality (Anwar et al., 2015). The use of such technologies in treating biodegradable wastes enables the wine sector to comply with environmental management system such as ISO 14000, which encourages the recycling of wastes (Oliveira and Duarte, 2016). Partially composted grape marc may be applied to soil to reduce soil temperature fluctuations and to increase the water-holding capacity and supply nutrients (Flavel et al., 2005).

Special attention on the mineralization rates of plant nutrients such as N and P is often required when organic materials and compost are used on croplands for their effective use and for environmentally acceptable crop production system (Eghball, 2000; Horrocks et al., 2016). Several studies have shown the patterns of release of some plant nutrients from grape marc compost and co-composted grape marc with other agricultural waste materials (Flavel et al., 2004; Flavel et al., 2005; Paradelo et al., 2011; Hannam et al., 2016). However, there is a dearth of published information on the nutrient release characteristics of compost resulting from co-composting of grape marc, grapevine prunings and spent wine filter materials. A preliminary 42-days laboratory incubation study by Kutu and Masowa (2018) revealed that the WSW compost could be used as an N and K source. Against this background, this study seeks to determine the effects of different application rates of WSW compost on the release of P and K, quantify the amount of P and K released and describe the patterns of nutrient release from WSW compost in sandy loam soil over a period of 126 days under field conditions. We hypothesized that the application of WSW compost in sandy loam soil will alter soil pH and promote increased P and K availability. The objectives of this study are to (i) determine the effects of different application rates of WSW compost on the release of P and K, (ii) quantify the amount of P and K released following WSW compost application and (iii) determine the effects of different application rates of WSW compost on soil pH.

MATERIALS AND METHODS

Description of study site

A field incubation study was conducted during the 2018 summer and winter seasons over a period of 126 days at the Exeprimental Farm (25°48’ S, 25°38’ E) of North-West University, Mafikeng Campus, South Africa. Mafikeng has a typical semi-arid tropical Savannah climate with summer mean annual rainfall of 571 mm (Materechera and Medupe, 2006). Data on the mean monthly minimum and maximum temperatures for Mafikeng obtained from the South African Weather Service (2018) during the period of the trial are contained in Fig. 1. The mean maximum monthly temperature in summer season was 29.6°C in March and 27°C in April, while the mean minimum temperature was 15.4°C in March and 12.5°C in April. The average maximum monthly temperature in the winter season ranged from 20.7°C (July) to 25.2°C (May), whereas the average minimum temperature was between 3.3°C (July) and 7°C (May).

Winery solid waste compost and soil used in this study

The WSW compost (INC1) used in this study was produced in heap on a hardened soil surface covered with high-density polyethylene plastic with effective microorganisms (EM) inoculation; and had an initial pile height of 1.0 m. The details of the production process and physico-chemical characterization of the compost were previously provided by Masowa et al., (2018). Briefly, a sample of the INC1 produced through an aerobic-thermophilic composting process was analysed and had a pH (KCl) value of 9.69 and total C, P, K and Ca contents of 19%, 6.04 g kg^{-1}, 251 g kg^{-1} and 55 g kg^{-1}, respectively. The surface soil (0-15 cm depth) used in this study was collected from the North-West University Agriculture Farm. Consequent upon

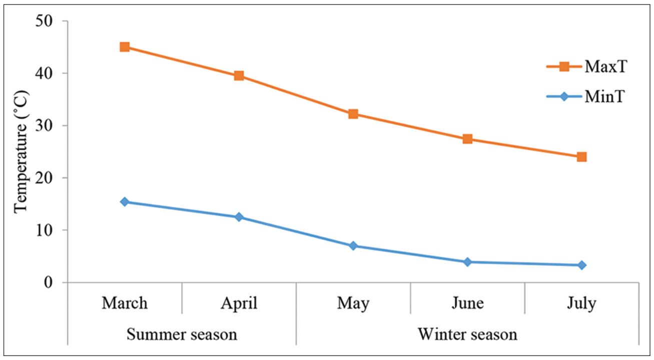

Fig 1. Mean monthly minimum (MinT) and maximum (MaxT) temperatures for Mafikeng during the experimental season.

collection, the soil was air-dried and passed through an 8-mm sieve to remove stones and plant debris. Physico-chemical analyses of the soil sample collected following standard laboratory procedures were carried out prior to the commencement of the study. The soil had sandy loam texture, 5.10% clay (hydrometer method, Estefan et al., 2013), pH (KCl) of 7.25, 197 mg kg^{-1} P (Ambic-1), and 138 mg kg^{-1} exchangeable K (1 M NH_4OAc) (NASAWC 1990). The soil water holding capacity was determined using a procedure described by Estefan et al. (2013) and was at 0.36 g H_2O per g soil. Materechera and Medupe (2006) classified this soil as Ferric Luvisol based on FAO/UNESCO system.

Incubation and quantification of nutrients mineralized

The study was conducted over a 126-day period under field conditions using a buried-bag procedure (Fig. 2, Hanselman et al., 2004). Treatments consisted of equivalent rates of 0, 5, 10, 20 and 40 t ha^{-1} of grounded INC1 mixed in Ziplock bags (15 x 180 cm) with 900 g of soil. Assuming that the weight of soil per hectare furrow-slice was 2 million kg, the required amount of compost for 900 g of soil were 2.25, 4.5, 9.0 and 18.0 g (Masowa et al., 2016). Soil water content was adjusted to approximately 50% water holding capacity of the soil by adding deionized water into bags containing treatments. The bags were zipped and buried at 30 cm depth. Destructive sampling was performed by removing one buried bag per treatment at 0, 7, 21, 42, 63, 84, 105 and 126 days after incubation (DAI). Approximately 50 g of soil were sub-sampled at each sampling period from each bag and oven dried at 105°C for 24 hours to determine the gravimetric moisture content of soil (Estefan et al., 2013). The remaining amount of each moist soil sample was air-dried, passed through a 2 mm sieve, and then analyzed for specific soil chemical properties. Standard laboratory analyses procedures were used to determine the pH (KCl), extractable P (Ambic-1) and exchangeable K (1 M NH_4OAc) according to NASAWC (1990). The net content of each of the mineral nutrients were determined by subtracting the mineral nutrient content of the un-amended control from the mineral nutrient content of each compost treatment (Masunga et al., 2016). The cumulative net content of each nutrient was calculated as the sum of all net contents of each nutrient recorded over the incubation duration.

Fig 2. (a) Preparation of trenches with 20 cm width and 30 cm depth; (b) mixed soil and compost in Ziplock bags; (c) placing of the Ziplock bags containing treatments in trenches; and (d) the experimental site after placing the bags and returning the soil into the trenches.

Data analysis

Data on pH, soil moisture content, net and cumulative net mineralized P and K contents were subjected to analysis of variance (ANOVA) using SAS 9.4 software and means were compared by Fisher's protected least significant difference (LSD) test at $p \leq 0.05$. The coefficients (r) of Pearson's correlation between the measured soil properties were calculated using IBM SPSS Statistics 23. The extent of variation in the net and cumulative net P as well as K mineralized were described based on the coefficient of variation (CV) of <15%, 15-35% and >35%, respectively implies low, moderate and high variability (Wilding 1985).

RESULTS AND DISCUSSION

Interaction effect of compost rate and incubation period on net soil P and K contents

The net P and K contents mineralized were significantly ($p<0.0001$) influenced by compost rate and incubation period interaction effect (Fig. 3). Over the 126 days incubation period, the content of net P ranged from -62 to 86 mg kg^{-1} while the net mineralized K content varied between 41 and 2047 mg kg^{-1}. An initial P immobilization was observed from 5, 20 and 40 t ha^{-1} rates followed by a net P mineralization up to 84 DAI suggesting microbial utilization of the P content of the applied compost and/or P released at the beginning of incubation (Fening et al., 2010). The study by Enwezor (1966) also showed an initial absorption of inorganic P by soil micro-organisms during the decomposition of organic materials in the soil under the laboratory incubation conditions. Phosphorus is also quickly adsorbed onto the surface of positively charged particles following its mineralization. This makes P availability in soil solution typically low even when its total content is high (Fening et al., 2010). The initial P immobilization reported in the current study contradicts an earlier finding by Gagnon et al. (2012) who reported that the P immobilization from fresh residues added to soil occurs during the early stages of decomposition when residue P is less than 2 g kg^{-1} or when the C: P ratio is less than 200. The contradiction was attributed to many factors influencing P mobilization and adsorption in soil such as soil pH, soil diagenesis stage and mineral composition (Schaller et al., 2019). Hence, the application of this high

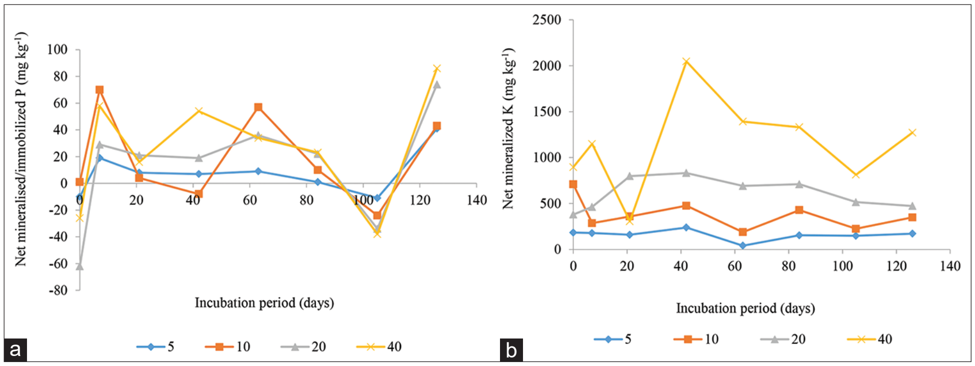

Fig 3. Effect of different rates of winery solid waste compost on (a) P mineralization (LSD = 47; CV = 203%) and (b) K mineralization over the incubation period of 126 days (LSD = 255; CV = 32%).

pH and Ca-rich compost may have favoured the reaction of CaCO$_3$ with orthophosphate anions to form a precipitate (Fuentes et al., 2006).

A general decrease in the net P mineralized was observed from 84 DAI until 105 DAI in which maximum P immobilization also occurred from the 5, 10 and 40 t ha^{-1} rates. Notwithstanding the highest P immobilization from the 20 t ha^{-1} rate at the beginning of incubation, a considerable net P mineralization occurred at the end of incubation following immobilization at 105 DAI. Earlier studies by Akhtar and Alam (2001) and Boukhalfa-Deraoui et al. (2015) reported that soil P availability decreased following application of organic and inorganic P sources with increasing time of incubation. The decrease in the amounts of available P can be generated by a P fixation by soil. The amounts of P retained can be increased when the contact time between the soil and the P supplied increases (Boukhalfa-Deraoui et al., 2015).

The K release patterns were inconsistent over the incubation period. Inconsistent decrease and increase in the net mineralized K from 5 and 10 t ha^{-1} rates were also observed. The net mineralized K from 20 t ha^{-1} rate showed an increasing trend from beginning of incubation until 42 DAI, followed by a steady downward trend until the end of incubation. The decrease in the net K mineralized recorded from treatments with 10 and 40 t ha^{-1} as the seasons changed from summer (42 DAI) to winter (63 DAI) was significant. The 10 t ha^{-1} rate significantly gave higher net mineralized P at 63 DAI in summer following immobilization at 42 DAI in winter season. The steep increase of net mineralized K from 40 t ha^{-1} rate from 21 to 42 DAI following a significant decrease at 21 DAI was in turn followed by a steep and significant decrease until 105 DAI. Thereafter, the net mineralized K increased at 126 DAI, but it was similar to that recorded at 63 and 84 DAI. This pattern of release is the function of compost rates with huge fluctuations at the 10 and 40 t ha^{-1} rates for K mineralization. However, with P mineralization, the fluctuation was intense with all compost rates. The 35% CV for net mineralized P measured suggests high variability while 15-35% CV for the net mineralized K depict moderate to high variability (Wilding, 1985).

Effect of compost rate on the net and cumulative P and K mineralized

Significant ($p<0.0001$) compost rate effects were observed on the net and cumulative K mineralized (Fig. 4 B and D, respectively). The net and cumulative P measured depicted in Fig. 4 A and C respectively, and K released were lowest with 5 t ha^{-1} rate but highest with 40 t ha^{-1} application rate. The cumulative net P mineralized ranged from 62 to 207 mg kg^{-1} while the cumulative net mineralized K varied between 1272 and 9206 mg kg^{-1}. The net P mineralized varied between 7.73 and 25.92 mg kg^{-1} while the net mineralized K ranged from 159 to 1151 mg kg^{-1}. The high net P and K mineralized may be associated with the high available P and K contents of WSW and indicated the possible potential of WSW compost as P and K source. Notwithstanding the potential amount of P and K mineralized in this compost, cautious use as a soil amendment is necessary to avoid soil nutrient imbalance, toxicity and their possible antagonistic effects with other plant nutrients. Excessive P application can lead to plant toxicity with undesirable consequences such as the inhibition of growth, leaf chlorosis, and micronutrient deficiency (Li et al., 2010; Pedas et al., 2011). The most commonly observed and studied P antagonistic interaction is with Zn (Barben et al., 2007). Mousavi et al. (2012) and Novais et al. (2016) described the mechanism of antagonistic of Zn deficiency triggered by excessive P in the soil. Excessive soil application of K increases cation competition resulting in reduced uptake of NH$_4$, Ca and Mg by plants (Gransee and Führs, 2013). Except at 63 DAI under the treatment with 5 t ha^{-1} rate, the net mineralized K measured was higher than the threshold level of 62 mg kg^{-1} (Uzohu et al., 2007), and the 80 to 120 mg kg^{-1} acceptable sufficiency level for maize (FSSA, 2007). The net K content mineralized from the 5 t ha^{-1} application rate was approximately two times higher than the threshold level for

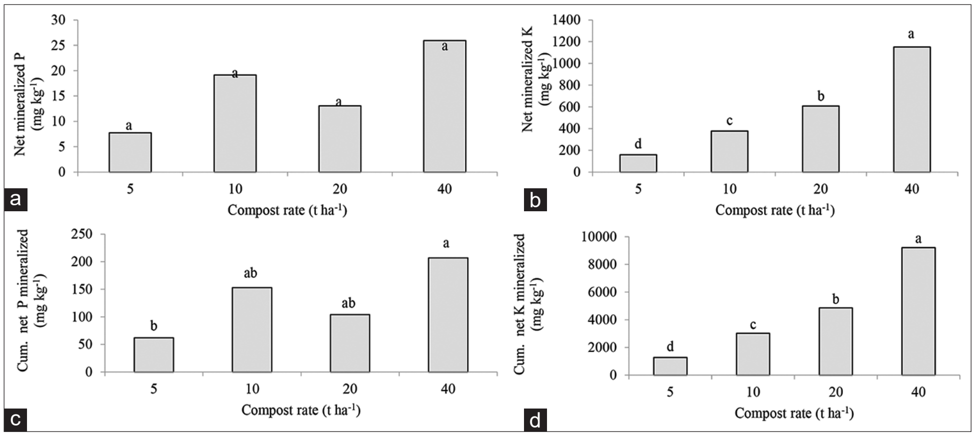

Fig 4. Effect of compost rate on the contents (a) net mineralized P (LSD = 22.13; $p<0.4026$; CV = 272%), (b) net mineralized K (LSD = 55; $p<0.0001$; CV = 55%), (c) cumulative net P mineralized (LSD = 105, $p<0.0538$, CV = 51%), and (d) cumulative net K mineralized across the incubation period (LSD = 769; $p<0.0001$; CV = 11%).

maize while the remaining rates were approximately 6 to 18 times higher. The high net K content mineralized from this compost is in agreement with the results of earlier research by Kutu and Masowa (2018) which revealed that the WSW compost has the ability to supply the needed K to crops. Hence, application rates of below 5 t ha^{-1} may be recommended when this compost is intended for use as a K source in maize production. The higher than 35% CV in the net and cumulative P mineralized, and net K mineralized across the incubation revealed high variability while the less than 15% recorded for the cumulative net K mineralized revealed low variability (Wilding,1985).

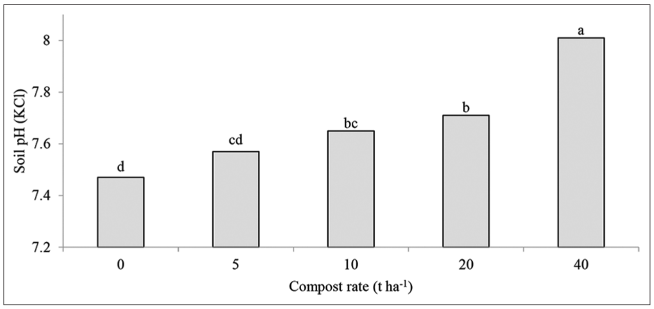

Fig 5. Effect of compost rate on soil pH (KCl) across the incubation period (LSD = 0.1129; $p<0.0001$; CV = 1.45%).

Effect of compost rate and its interaction with incubation on soil pH and moisture content

Plant nutrient availability is regulated by the soil pH, which controls the chemical forms and availability of different nutrients; and influences their chemical reactions (Oshunsanya, 2019). Application of variable compost rates exerted significant effect on soil pH (Fig. 5). The 5 t ha^{-1} rate resulted in insignificant increase in soil pH with reference to the untreated soil. The 40 t ha^{-1} rate gave the highest soil pH value followed by the 20 t ha^{-1} rate which was statictically comparable with the 10 t ha^{-1} rate. The 5 and 10 t ha^{-1} had statistically similar effects on soil pH. The interaction of compost rate and incubation period exerted significant effects on soil pH and soil moisture content (Table 1). Soil pH ranged from 7.28 in unamended soil at the commencement of incubation period to 8.18 in the 40 t ha^{-1} compost rate at 42 DAI resulting in 9.50% pH increase value during the incubation period. This rise in soil pH value following compost addition to soil may be attributed to the strongly alkaline nature of this compost. Ebid et al. (2007) also recorded an increase in soil pH following application of weakly alkaline composts with pH values ranging from 7.70 to 8.90. Such increases in soil pH can exacerbate the problem of pH related deficiencies of nutrients such as P, Fe, Mn, B, Cu and Zn in very high pH soils (Goulding, 2016). However, the use of this compost on acidic soil may be helpful in increasing the soil pH, thus alleviating associated nutrients deficiency problems associated with acid soil. A general increase in soil pH with increasing compost rate was observed during the incubation period. However, the measured pH increases were not always proportionate to the compost rates within each sampling day. A similar observation was noted from 10 t ha^{-1} compost treatment with the exception that the measured soil pH value at 63 DAI was significantly lower as compared to that recorded at the beginning of the incubation and at 21 DAI. The positive and significant correlations were identified between soil pH and contents of net mineralized K ($r = 0.69$; $p<0.01$) and cumulative net mineralized P ($r = 0.50$; $p<0.05$) and K ($r = 0.91$; $p<0.01$) (Table 2). The positive correlation between the soil pH and mineralized P suggests that the compost have possibly altered the soil chemical properties by fixing Al and Fe instead of P (Ch'ng et al., 2014). Abreu-Jr et al. (2003) and Angelova et al. (2013) have previously established positive correlations of pH with P and K contents of the soil.

The soil moisture content ranged from 14.8% in the 5 t ha^{-1} compost rate on 84 DAI to 21.2% in the 10 t ha^{-1} on 105 DAI. Except at 105 DAI whereby the 5, 10 and

Table 1: Interaction effect of compost rate and incubation period on pH (KCl) and percent gravimetric soil moisture content

Compost rates (t ha^{-1})	Incubation period (days)							
	Summer season				Winter season			
	0	7	21	42	63	84	105	126
	pH (KCl)							
0	7.28	7.54	7.57	7.47	7.40	7.53	7.35	7.62
5	7.65	7.67	7.67	7.54	7.44	7.62	7.38	7.61
10	7.82	7.72	7.83	7.63	7.44	7.63	7.48	7.67
20	7.64	7.81	7.84	7.65	7.73	7.68	7.63	7.69
40	7.86	8.07	8.08	8.18	7.97	7.94	7.99	7.97
LSD $_{(0.05)}$ value	*0.340*							
p-value	*<0.0001*							
Coefficient of variation (%)	*1.57*							
	Gravimetric moisture content (%)							
0	15.6	19.2	18.1	17.8	16.9	17.8	16.0	15.8
5	16.7	18.2	19.0	17.2	15.1	14.8	20.9	18.0
10	16.2	17.7	18.3	16.8	15.8	18.0	21.2	16.3
20	16.4	18.6	17.4	15.9	17.9	16.9	19.5	17.0
40	17.6	17.0	17.3	17.4	17.5	17.6	17.3	15.8
LSD $_{(0.05)}$ value	*3.188*							
p-value	*<0.0001*							
Coefficient of variation (%)	*6.51*							

LSD=least significant difference

Table 2: Results of correlation analysis between net mineralized *P* and K, cumulative net mineralized P and K, soil pH and soil moisture content

Soil properties	pH	Soil moisture content
Net mineralized P	0.17	-0.14
Cumulative net mineralized P	0.50*	-0.20
Net mineralized K	0.69**	-0.11
Cumulative net mineralized K	0.91**	-0.15

*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed)

20 t ha^{-1} rates resulted in greater soil moisture contents, the different compost rates exerted statistically similar effect on soil moisture content as compared to the control treatment during each sampling date. The significant and higher soil moisture content recorded from 5 and 10 t ha^{-1} rates as compared to that recorded from the 40 t ha^{-1} rate at 105 DAI were not expected. Unexpectedly, the soil moisture content corelated negatively and insignificantly with the net and cumulative net mineralized P and K (Table 2). The negative correlation suggests that excessive soil moisture may exert unfavourable effects on P and K mineralization from the WSW compost possibly through the influence on the microbial activities that regulate nutrient transformations (Classen et al., 2015). The excessive soil moisture could lead to a lower biomass of microorganisms, mostly due to the formation of oxygen conditions that are unfavourable to aerobic bacteria and mycorrhizal fungi (Borowik and Wyszkowska, 2016). In this regard, Torbert and Wood (1992) reported that microbial activity decreased with the increase of water-filled pore space. Although the precise cause of the non-significant negative correlation between the soil moisture content and mineralized P and K contents were difficult to isolate, the observation possibly suggest that the soil moisture was not excessive to strongly influence the mineralization of P and K (Classen et al., 2015; Huang and Hall, 2017; Kaneda and Kaneko, 2011; Samuel and Ebenezer, 2014).

CONCLUSIONS

Soil nutrient management remains a crucial aspect of soil health maintenance for sustainable crop production. Amending sandy loam soil with the winery solid waste compost in our study resulted in increased P and K mineralization across the incubation period, and the cumulative net mineralized P and K indicated the possible potential of this compost to be used as P and K source. The observed significant soil pH increases following 40 t ha^{-1} compost application rate throughout the incubation period raises serious soil health concerns about the use of this compost on high pH soils. Hence, cautious use of this compost as a soil amendment is necessary to avert unnecessary pH increases, nutrient imbalance, toxicity, and the antagonistic effects of P and K on other plants nutrients. Field studies on the nutrient release characteristics and agronomic effectiveness of the 5 t ha^{-1} WSW compost rate as well as the potential P and K toxicity of higher rates are recommended, particularly under different soil and climatic conditions.

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AUTHORS' CONTRIBUTIONS

Manare Maxson Masowa: conceptualization, data curation, drafting manuscript, redaction of review.

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Azwimbavhi Reckson Mulidzi: funding acquisition, supervision, methodology review, redaction of review.

Phesheya Dlamini: funding acquisition, redaction of review.

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