Assessment of maize productivity and soil health indicators following combined application of winery solid waste compost and inorganic fertilizers

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Thesis accepted in fulfilment of the requirements for the degree
Doctor of Philosophy in Agriculture with Agronomy
at the North-West University

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Graduation ceremony: April 2020
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ABSTRACT

Grape growing and winemaking process generate enormous amounts of solid waste materials that demand more economical and safe disposal technologies. In this study, co-composting and effective microorganisms (EM) technologies were employed to treat the winery solid waste (WSW), thereafter, the resultant compost was assessed for its physico-chemical properties, phyto-toxicity, nutrient release patterns and agronomic potential. Four WSW compost types produced comprised of EM inoculated or uninoculated compost with an initial heap height (hereinafter pile size) of 1.0 or 1.5 m. Samples of the cured composts were evaluated for physico-chemical properties and germination attributes at different extract concentrations (0, 10, 25, 50 and 100%) using cowpea, maize and tomato seeds. The results demonstrated that EM inoculation exerted a significant effect on compost Bray-2 P content while the interaction of EM inoculation and pile size similarly had significant effects on the ammonium-N content. The produced composts possessed high electrical conductivity values due to high concentrations of soluble salts that could be potentially toxic to crops and soil. The use of 1.0 m pile size promoted extended thermophilic phase during compost production that could ensure better sanitization of the final product. Maize and tomato showed higher degrees of phyto-toxicity at 50% extract concentration and above. The phyto-toxicity effects recorded in maize and tomato may be minimized by using lower application rates.

The incubation study was carried-out using a buried-bag procedure to determine the P and K release patterns of inoculated compost with 1.0 m pile size in sandy loam soil under field conditions. Grounded compost was thoroughly mixed in zip-lock bags with 900 g surface soil at rates equivalent to 0, 5, 10, 20 and 40 t ha^{-1}. One bag per treatment was destructively sampled at 0, 7, 21, 42, 63, 84, 105 and 126 days of incubation during which the available P and exchangeable K were analyzed. Net mineralized P ranged from -62 to 86 mg kg^{-1}, while the net mineralized K varied between 41 and 2047 mg kg^{-1}. The high net P and K mineralization suggests that the WSW compost can be used as a P and K source. However, its utilization as soil amendment must be cautious to mitigate the potential risks of unnecessary soil pH increase, nutrient imbalance, toxicity and the antagonistic effects of P and K on other plants nutrients.

The study was conducted under tunnel house conditions to determine the optimum application rates and agronomic potentials of the WSW compost. The treatment factors comprised of four WSW compost types, seven compost rates (0, 5, 10, 20, 40, 80 and 100 t ha^{-1}) and two sandy loam soils. The results showed a general increase in stem girth, plant height, number of functional leaves per plant, dry matter yield and relative agronomic effectiveness with increasing compost rate. The microbial inoculation and variation of compost with pile size did not induce significant effects on maize performance and soil chemical properties. In most cases, the higher optimum rates predicted by the quadratic model were associated with dry matter yield that were slightly higher in comparison to the optimum dry matter yield predicted by the linear-plus-plateau model. The 80 t ha^{-1} rates and above significantly increased the exchangeable soil-Na content by up to 175%, thereby causing harm to maize seedlings. Although the WSW compost has an immense potential for the improvement of maize productivity, its application at rates above 40 t ha^{-1} is detrimental to both plants and the soil.

Field trials were conducted during the 2018 and 2018/19 summer cropping seasons to evaluate the effects of sole and combined application of inorganic N and P fertilizers (INPF) and WSW compost on maize performance and soil chemical properties. Inoculated and uninoculated compost types with pile size of 1.0 m were used. The INPF and each compost type were combined in different ratios (0:0, 75:25, 50:50, 25:75 and 0:100, w/w) in such a way that the total mineral N and P supplies from both sources were equivalent to that supplied by the established optimum rate of WSW compost under the tunnel house conditions. The recommended rates of inorganic fertilizers of 200 kg N ha^{-1} and 90 kg P ha^{-1} were mixed and included as a standard control. Treatments were arranged in factorial arrangement fitted in a RCBD with three replicates. The results showed a significant interaction effect of compost type and application rate on plant height and leaf area index during the 2018 season, and on number of leaves and stem girth at tasselling during the 2018/19 season. The grain yields recorded from the 25:75 and 50:50 compost-INPF combinations were 6649 and 6246 kg ha^{-1} respectively and were significantly higher than 4557 kg ha^{-1} for the untreated control under the harsh environmental conditions of the 2018/19 season. Compost application alone or combined with INPF increased soil pH and the contents of soil organic C, P, K, Na and Zn.

Keywords: maize production, mathematical model, nutrient mineralization, optimum compost rate, organic farming, soil health indicators, winery solid waste

DEDICATION

This thesis is dedicated to the memory of my late mother, Mrs. Machoene E. Masowa.

ACKNOWLEDGEMENTS

My utmost gratitude goes to the Almighty God for giving me life and strength to undertake this study. I have the immense pleasure of expressing my heartfelt gratitude to my supervisors, Prof. FR Kutu, Prof. OO Babalola and Dr AR Mulidzi for their constructive criticisms and insightful guidance throughout the duration of this study, and for their assistance in publishing some parts of this study in refereed journals and conference proceedings. I am extremely grateful to my parents and siblings for their love and constant support. I appreciate the kind efforts of my MSc. mentor, Mrs LP Augustine (Retired researcher, ARC-Infruitec/Nietvoorbij) for ensuring that I received the relevant academic support at the ARC-Infruitec/Nietvoorbij. I would also like to extend my profound gratitude to the Koelenhof Wine Cellar and Douglas Green Company for providing me with the waste materials used in the compost production. I acknowledge the financial assistance of the National Research Foundation of South Africa (Grant UID: 108605), North-West University and Agricultural Research Council. I also thank the North-West University for awarding me the 2017 Top Performers PhD Bursary.

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LIST OF ACRONYMS AND SYMBOL

Acronym/Symbol		**Description**
%	:	Percent
°C	:	Degrees Celsius
a.m.	:	Ante meridiem
Al	:	Aluminium
As	:	Arsenic
C	:	Carbon
C:N	:	Carbon to nitrogen ratio
Ca	:	Calcium
Cd	:	Cadmium
CFU mL^{-1}	:	Colony forming units per millilitre
cm	:	Centimetre
Cr	:	Chromium
Cu	:	Copper
cv.	:	Cultivar
CV	:	Coefficient of variation
dS m^{-1}	:	Decisiemens per meter
Fe	:	Iron
g	:	Gram
g cm^{-3}	:	Gram per cubic centimetre
g H_2O g^{-1}	:	Gram of water per gram
g kg^{-1}	:	Gram per kilogram
g pot^{-1}	:	Gram per pot
H_2O	:	Water
ha	:	Hectare
Hg	:	Mercury
K	:	Potassium
K_2SO_4	:	Potassium sulphate
KCl	:	Potassium chloride
kg	:	Kilogram
kg ha^{-1}	:	Kilogram per hectare
kg m^{-3}	:	Kilogram per cubic meter

L m^{-3}	:	Litre per cubic meter
m	:	Meter
m/v	:	Mass per volume
m^{-2}	:	Per square meter
Mg	:	Magnesium
mg GAE g^{-1} DW	:	Milligrams gallic acid equivalents per gram dry weight of sample
mg kg^{-1}	:	Milligram per kilogram
mL	:	Millilitre
mm	:	Millimetre
Mn	:	Manganese
mS cm^{-1}	:	Millisiemens per centimetre
N	:	Nitrogen
Na	:	Sodium
NH_4	:	Ammonium
NH_4AOc	:	Ammonium acetate
Ni	:	Nickel
NO_3	:	Nitrate
P	:	Phosphorus
Pb	:	Lead
R^2	:	Coefficient of determination (R-squared)
t ha^{-1}	:	Ton per hectare
w/v	:	Weight per volume
w/w	:	Weight per weight
Zn	:	Zinc

CHAPTER 1

General introduction

1.1 Background information

The winery solid waste (WSW) consists of grape marc (skins, seeds, pulp, and stems) and filter cakes that are primarily of filter aids (Bustamante et al. 2005). The safe and responsible disposal of the prodigious amount of wastes generated in the wineries and vineyards across South Africa constitute an issue of pertinent concern for both environmental and health reasons. There is an increasing global interest in the use of composting to reduce the weight and volume of composted wastes and to improve the properties for its use as soil amendment (Insam et al. 1996; Preusch et al. 2002). Composting involves a biological decomposition process driven by microbial activities (Shepherd et al. 2011). It is advocated as an indispensable winery waste management strategy possibly due to its low costs which are almost negligible when compared to other waste management options (Ruggieri et al. 2009). In South Africa (SA), WSW compost is produced and used by farmers in the vineyards without sufficient scientific knowledge about its chemical characteristics and agronomic potentials (Masowa et al. 2016).

Maize (*Zea mays* L.) is an important crop with regard to area of coverage and productivity (Unagwu et al. 2012) and it ranks third globally after wheat and rice (Adamas et al. 2015). It is widely grown as food crop in the Western, Central, Eastern and Southern regions of Africa and as a cash crop in the Northern Africa region (Babalola & Glick 2012). In SA, it is the second largest crop produced after sugarcane (*Sacharum officinarum*) and the most important grain crop. Maize is also the major feed grain and primary staple food crop for majority of the South African population (DAFF 2013). In SA, white maize is cultivated mainly for human consumption whereas yellow maize is cultivated for animal feed (Europa Publications 2003). Maize has enormous nutritional value containing about 66.7% starch, 10% protein, 4.8% oil, 8.5% fibre, 3% sugar and 7% ash (Chaudhary 1983). Besides its carbohydrate content, it is an important source of protein, iron, vitamin B and minerals comparing favourably with other starchy crops such as rice and potatoes (Olaniyan 2015). Its nutritional value can be enhanced through proper production management systems such as proper fertilization, which could maximize its productivity.

1.2 Problem statement

The degradation of South African soil resource base poses a serious threat to sustainable agricultural production in the country (Du Preez et al. 2011). The issue of land degradation relates to the decline in soil organic matter (Du Preez et al. 2011; Tibane & Vermeulen 2014), which is aggravated by different forms of erosion. In SA, an estimated 25% of potentially suitable agricultural soils comprising of the sandy soils in the western half of the "maize quadrangle" in the North-West and north-western Free State provinces is highly susceptible to wind erosion (Tibane & Vermeulen 2014). Human-induced soil acidification constitutes a major part of the problem and it is caused by injudicious fertilizer application practices and inadequate lime applications (Tibane & Vermeulen 2014). In addition to the problems of low organic carbon stocks (Baloyi et al. 2014a), the soil also experiences compaction and crusting (Tibane & Vermeulen 2014). These constraints require urgent investigations and the development of feasible management interventions that strive to create a balance between the maximization of maize production and the sustainability of soil health in South Africa.

The smallholder crop production in SA and several other countries in Sub-Saharan Africa (SSA) is often characterized by the poor use of mineral fertilizers, low inherent soil fertility, and nutrient-depleted soils (Masenya et al. 2015). Together with aridity (low rainfall) and acidity, these factors limit the soil productivity levels on arable farmlands (FAO 2001). Also, the continuous use of mineral fertilizers has proved detrimental under intensive agriculture, because it is often associated with reduced yield, soil acidity, nutrient imbalance (Ayoola 2006; Akande et al. 2010), and soil microbial species richness and evenness (Babalola 2014). Furthermore, farm-level mineral fertilizer prices in Africa are among the highest agricultural input costs in the world (Bationo et al. 2006) with frequent scarcity, which aggravates the existing problem of unaffordability by farmers and low to suboptimal use (Unagwu et al. 2012; Kutu 2012). Therefore, the need for more renewable forms of fertilizers has revived the use of organic fertilizers (Ayoola 2006; Zafar et al. 2012) even though organic agriculture on its own cannot feed the world (Connor 2008).

Wine production processes result in large quantities of both liquid and solid organic wastes (Lofrano & Meric 2016) that could exert negative impacts on the environment and soil if poorly treated and managed (Bustamante et al. 2005; Van Schoor 2005; Voća et al. 2010). A substantial amount of the wastes generated in cellar (80-85%) are organic wastes (Ruggieri et al. 2009). However, unlike the winery liquid waste that has received adequate research attention including the development of appropriate and efficient management systems through the Integrated Production of Wine guidelines (SAWSB 2012), there is currently no approved guideline for the management of WSW in South Africa. The disposal of poorly treated wine organic wastes in huge piles on sites may result in surface and subsurface pollution, cause air pollution during degradation and attract pests and flies that could in turn spread different kind of diseases (Voća et al. 2010). Previous studies have shown that the direct utilization of improperly conditioned WSW as agricultural fertilizers exerts negative effects on soil through nitrogen (N) immobilization (Flavel et al. 2005; Bustamante et al. 2007). Moreover, the direct application of grape marc to soil is inappropriate since it contains high amounts of phenolic substances (Ramirez-Lopez & DeWitt 2014), which are reported to result in undesirable effects on soil and crop growth and development (Tiquia 2010; Haq et al. 2014). Consequently, wine cellars experience serious challenges regarding the safe disposal of the solid wastes they generate. In SA, the challenge of WSW disposal has been exacerbated by the introduction of the Waste Management Act number 59 of 2008, which compels the holders of waste to reduce, re-use, recycle and recover the waste (RSA Government Gazette 2009). The Act compels wine cellars to devise efficient waste treatment strategies since massive generation of organic waste in the wine production process is unavoidable. This has prompted the urgency for investigating cost-effective and environment-friendly solutions of treatment and effective utilization of the waste materials generated in the wine industry.

The introduction of effective microorganisms (EM) technology started through nature farming systems (APNAN 1995). Its use has since increased as part of the efforts to resolve the environmental problems stemming from the re-use of wastes (Jusoh et al. 2013). The EM inoculants is a liquid microbial concoction comprising co-existing beneficial microorganisms, mainly species of photosynthetic bacteria, lactic acid bacteria, yeast and actinomycetes (Javaid & Bajwa 2011). Besides the reported successful use in the Natuurboerdery of ZZ2 in SA (Erasmus 2009), studies also abound on the co-application of EM with compost under research conditions for tomato production (Lindani & Brutsch 2012). However, there is a paucity of research on the effect of co-composting of WSW with EM. This necessitates detailed investigations on the potential impact(s) of co-composting of WSW with EM on the quality of the resulting EM-compost and its effectiveness for improved maize performance and soil health indicators. Based on the foregoing, this study seeks to address the following central questions:

(i) Can co-composting of WSW with the EM inoculant improve the quality of the WSW compost?

(ii) What are the optimum application rates and the agronomic effectiveness of EM-WSW compost for maize production in soils with varying textural and chemical characteristics?

(iii) Can the combined use of EM-WSW compost and inorganic fertilizers improve maize performance and soil health indicators?

(iv) What is the appropriate combination of EM-WSW compost and inorganic fertilizers that will guarantee high yield of maize and healthy soil?

(v) What are the residual effects of EM-WSW compost with and without inorganic fertilizers application on soil health indicators?

The findings from this study will contribute towards the formulation of appropriate guidelines on the production of high-quality WSW compost through the provision of empirical data on the value of EM inoculant in composting including the agronomic potential of the resulting EM-WSW compost. The results of the study will also provide empirical evidence that could be instrumental to the advocacy for the combined use of inorganic fertilizers and EM-enriched compost to improve maize production and soil health. The study will also present valuable information regarding site-specific experimentally optimum EM-WSW compost application rate for maize production as opposed to the present blanket rate currently adopted in most parts of the country.

1.3 Justification for the study

Soil degradation refers to the temporary or permanent loss of productive capacity of agricultural land (Iqbal et al. 2014), which can be effectively curbed and reversed through the increase of the soil's organic matter (Barnard & du Preez 2004). Maize production in SA is mostly under sandy and light-textured soils that are highly subjected to occasional nutrient leaching making them deficient in major plant nutrients (Baloyi et al. 2014). Thus, the production of maize on these kinds of soils requires proper management of fertilization. In this regard, the recycling of organic waste materials is one of the most viable ways of improving soil fertility and reducing the use of mineral fertilizers (Abedi et al. 2010). It is also a cost-effective and environment-friendly management strategy for waste disposal (Ahmad et al. 2006). The use of compost has been proven to improve soil physico-chemical and biological properties (Cox et al. 2004; García et al. 2008; Brown & Cotton 2011). Therefore, the proper use of adequately composted WSW for crop production may not only solve the WSW disposal problems and improve the compliance of the South African wine industry to the environmental legislation, but it could also potentially improve soil health indicators and crop productivity. The WSW can be a useful bio-fertilizer due to its high organic matter content and potassium

(K) level, as well as its considerable levels of phosphorus (P) and N (Voća et al. 2010). Hence, the application of composted product of such waste on soil could improve the soil's chemical health indicators and crop performance.

Existing research confirm the increased speed of breakdown of organic materials following EM application during composting (Boraste et al. 2009). Similarly, the use of EM inoculant in bio-fertilizer preparation reportedly helps to increase the number of beneficial microorganisms in the compost (Erasmus 2009), and soil thus improving the microbial health of soil and promoting healthy environment for plants (Boraste et al. 2009). Therefore, the use EM inoculant in co-composting of the WSW may not only reduce the period of composting process, but it could also improve the quality of the WSW compost and its effects on soil health indicators and crop performance. For instance, Padmaja and Sangeeth (2008) reported a 55% decrease in total phenolic content (TPC) during composting of waste with effective microorganisms. Therefore, co-composting WSW with EM may decrease the TPC in the WSW compost supplied by the grape marc.

The use of organic materials on crop fields is beneficial for the improvement of environmental conditions and the reduction of the exorbitant costs of crop fertilization (Akande et al. 2010; Baloyi et al. 2014a). However, the sole use of organic materials such as manures have been reported to be inadequate to sustain cropping because they are required in rather large quantities to meet crops nutrient requirements (Makinde & Ayoola 2010). Previous studies have shown that the combined use of compost and inorganic fertilizers yielded positive effects on crops resulting in increased crop yields (Abedi et al. 2010; Zafar et al. 2012; Adamas et al. 2015). Studies on cost-effective strategies that may improve maize production as a key agricultural commodity in SA for improving food security, better nutrition, and provision of healthy soils are important (Kutu 2012). A preliminary study conducted at the University of Limpopo revealed that the WSW compost could be a good source of K and zinc for maize (Masowa et al. 2016). However, the N and P contents in maize shoots from the compost treatments were lower than the critical level of N and P. This suggests the need for supplementary N and P through fertilizers with high concentrations of soluble N and P when this compost is used. Against this background, this study intends to assess the effects of various rates of EM-WSW compost combined with inorganic NPK fertilizers on maize performance and soil health indicators.

1.4 Research aim, objectives and hypotheses

1.4.1 Aim

This study aims to assess the potential quality of microbial enriched WSW compost and the effects of its combined application with inorganic fertilizers on maize performance and soil health attributes.

1.4.2 Specific objectives

The specific objectives of the study are to:

i. evaluate the effects of co-composting of WSW with microbial inoculant (EM) on quality parameters of WSW compost (Chapter 3).

ii. assess P and K release characteristics of the WSW compost (Chapter 4).

iii. predict the optimum application rate of the WSW compost using appropriate mathematical models and evaluate the crop performance and soil properties following WSW compost application (Chapter 5).

iv. assess the growth, nutrients composition and yield of maize following sole and combined application of the WSW compost and inorganic fertilizers (Chapters 6 and 7).

v. determine an appropriate combination of the WSW compost and inorganic fertilizers that will optimize maize yield (Chapter 7).

vi. evaluate the effects of sole and combined application of the WSW compost and inorganic fertilizers on selected physical and chemical health indicators of soil (Chapter 8).

1.4.3 Hypotheses

The study seeks to validate the following hypotheses:

i. Co-composting of WSW with microbial inoculant will improve the physico-chemical properties of compost.

ii. The P and K release characteristics of the different rates of WSW compost differ.

iii. The optimum application rate of the WSW compost for maize can be predicted using a suitable mathematical model and the application of WSW compost will improve the maize performance and soil chemical properties.

iv. Combined application of WSW compost and inorganic fertilizers will lead to improved maize plant growth, nutrients composition and grain yield than sole application of either the WSW compost or inorganic fertilizers.

vi. The different combinations of the WSW compost and inorganic fertilizers will exert different effects on maize performance and soil health indicators.

v. The combined application of the WSW compost and inorganic fertilizers will improve the physical and chemical health indicators of soil in comparison to sole application of either the WSW compost or inorganic fertilizers.

1.5 Thesis overview

The thesis comprises of nine chapters. The first chapter provides the background information, problem statement, justification, aim, objectives, and hypotheses of the study. The second chapter presents a literature review on grape and wine production in South Africa, WSW generation and its impact on the environment, composting technology, compost or organic materials use in crop production, EM technology in composting, maize production, and soil health parameters. The production process, physico-chemical characterization and phyto-toxicity evaluation of winery solid waste compost used in this study are presented in chapter 3. A summarised version of this chapter was published in the Research on Crops journal. Also, an abstract from this chapter was published in the 2018 conference proceedings of the African Combined Congress. The fourth chapter reports the findings of the experiment that aimed to quantify the amount of phosphorus and potassium released from the WSW compost in sandy loam soil under field conditions. This chapter also describes the phosphorus and potassium release patterns and soil pH changes following WSW compost application. An abstract from this chapter has been published in the 2019 conference proceedings of the American Societies of Agronomy, Crop Science and Soil Science. This chapter will also be submitted to the South African Journal of Science for publication. The fifth chapter reports the predicted optimum WSW compost application rate for optimum maize dry matter production and the effects of WSW compost application on maize productivity and selected soil chemical properties. This chapter was submitted for publication in the Compost Science and Utilization journal. Chapter 6 evaluates the effect of the optimum application rate of WSW compost complemented with the inorganic fertilizers on maize growth and yield indices, while chapter 7 presents the effect of the combined application of WSW compost and inorganic fertilizers on maize yield and tissue nutrient content and uptake. Two conference abstracts were prepared using data from chapters 6 and 7. One of these abstracts has been published in the proceedings of the 2019 Combined Congress of South African Society of Crop Production, Soil Science Society of South Africa, Southern African Society for Horticultural Science and Southern African Weed Science Society while the other has been published in the proceedings of the November 2019 international conference of American Societies of Agronomy, Crop Science Society and Soil Science Society of America (ASA-CSSA-SSSA). The findings on the assessment of the soil health indicators following the application of WSW compost in combination with the inorganic fertilizers are reported in chapter 8 while chapter 9 consists of the general conclusions and recommendations.

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CHAPTER 2

Literature review

2.1 Introduction

Waste generation is an inevitable outcome of most human activities while irresponsible waste disposal regrettably constitutes an issue of global concern. This has made the management of solid waste one of the most pertinent and challenging contemporary topics. Waste includes a wide variety of items that have outlived their utility, which humans either intend to dispose or are required to discard, for example, because of their hazardous properties (EU 2010). Municipal solid waste (MSW) is a category of waste generated from diverse sources, each of which is heterogeneous (Ismail & Manaf 2013). There are six primary sources of waste generation namely domestic, commercial, industrial, agricultural, institutional, and natural (Ogola et al. 2011). The issue of solid, liquid, and toxic-waste management in Africa has escalated with increasing urbanization and industrial developing world (Makgae 2011) induced by the rapid growth of cities and metropolitan areas (Yoada et al. 2014). The rapid social and economic changes experienced by most African countries since the 1960s has contributed to an increase in the waste generated per capita (Yoada et al. 2014). South Africa (SA) is a developing country with the fastest growing economies in the world with recorded 2016 gross domestic product (GDP) values of 294.841 billion United States dollars (The World Bank Group 2017). The improvement of the country's economic conditions increases urbanization, the living standard, and the rate of consumption of materials, which in turn lead to increased MSW (Khajuria et al. 2010). The surge in waste generation requires SA to establish and implement effective waste management policies and programmes.

Management of solid waste is one of the key challenges of the 21st century, and one of the key responsibilities of any city's government (Ahsan et al. 2015). South Africa's re-integration into the global economy and the Southern African political arena necessitates an improved pollution and waste management system (Makgae 2011). However, most commercial waste recycling initiatives have been developed on an ad hoc basis and have been driven by the private sector, with little or no financial inputs or support from the South African government (DEA 2009). The government therefore promotes an integrated approach to pollution and waste management as a key factor in achieving sustainable development. The estimated employment creation by the total waste sector is around 113,000 people (DEA 2012). It is estimated that the total annual expenditure on solid waste management in SA amounts to R10 billion per annum, 70% from the public sector, specifically the local government, while 30% stems from the private sector expenditure. However, waste management within municipalities contributes significantly towards municipal income and revenue due to the user-pay principle applied to waste management. It is estimated that municipalities receive a total income of around R6.5 billion for solid waste in SA (DEA 2012).

Biodegradable material, especially food waste, normally accounts for over 50 weight percent of the municipal/residential waste stream in less developed countries (Wei et al. 2017). The disposal of untreated waste has deleterious impacts on human health and the environment. To ensure public health, environmental safety and the protection of natural resources such as fertile soil, there is an urgent need for the adoption of affordable and judicious waste management strategies such as co-composting. Composting refers to the aerobic biological decomposition and stabilization of organic substrates under conditions that enable the development of thermophilic temperatures due to biologically produced heat to obtain a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land (Bertran et al. 2004). This chapter reviews some relevant literature on the discourse of wine grape and wine production in SA, winery waste generation and its impact on the environment, composting technology, compost, or organic materials use in crop production. It also discusses EM technology in composting, maize production, and soil health parameters.

2.2 Production of wine grapes and wine in South Africa

Globally, South Africa ranks 14th place in terms of hectares destined for wine grape production (Siphugu & Terry 2011) and it is the 8th largest wine producing country in the world (Tibane & Vermeulen 2014; OIV 2015). It has approximately 100 000 ha under wine grape cultivation (Sikuka 2015). The South African wine industry creates employment for about 289 000 people (SAWIS 2015a), and it currently has about 3314 grape producers, 559 wine cellars and 109 bulk wine buyers (SAWIS 2015b). It contributes about 2.2% towards the country’s Gross Domestic Product with an estimated macroeconomic impact of R26.2 billion (Siphugu & Terry 2011). The wine industry represents a major tourist attraction with numerous overseas visitors yearly making it one of the country’s top five sources of hard currency income (Siphugu & Terry 2011).

The Western Cape Province produces 90% of South Africa's wine (Macaskill 2011). In 2014, the wine industry in SA crushed about 1.5 million tons of grapes and produced about 1200 million litres of wine (SAWIS 2015a). The production of wine grape occurs predominately in the Western Cape Province specifically around Worcester, Paarl, Stellenbosch, Malmesbury, and Robertson; and also along the Olifants River, the KleinKaroo, and the Orange River region of the Northern Cape (Masowa et al. 2016). The regions along the Orange and Olifants rivers are characterized by a hot, dry climate and soils formed from limestone, and are renowned for the production of white wine grapes. While the production of red wine grape occurs mainly in the Western Cape regions of Stellenbosch, Paarl and Malmesbury on acidic and alluvial soils formed from granite from the mountain slope (Siphugu & Terry 2011).

2.3 Winemaking process and origin of winery waste

The major steps in red and white winemaking process and the generated solid wastes at different steps of winemaking are as shown in Figure 2.1. Grape berries are harvested from the stems either manually or mechanically (Janick & Paull 2008) and crushed mechanically to break the skins (Zacharof 2017). Enzymes are then added to break down the cell walls of grape pulps and skins to promote the release of juice (Sparrow et al. 2006). Subsequently, the berries are pressed to extract the juice. Afterwards, sulphur dioxide is added to the juice to control the growth of microorganisms and inhibit wild yeast that occurs naturally on the wine grapes (Novo et al. 2012). The inoculation of the juice with live yeast is done to initiate fermentation reaction (Safriet 1995). The wine is clarified after maturation either naturally or chemically using filtering and fining agents. Filtration earths (diatomaceous earth (DE) and perlite) and fining agents (such as tannin, gelatine, bentonite, albumen, and casein) are used for wine clarification (Ribéreau-Gayon et al. 2000). Diatomaceous earth is often used in depth filtration (Grainger & Tattersall 2016). It is used in wine filter materials (FM) because its commercial products provide fine, irregular-shaped, and porous particles that have large surface area and high liquid absorptivity, and these properties enhance filtration (Antonides 1997). Perlite is equally used as an alternative filter aid for DE (Franson 2012). The generation of winery solid waste materials occurs from multiple steps of winemaking. The winery solid waste includes plant remains derived from de-stemmed grapes, bagasse from pressing, lees obtained from different decanting steps, sediments, fining materials and filter waste obtained during clarification process (Van Schoor 2005; Devesa-Rey et al. 2011).

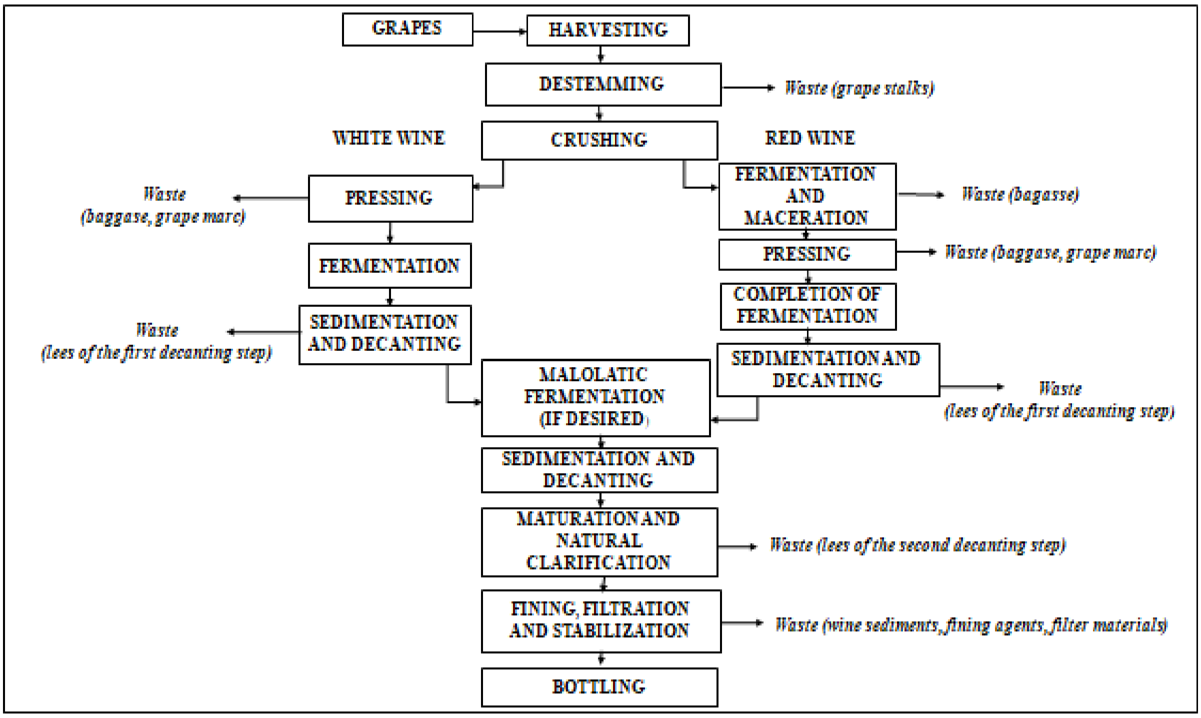

Figure 2.1: Major steps of winemaking process and the origin of waste during the production of white and red wine (Sources: Bustamante et al. 2005; Devesa-Rey et al. 2011; Conradie et al. 2014; Zacharof 2017).

2.4 Winery waste and its impact on the environment

Grape marc, lees and filter materials residues are among the by-products of wine cellar process (Bustamante et al. 2005; Van Schoor 2005). In total, more than 20% of the raw materials used for production of wine end up as thousands of tons of waste (Arvanitoyannis et al. 2006). The main organic wastes produced in modern wine industries consist of 62% grape marc, 14% lees, 12% stalk and 12% dewatered sludge (Ruggieri et al. 2009; Cotoras et al. 2014). Untreated grape marc can emit unpleasant odours and pollute the air. Furthermore, its leachate contains tannins and other chemical compounds that infiltrate the surface soil and ground water leading to oxygen depletion and ground water pollution (Conradie et al. 2014). Winery organic waste can be used as a bio-fertilizer due to its high organic matter content, K level, and considerable levels of N and P (Voća et al. 2010). However, continuous application of this organic material should be done with caution since it can lead to organic overload that could block the soil pores and reduce the quality of the soil (Conradie et al. 2014).

The use of DE to filter cold-processed wines has environmental drawbacks linked to filtration residues and electrical energy consumption (Bories et al. 2011). Diatomaceous earth is a carcinogenic material (Grainger & Tattersall 2016). The oven-dried DE typically contains 70 to 90% silica, 0.6 to 8% alumina, 0.2 to 3.5% iron oxide and 0.3 to 3% calcium oxide (Reza et al. 2015). Diatomaceous earth is also used as a soil amendment for preventing soil compaction in sports turf, improving root growth, lessening transplant shock for landscape plantings, and reducing water and chemical consumption for all turf and ornamental applications (Breese & Bodycomb 2006). Perlite is a naturally occurring siliceous rock that is exceptionally light and white (Cheremisinoff 2002). Apart from clarifying wine, perlite is also used as a component of soil-less growing mixes and as a carrier for fertilizer, herbicides, and pesticides (Bamforth 2006). Therefore, the injudicious dumping of untreated waste from such materials that contain high amount of silica poses a threat to environmental health.

2.5 Composting process

2.5.1 Description of composting process

The process of composting can occur in two ways, aerobically or anaerobically (Marya 2011). During aerobic composting, aerobic microorganisms oxidise organic compounds to carbon dioxide, nitrite and nitrate (Marya 2011). The carbon present in the composting materials serve as both a source of energy and as an element in the cell protoplasm for the microorganisms (Chummun et al. 2011). In anaerobic composting, anaerobic microorganisms break down the organic compounds through a process of reduction while metabolising the nutrients (Wadkar et al. 2013b). The temperature of the mass rises due to exothermic reaction under aerobic composting, but it does not rise much under anaerobic composting due to the miniscule amount of energy released (Wadkar et al. 2013b). The composting process involves a wide variety of mesophilic, thermo-tolerant and thermophilic aerobic microorganisms such as bacteria, actinomycetes, yeasts and fungi (Boulter et al. 2002).

Conventional composting process is divided into four different phases according to the temperature of the compost pile namely the mesophilic, thermophilic, cooling and curing phases (Xiao et al. 2009; Irvine et al. 2010; Bougnom et al. 2014). The mesophilic phase is the first stage of the composting process in which the mesophilic bacteria proliferate and raise the temperature of the composting mass up to 44°C (Jenkins 1999). During this stage, the bacteria decompose the readily degradable organic matters such as proteins, starch, and fats (Guo 2012). The mesophilic bacteria become increasingly inhibited by the temperature, as the thermophilic bacteria take over (Aziz et al. 2014) in the transition range of 44 to 52°C (Jenkins 1999; Ramachandra 2006). The compost enters the thermophilic phase when the temperature reaches

40°C (Haug 1993; Rudnik 2008). During this phase, the prevalence of elevated temperatures of 55°C to 70°C leads to the destruction of less biodegradable cellulosic substances (Hoitink et al. 996) and the thermophilic microorganisms dominate during this part of the process (Haug 1993; Hoitink et al. 1996). The thermophilic phase is considered as the most productive stage of composting and lasts for approximately two weeks (Oviasogie et al. 2010). The cooling phase follows the thermophilic phase. During this phase, the microorganisms that were expelled by the thermophiles migrate from the outer low temperature layer into the compost windrow or pile and digest the more resistant organic materials (Hoitink et al. 1996; Jenkins 1999). Fungi and macroorganisms such as earthworms and sowbugs that breakdown the coarser elements (for example, lignin) into humus also move back in (Jenkins 1999). The last phase of composting process is called the curing phase. This phase is attained when the composted material does not warm-up on turning, go anaerobic on storage, nor rob the soil of nitrogen when incorporated into it (Biddlestone et al. 1981). A long curing period adds a safety net for pathogen destruction (Jenkins 1999).

2.5.2 Factors affecting the composting process

The most crucial factors to the formulation of the compost mix or management of composting process include nutrient balance (C:N ratio), moisture content, particle size, porosity, pH, oxygen concentration and compost temperature (Keener 2011). These factors affect the microbial growth (Mangkoedihardjo 2006). Table 1 shows some vital factors of the composting process and their acceptable and ideal ranges. Temperature is the most critical factor for controlling composting reaction rates because of its effect on microbial metabolic rate and population structure (Tang et al. 2007). According to Pichtel (2005), the temperature of the compost pile should be kept maximally at about 65°C. The temperature of the unventilated composting pile can reach 70°C whereas in an aerated pile the temperature typically reaches between 55 and 65°C (Rudnik 2008). Maintaining the temperature between 60 and 70°C for 24 hours precipitates the killing of pathogens and weed seeds (Saranraj & Stella 2014). For example, Idris et al. (2010) indicated that if a high composting temperature (optimum, 50-55°C) is not maintained throughout the material for a sufficient period of time (>2days), the destruction of pathogens will not occur. Compost piles attaining an ‘over-heat’ level (>75°C) lead virtually to the cessation of microbial activity with only spores surviving and germinating when the favourable temperature is restored (Guo 2012). The spore-forming stage is the resting stage, which is undesirable in the composting process as it reduces the decomposition rate of composting material (Pichtel 2005). It is recommended that the pile should be cooled by turning it or increasing the aeration rate when the pile temperature approaches 71°C (Sweeten & Auvermann 2008). The heat production depends on the size of the pile, its moisture content, aeration, and C:N ratio (Trautmann 1996).

Table 2.1: Acceptable and ideal ranges of factors affecting the composting process (Adapted from Rudnik 2008)

Factors	**Acceptable**	**Ideal**
Temperature	43-66°C	54-60°C
C:N ratio of combined feed stocks	20:1 to 40:1	25:1 to 35:1
Moisture content	40-65%	45-60%
Available oxygen concentration	>5%	>10%
pH	5.5-9.0	6.5-8.0

The cell growth of microorganisms involved in the composting process primarily requires C and N (Ravindran & Mnkeni 2016). The C:N ratio of the material must be between 25:1 and 35:1 (Ivanov 2016). This is because, a higher C:N ratio reduces the rate of the decomposting process, while a lower C:N ratio leads to nitrogen loss (Stabnikova et al. 2010). According to Aziz et al. (2014), the C:N ratio of the material greater than 35:1 limits the growth of microorganisms that consequently lead to a longer composting time. The optimum pH range preferred for composting is normally between 6.5 and 8.5 (Aziz et al. 2014; Rajaram et al. 2016).

Moisture content is another influential factor in the microbial activity and the physical structure in the composting process (Makan et al. 2013). Microbially induced decomposition occurs most rapidly in the thin liquid films found on the surfaces of the organic particles (Trautmann 1996). The initial moisture content of the organic material may be between 45 and 75% (Saranraj & Stella 2014) with 50 to 60% generally considered optimum for composting (Holmer 2002). Moisture content above 70% decreases the rate of organic decomposition and creates anaerobic conditions and odour problems (Stabnikova et al. 2010; Ivanov 2016). Similarly, moisture content above 65% decreases the supply of oxygen to the microorganisms as the pores are filled with water (Zein et al. 2015). When the moisture content is below 45%, it becomes inconducive for the microorganisms to live (Zein et al. 2015).

Mitchell (2012) reported that oxygen is required to support the growth of beneficial organisms and to eliminate the risk of pathogens and other toxic compounds. Too little aeration can lead to anaerobic conditions, while excessive aeration can lead to extreme cooling which may prevent the thermophilic conditions required for optimum rates of decomposition (Gao et al. 2010). Hence, it is vital to carefully regulate the amount of aeration during composting process. Practices such as mechanical mixing or turning (Oviasogie et al. 2010), drilling air holes, inclusion of aeration pipes, and forced air flow help to improve and maintain the aerobic conditions of the pile (Trautmann 1996). This ensures that oxygen levels do not drop low enough to kill the good organisms and grow pathogens (Mitchell 2012). Oxygen is highly consumed by the microorganisms that are breaking down the organic material within the temperature range of 28 to 55°C (Pichtel 2005).

The energy lost exceeds heat produced during the composting process when the substrate porosity is higher than 50%, causing the composting pile to remain at low temperature (Kiyasudeen et al. 2016). The preferred air-filled pore space of composting piles ranges from 35 to 55%, while 30 to 60% is considered reasonable (Keener 2011). An exceptionally low porosity leads to anaerobic conditions and the generation of unpleasant odour (Kiyasudeen et al. 2016). A smaller particle size significantly influences the biodegradation rate by ensuring greater surface area and enhancing mass transfer between the biodegradable material and microorganisms (Ivanov 2016). A bulk density of compost piles below 640 kg m^{-3} is reasonable (Keener 2011).

2.5.3 Composting methods

2.5.3.1 Open composting methods

Open composting systems include methods such as turned windrows, passively aerated static piles, and forced aerated static piles and bins (Rynk & Richard 2001). Turned windrows are elongated composting piles that are turned frequently to maintain aerobic composting conditions (USEPA 1995), and to expose all particles of the mass to similar conditions within the windrows (Martin & Gershuny 1992). The turning frequencies can range from twice per week to once per year (USEPA 1995) depending on how quickly the finished compost is required (Gershuny 2011). The composting time for waste materials such as MSW range from 2 to 6 months under the windrow composting (Thassitou & Arvanitoyannis 2001). The base width and height of windrows at any length can range from 2 to 6 m and 1 to 3 m, respectively. However, the most practical windrow size is 3 to 5 m at the base and 2 to 3 m in height (Kuhlman 1990). Under natural aeration, the optimum height of compost pile is 1.5 m (Biddlestone et al. 1981). The turning of pile requires high capital input since it is labour intensive. This explains the preference of passive aeration method or natural convection method to minimize labour costs (Tanpanich et al. 2009).

The passively aerated static piles method relies on natural air convection created by temperature differences within and outside the pile (Gershuny 2011). The pile is usually constructed over perforated pipes (Mukerji & Manoharachary 2006; Gershuny 2011) that are used to draw the cool air into the pile when the centre of the pile becomes hot (Epstein 2011). The composting materials are not turned or agitated once the pile is formed (Wadkar et al. 2013a). To improve the structure for satisfactory aeration without turning, amendments such as straw and wood chips are incorporated in the pile (Seyedbagheri 2010). As a low-cost technology, the passively aerated static piles method has the potential to be widely utilized by farmers for composting animal waste (Epstein 2011; Gershuny 2011).

The forced aerated static pile method uses blowers that either suction air from the pile or blow air into the pile using positive pressure (Chandra & Yadav 2015) through perforated pipe systems located underneath the compost pile (Tiquia & Tam 1998). Decay-resistant bulking agents such as wood chips are incorporated into the pile to provide the necessary porosity (Chandra & Yadav 2015) which will ensure adequate aeration (Tiquia & Tam 1998). As with passively aerated static piles, the composting materials are not turned or agitated once the pile is formed (Wadkar et al. 2013a).

2.5.3.2 In-vessel methods

In-vessel composting methods encompass horizontal agitated bed method, aerated containers method, aerated-agitated containers method, silo or tower reactors method and rotating drum reactors method. These methods confine the composting materials within a building, container, or vessel (Sethuraman & Naidu 2008). This enables the closer regulation of temperature, moisture, aeration, and composting materials mixing rates (Mathur 1998). An in-vessel composting process can last up to 14 days (Mathur 1998; Thassitou & Arvanitoyannis 2001). These methods require less space compared to traditional outdoor windrow/pile composting methods (Sangamithirai et al. 2015). However, the in-vessel composting methods are costly to install and operate, and they require intensive and skilful management (Thassitou & Arvanitoyannis 2001). Under the horizontal agitated bed method, materials are composted between the walls that form long and narrow channels with an open top. Bed width and depth under commercially available systems range from 1.83 to 6.10 m and 0.91 to 3.05 m, respectively. However, the composting process for commercial agitated-bed systems may range from 2 to 4 weeks (USEPA 1995).

The aerated-agitated containers system uses the containers that provide forced aeration and agitation (Rynk & Richard 2001) to mix the composting materials. These containers are usually rectangular and fitted with a water system for water addition (Diaz et al. 2007). The higher temperatures are maintained in the first zone for the destruction of pathogens (Rynk & Richard 2001), and thus ensuring better compost quality. Silos or towers reactors systems use vertical units operating on a continuous basis (Williams 2005). The composting materials are added at the top of the silo, while the composted product is collected at the bottom of the tower after several days followed maturation (Williams 2005). The rotating drum reactors systems usually uses a rotating cylinder, which is placed on an inclined surface to facilitate the movement of the composted material from one end to another (Diaz et al. 2007). Moisture and oxygen concentration in the reactor are maintained at optimum or near-optimum levels (Diaz et al. 2007). The processed composting material in the drum is cured using either windrow (Diaz et al. 2007) or horizontal agitated bin system (Lang & Jager 1992).

2.6 Compost maturity, stability, and quality

Compost maturity refers to the amount of degradation of phyto-toxic organic substances and it is measured by the germination index (GI) or plant bioassays (Nada 2015). The GI test is based on seed germination and initial plant growth using a liquid extract from the compost (Zucconi et al. 1981). The GI reflects the phyto-toxicity of the compost extracts at distinct stages of composting (Selim et al. 2012). Compost is considered matured when the GI is greater than 60% (Zucconi & de Bertoldi 1987). A GI value of 80% is an indicator of the disappearance of phyto-toxicity in composts (Zucconi et al. 1981). Tiquia et al. (1996) used this value as an indication of the phyto-toxic-free and mature compost. The C:N ratio is an important parameter for compost maturity (Mangkoedihardjo 2006). This is because a decrease in the C:N ratio indicates an increase in the degree of organic matter humification (Satisha & Devaranjan 2007). The C:N ratio of less than 20 is common throughout the international composting industry as an indication of compost maturity (Mangkoedihardjo 2006). According to the Fertilizer (Control) Order of 1985, compost should have a C:N ratio of 20:1 or less, pH value of 6.5 to 7.5, electrical conductivity of less than 4.0 dS m^{-1}, moisture content of 15 to 25 percent by weight, and bulk density of less than 1.0 g cm^{-3}. Furthermore, matured compost should contain minimum amounts of total organic C, N, phosphates (as P_2O_5) and potash (as K_2O) of 12.0, 0.8, 0.4 and 0.4 percent by weight, respectively (Singh & Nain 2014). The maximum acceptable heavy metal concentrations used in determining the quality of compost or bio-solids are shown in Table 2.2.

Table 2.2: The maximum acceptable heavy metal concentrations by various countries (mg kg^{-1}, on dry weight basis)

Metal	Indian[1]	EU[2]	U.S.[2]	Germany[3]	Belgium[3]	Canada[3]	France[3]	Sweden[3]
As	10	-	41	-	-	-	-	-
Cd	5	10	39	2	5	3	8	3
Cr	50	200	1200	150	150	210	-	150
Cu	300	600	1500	150	100	100	-	150
Hg	0.15	10	17	-	-	-	-	-
Ni	50	200	420	50	50	62	200	50
Pb	100	1000	300	200	600	150	800	150
Zn	1000	4000	2800	400	1000	500	-	500

Sources: [1](Singh & Nain 2014); [2](CIWMB 2009); [3](Mandal et al. 2014)

Compost stability refers exclusively to the resistance of compost organic matter to further degradation (Brewer & Sullivan 2003). There are no universally accepted standards for the evaluation of compost stability (Cabañas-Vargas et al. 2005). The compost indicates a good degree of stability when the temperature during composting approaches the ambient level (Raj & Antil 2012). Laboratory tests of compost respiration rate are used to assess compost stability (Brewer & Sullivan 2003). A decreasing respiration rate in a laboratory test implies a reduction in biodegradable C and increasing C stability (Brewer & Sullivan 2003). Composts must comply with hygienic requirements (Barth 1996). According to Woods End Research Laboratory (2005), it is unacceptable to have detectable *E. coli* or *Salmonella*, or faecal coliform greater than 1000 MPN g^{-1}. Compost with appreciable *E. coli* (>100 MPN) should be assessed for *E. coli 0157:H7* which should be non-detectable at <0.02 CFU g^{-1} (<1/50g) (Woods End Research Laboratory 2005).

2.7 Benefits of composting of organic waste

Composting is a useful strategy for the sustainable recycling of organic wastes (Haq et al. 2014). It involves intense microbial activity that leads to the decomposition of biodegradable materials (Boulter et al. 2002). Composting results in the formation of stable, hygienic, and humic-rich materials that is suitable for use as an organic fertilizer in agricultural soils (Bustamante et al. 2010). It is advantageous because it reduces the pathogens in waste and the volume of waste, and thus making waste easier to handle, store, transport, and apply than un-composted organic residues (Preusch et al. 2002). The microorganisms involved in composting are capable of degrading contaminants and phenolic compounds (Kefeli et al. 2003; Cascant et al. 2016). Ntougias et al. (2013) ascribed the increases in dehydrogenase, β-glucosidase, and urease activities during composting of olive mill wastes to the transformation of phenolics. The composting product may be used as a soil amendment, seed starter, mulch, container mix, natural fertilizer (Cooperband 2002).

2.8 The concept of effective microorganisms (EM)

The technology of EM was originally developed in the 1970s at the University of the Ryukyus, Okinawa, Japan (Jadhav 2014) for natural or organic farming systems. However, it has been adopted in waste management to facilitate the re-use of waste (Jusoh et al. 2013). Effective microorganisms inoculum consists of a mixture of selected and cultured naturally-occurring, beneficial microorganisms that have been studied and proven to improve soil quality, plant growth (Lindani & Brutch 2012) and yield of crops (Yamada & Xu 2001). It has been described as a combination of about 80 co-existing beneficial microorganisms, which were selected from more than 2000 species isolated from various environments (Mayer et al. 2010). The main microorganisms in EM are lactic acid bacteria, photosynthetic bacteria, yeasts, actinomycetes (Mayer et al. 2010; Xu 2000) and the fermenting fungi (Zakaria et al. 2010). These microorganisms are mutually compatible with one another and can co-exist in liquid culture (Higa & Parr 1994).

The use of EM is not yet widespread in SA, although reports indicate that some commercial farmers have used it with possitive results (Ncube et al. 2011). The use of EM is eco-friendly, safe, and organic (Shalaby 2011). In addition, it has the potential of acting as crop strengtheners, phytostimulators and plant health improvers (Babalola & Akindolire 2011; Lawal & Babalola 2014). The EM producers also claim that it can accelerate the decomposition of organic waste, enhance soil physical characteristics and increase beneficial microorganisms in the soil (Cóndor-Golec et al. 2007).

2.9 Effects of microbial inoculation on composting and compost quality

Microbial inoculation entails adding specific populations of microorganisms, selected for certain goals to a medium to obtain different responses from what is usually applicable under natural conditions (Acevedo et al. 2005). Wei et al. (2007) suggested that the inoculation of compost with microbes lead to a greater degree of the aromatization of humic acid, improvement of humification and the acceleration of compost maturation processes. Lignocellulolytic microorganisms are instrumental to the rapid decomposition of agricultural residues (Mishra & Nain 2013). Hence, such addition to composting materials may enhance rapid decomposition, thereby reducing the composting period.

A study by Suárez et al. (2004) suggests that the inoculation with thermophile bacteria and actinomycetes is beneficial for the degradation of lignin fractions during horticultural waste composting. Affirmatively, Ma et al. (2010) noted an increase in the number of microorganisms in compost produced with inoculation of compound microbial preparations than in compost prepared without inoculation of compound microbial preparations. For Mishra and Nain (2013), the artificial supplementation of cellulolytic bacteria and fungi enhanced the composting process due to their hydrolytic enzymes. Similarly, Sangakkara et al. (2008) assert that compost inoculated with EM was of the highest quality and the most beneficial in terms of plant growth, yields and microbial populations of the roots. In a study conducted by Jusoh et al. (2013), the thermophilic phase for compost with EM lasted for 23 days, and 30 days for compost without EM. This shows that the use of EM inoculation may reasonably reduce the composting period.

Furthermore, this study demonstrated that compost with EM had higher N, P, K, and iron content in comparison with compost without EM. The inoculation of the vine branch compost with fungus (*Cephalosporium* species) had a positive effect on the yield and quality of ryegrass and tomatoes (Kostov et al. 1996). Mupondi et al. (2006) also reported improved cabbage seedling growth with co-composted pine bark with effective microorganisms. Based on the foregoing, it is evident that microbial inoculation has beneficial effects on composting and compost quality.

2.10 Maize production in South Africa and its growth requirements

Cereal crops such as maize are particularly important for direct human consumption due to high food insecurity in Sub-Saharan Africa (FAO 2016). South Africa is the major maize producer in the Southern African Development Community with production averaging about 10.4 million tons a year over the past 10 years (Tibane & Vermeulen 2014). Maize production occurs throughout SA, but more predominately in the Free State, Mpumalanga and North West provinces under dry land where it account for approximately 83% of total production with less than 10% produced under irrigation (DAFF 2013). More than two thirds of the locally-produce maize is consumed by the local market in the following pattern: humans (50%); the animal feed industry (40%) and the reminder of 10% are used for seed and industrial uses (DAFF 2013).

Maize requires warm weather conditions and it is not often grown in areas where the mean daily temperature is below 19°C or where the mean daily temperature in summer is below 23°C (Du Plessis et al. 2003). Temperatures ranging between 19 and 25°C are best for maize flowering (DAFF 2008). In Africa, temperatures higher than 30°C are critical for maize and may affect yield (Lobell et al. 2011). Soils with pH (H_2O) values ranging from 5.5 to 7.5 (FSSA 2003), good effective depth, an optimal moisture regime and balanced quantities of plant nutrients are most suitable for maize (Du Plessis et al. 2003). Maize requires about 600 to 700 mm of water for optimum growth and yield (Hammad et al. 2011).

Profitable maize production requires adequate amounts of N and P (Alley et al. 2009). Nitrogen and P are required by maize for good vegetative growth and grain development (Onasanya et al. 2009). The maximum amounts of N, P and K required by maize are 200, 90 and 70 kg ha^{-1}, respectively (Soropa et al. 2012). Nitrogen, P and K assimilation in maize reaches peak during flowering (Du Plessis et al. 2003). Nitrogen influences biomass production by influencing leaf area development and the photosynthetic efficiency (Baloyi et al. 2014). Furthermore, N mediates the utilization of P, K, and other elements in plants (Onasanya et al. 2009) and their optimal amounts in the soil cannot be utilized efficiently if plants are N deficient (Mikkelsen & Hartz 2008). The uptake of N is low during early development and increased at maize tasselling (Amin 2010). Nitrogen makes up 1 to 4% of dry matter of the plants while P makes up 0.1 to 0.4% of the dry matter of the plant (FAO 2000). Phosphorus plays a key role in plant processes such as photosynthesis and other chemico-physiological processes involving transfer of energy (FAO 2000; Onasanya et al. 2009). Therefore, the proper management of both N and P is very vital for good crop production.

2.11 Combined effects of organic and inorganic fertilizers on crop production

The integrated use of organic and inorganic fertilizers does not only enhance crop yields, but it also has a greater beneficial residual effect that can be derived from use of either organic or inorganic fertilizers applied alone (Akande et al. 2010). Adamas et al. (2015) reported that maize yields obtained from application of a combination of organic and inorganic fertilizers were significantly better improved than those from sole use of either of them. Abedi et al. (2010) indicate that the combination of 160 kg N ha^{-1} of mineral fertilizer and compost gave the maximum amount of winter wheat yield. In a similar vein, Zafar et al. (2012) reported that the integrated use of inorganic P sources and compost not only increased crop yield but also increased protein content and P uptake in maize. The improved crop performance following the application of combined organic and inorganic fertilizers may be due to the enhancement of soil fertility factors by organic fertilizers, which expedited the functionality of the mineral fertilizers (Odhiambo & Magandini 2008). Therefore, the combined use of organic and inorganic fertilizers may minimize the use of scarce and costly inorganic fertilizers (Unagwu et al. 2012).

2.12 Limitations of organic materials use in crop production

Composts contain relatively low concentrations of N, P and K (Mikkelsen & Hartz 2008). Hence, the use of organic materials is considered inadequate for sustained cropping because they are required in rather copious quantities to meet the crop's nutrient requirements (Nziguheba et al. 1998; Makinde & Ayoola 2010). The excessive use of organic materials leads to ground water pollution (Lazarovits 2001). For example, the repeated application of poultry manure and other manure often results in accelerated eutrophication of waterways (Preusch et al. 2002).

The use of animal manures is always accompanied by risks of contamination by human or animal pathogens (Lazarovits 2001). Some manures are contaminated with hormones, antibiotics, pesticides, disease organisms, heavy metals, and other undesirable substances (Wander 2015). High-temperature aerobic composting eliminates several organic compounds, pathogens, protozoa, or viruses. However, disease-causing agents such as *Salmonella* and *E. coli* bacteria may survive the composting process (Wander 2015). Therefore, the application of composted waste materials to soil must be done cautiously to avoid unnecessary spread of diseases and ground water pollution.

2.13 Effects of application of organic materials on soil health

Soil microbial biomass, activity, and community structure are useful indicators of soil quality and health because these parameters are sensitive to changes in cropland management practices (Zhen et al. 2014). The application of organic amendments increases the populations of soil microorganisms by up to 1000-fold (Lazarovits 2001). The application of organic amendments increases the presence of microorganisms such as bacteria, fungi, actinomycetes and microalgae, which play a key role in organic matter decomposition, nutrient cycling, and other chemical transformations in soil (Murphy et al. 2007). The on-going formation and decomposition of organic matter in soil plays a major role in determining plant and ecosystem productivity through a combination of its role in the storage and provision of nutrients and water, together with the development and maintenance of physical structure (Condron et al. 2010).

Compost can bind heavy metals and other contaminants hence, its application on soils can reduce both the leaching and absorption of heavy metals and other contaminants by plants (Van Herwijnen et al. 2007; USCC 2008). Amlinger et al. (2007) linked the increases in the bioremediation of soils contaminated with organic compounds to both the amount of organic matter and the biological activity following the addition of compost. The ability of compost to improve cation exchange capacity of soils promotes the retaining of nutrients longer in the rootzone for the plant to use when needed (Wahba & Darwishi 2008; Fulekar 2010). This ensures the effective utilization of nutrients by crops, while minimizing nutrients loss through leaching. Therefore, improving the cation exchange capacity of highly drained soils such sandy soils through compost application can improve the retention of plant nutrients in the root zone (Fulekar 2010).

The level and type of organic matter and microorganisms in soils influence the disease incidence on diverse plants (USCC 2008). For example, some composts have been found to have suppressive effects on different soil-borne pathogens in various cropping systems (Noble & Coventry 2005; Pugliese et al. 2008). This may be attributed to the increase in the population of microorganisms supplied by composts that either kill or compete with pathogens in the soil resulting in the suppression of diseases (Sullivan 2004). Furthermore, the degradation of organic amendments containing high amounts of N generate ammonia and (or) nitrous acid which could kill certain pathogens in the soil (Lazarovits 2001).

2.14 Conclusions

The production of wine in SA generates massive solid waste materials and the disposal of the untreated waste constitutes an issue of environmental concern. This necessitates the adoption of safe waste management technologies that can be implemented easily and at a low cost. The literature reviewed herein show that the composting technology is a safe alternative waste management strategy unlike incineration and landfill. Composting technology offers not just waste treatment solutions, but it also provides a high-quality product that can be used in crop production as a valuable soil amendment to improve soil health. The organic fertilizers cannot meet the crop nutrients demand due to their slow release of nutrients into the soil solution. However, the use of organic fertilizer in combination with inorganic fertilizer has been proven to improve the performance of crops than the sole use of either of them. As the discussions here have shown, the inclusion of EM in composting enhances the rapid decomposition of waste and compost quality parameters. However, further research is required to evaluate the effects of the use of EM and EM-compost on crop growth and yield, especially since the use of EM use is not yet widespread in SA. Lastly, maize is an invaluable crop in Sub-Saharan Africa for direct human consumption and ensuring food insecurity. It grows well on soil that is in a good condition, particularly those with sufficient amounts of available N, P and K.

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CHAPTER 3

Physico-chemical properties and phyto-toxicity assessment of co-composted winery solid wastes with and without effective microorganism inoculation

Abstract

This study assessed both the physico-chemical properties of winery solid waste (WSW) composts with or without microbial inoculation and the phyto-toxicity of their extract. Four different composts with initial pile height of 1.0 or 1.5 m were prepared through aerobic thermophilic process by mixing the filter materials (FM) and waste plant materials at 40:60 ratio on dry volume basis. Cured composts were evaluated for selected physico-chemical properties and germination attributes at varied extract concentrations (0, 10, 25, 50 and 100%) using cowpea, maize, and tomato seeds. Microbial inoculation exerted significant effects on compost Bray-2 P content, while interaction between inoculation and compost pile size similarly had significant effect on the ammonium-N content. The of bulk density, water holding capacity, pH, electrical conductivity (EC) and contents of volatile solids nitrate-N and exchangeable K among the various composts did not differ significantly. The composts possesed high EC (range: 9.03-10.23 dS m^{-1}) suggesting high soluble salts concentrations. Compost type and extract concentration interaction exerted significant effect on the germination index (GI) of all three crops with the phyto-toxic effects on maize and tomato at 50% extract concentration and above. The compost extracts showed varying degrees of phyto-toxicity to maize and tomato, whereas no phyto-toxicity effect was recorded for cowpea. The composts also showed phyto-nutrient and phyto-stimulant capabilities with more than 100% root length and GI values. Nonetheless, the phyto-toxicity recorded in maize and tomato can be eliminated using lower application rates.

Keywords: germination index, microbial inoculation, phyto-toxicity, winery solid waste compost

3.1 Introduction

The effective microorganisms (EMs) technology is one of the new technologies that have been proposed in an attempt to improve the management of solid and liquid wastes, and for diverse agronomical uses. Effective microorganisms' inoculum refers to a combination of about 80 coexisting beneficial microorganisms selected from more than 2000 species isolated from various environments (Mayer et al. 2010). The main microorganisms employed in the EM include Lactic acid bacteria, photosynthetic bacteria, yeasts, actinomycetes and fermenting fungi (Mayer et al. 2010; Zakaria et al. 2010). Producers of EM opine that it could accelerate the decomposition of organic wastes (Cóndor-Golec et al. 2007). Numerous studies have also suggested that its uses and applications for a wide range of activities including agriculture, livestock, gardening and landscaping, composting, bioremediation, cleaning septic tanks, algal control and household uses (Namsivayam et al. 2011).

Composting is a biological waste treatment technology that transforms organic wastes into organic fertilizer and soil conditioners; and is currently a widely used solid organic waste treatment method (Malakahmad et al. 2017). However, it is important to understand the characteristics of the composted products to avoid the potential negative effects (Soares et al. 2013) stemming from their misuse. The possible negative effects of compost utilization include the introduction of toxic heavy metals (Tittarelli et al. 2007), phenolic compounds, ethylene and ammonia, and excess accumulation of salts and organic acids into the soil (Soares et al. 2013). These deleterious effects may lead to the retardation of seed germination and plant growth (Selim et al. 2012). More importantly, toxic heavy metals can also enter the food chain in significant amounts through their uptake by plants from the soil (Tittarelli et al. 2007) with devasting health risks for humans and animals. Phyto-toxicity assessment is, therefore, one of the most important criteria for evaluating the suitability of composts for application on agricultural soils (Obuotor et al. 2017) for crop production. Diverse physical, chemical, and biological parameters are used to assess compost maturity. These include C:N ratio, changes in nitrogen species, pH, EC, cation exchange capacity, organic chemical constituents, reactive carbon, humification parameters, optical density, temperature, colour, odour, structure, specific gravity, plant assays, respiration, microbial population changes, enzyme activity, germination tests (Kumar et al. 2016; Obuotor et al. 2017), and calorimetric and spectroscopic tests (Quatmane et al. 2013). The objective of this study was to assess the physico-chemical properties of winery solid waste (WSW) composts with or without microbial inoculation and their toxicity effect on seed germination attributes.

3.2 Materials and methods

3.2.1 Description of study site and compost preparation processes

The WSW composts were produced in heaps through aerobic-thermophilic composting on an open field at the research farm of the Agricultural Research Council/ Nietvoobij (-33.9168°S, 18.85988°E), Western Cape, South Africa (Figure 3.1). The WSW materials used for the co-composting included (i) filter materials (FM) that comprised diatomaceous earth (DE) and perlite, and (ii) chopped grapevine pruning canes (GPC), grape stalks (GS), and grape seeds and skins mixture (MSS), which were collectively described as waste plant materials (WPM). Table 3.1 depicts the quantity of each waste material used in each compost heap. Prior to the WSW compost preparation, samples of the waste plant materials used were subjected to laboratory analyses for chemical characterization following standard laboratory procedures. The EM used during the compost preparation comprised microbial inoculum (EM-1) that was activated using dechlorinated water and molasses (voermolas). The EM-1 inoculum, a product of Microzone Polokwane CC, had a pH value of 3.34, contained 6.8 × 107 CFU mL^{-1} of lactic acid bacteria (*Lactobacillus casei*) and 2.4 × 102 CFU mL^{-1} of yeast (*Saccharomycess cerevisiae*). The activation of the EM-1 was performed following the procedure described by EMROSA (2008). The activated EM (EM-A) was considered ready for use when its pH value was below 4.0 (Sreenivasan 2013).

Four WSW compost types were produced over a 19 week period and comprised inoculated compost with an initial heap height (hereinafter pile size) of 1.0 m (INC1), inoculated compost with pile size of 1.5 m (INC1.5), uninoculated compost with pile size of 1.0 m (UNC1), and uninoculated compost with pile size of 1.5 m (UNC1.5). The compost pile size of 1.5 m was considered an optimum pile size under natural aeration (Biddlestone et al. 1981). The piles were 1.5 m long and 1.5 m wide. Each WSW compost pile size (1.0 and 1.5 m) type was produced in triplicates on a hardened soil surface lined with a high-density polyethylene liner. All compost piles were prepared by mixing FM and WPM at a ratio of 40:60 on percent volume basis. The 40% FM comprised 90% perlite and 10% DE, while the 60% WPM consisted of 80% GPC, 10% GS and 10% MSS on dry volume basis. Diluted EM-A (1:50, v/v) was sprayed per heap at 3 L m^{-3} on appropriate piles once fortnightly (EMNZ 2016). Additional water was added as required until the moisture content of each compost heap reached 60% on weight basis (AAFRD 2005). Compost piles were turned at bi-weekly intervals with the moisture content monitored throughout the composting period and maintained at 70% (w/w) to facilitate optimal microbial activities and proper curing.

Figure 3.1: Waste collection and preparation of composting piles

Table 3.1: Winery solid waste proportion of compost pile

Waste material	**Mass of raw materials**	
	1.0 m pile (kg/2.25 m^3)	**1.5 m pile (kg/3.38 m^3)**
Perlite	380.7	573.4
DE	41.4	59.8
Stalks	3.84	5.48
Skins and seeds	47.6	68.0
Grapevine pruning canes	172.8	259.2
Total	*646.34*	*965.88*

3.2.2 Temperature monitoring of compost piles

The process of temperature monitoring on each compost pile including the ambient commenced a day after the first turning with daily readings taken using a digital TCL 305 thermometer at depths of 50 and 75 cm for the 1.0 and 1.5 m piles, respectively. Both compost pile temperature and ambient temperature were measured at 8 a.m. and monitoring continued until compost temperature approached ambient temperature (Antil et al. 2013). Random compost sub-samples were collected at three locations in each compost pile at maturity and bulked into a composite sample per pile air-dried, ground, sieved (0.85 mm), and used for physico-chemical characterization and phyto-toxicity test.

3.2.3 Analyses of physico-chemical characteristics of the waste materials and cured composts

Moisture content of the composts was determined gravimetrically using the loss on ignition method (Mupondi et al. 2010), while bulk density and water holding capacity (WHC) were determined according to the methods described by Ahn et al. (2008). Total volatile solid (VS) was determined through incineration and the final content estimated as described by Chummun et al. (2011). The pH in 1 M KCl and electrical conductivity (EC) in water (1:10; m/v) of the composts and waste materials measured were determined using PHS-3BW microprocessor pH meter and DDS-11AW conductivity meter, respectively (Masowa et al. 2016). Total C and N contents were determined on Leco TruMac CNS analyzer, while total mineral N (TMN) was computed as the sum of nitrate (NO_3) and ammonium (NH_4) N concentrations determined colorimetrically following extraction with 0.1 N K_2SO_4 solution (Okalebo et al. 2002). Available P content in the composts was determined colorimetrically using Bray-2 procedure (Bray & Kurtz 1945), while exchangeable K was extracted with 1 N NH_4AOc solution and its concentration determined on atomic absorption spectrophotometer (Okalebo et al. 2002). The total contents of P, K, Na, Ca, Mg, B, Al and trace elements (As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb and Zn) were measured in samples following wet acid digestion procedure using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS, Model: NexIONTM 300Q, Perkin Elmer). Briefly, 0.25 g of each waste materials and compost sample was digested with 6 mL hydrochloric acid (32%) and 5 mL of nitric acid (55%) at 66°C for 45 min in a microwave reaction system (Microwave 3000, Anton Paar). Sample digests were transferred into separately labelled 100 mL Erlenmeyer flasks and 2 mLperchloric acid (70%) was added. Each digest including a blank was diluted to 100 mL with deionized water and thereafter filtered using Munktell filter paper (110 mm). The concentration of P, K and Na in the filtrate was subsequently read on the ICP-MS. Total phenolic content (TPC) in compost (1:10 m/v, compost per pure methanol) was determined following the Folin-Ciocalteu method using a UV spectrophotometer at 760 nm (Slinkard & Singleton 1977). The contents of acid detergent lignin (ADL), acid detergent fibre (ADF), and neutral detergent fibre (NDF) including the residual ash were determined following the filter bag technique.

3.2.4 Germination index test

The germination index (GI) test involved the procedure described by Tiquia et al. (1996) with slight modification. Precisely, compost extracts were made by separately mixing each compost sub-sample with deionized water (1:10; w/v). Each compost extract was subsequently diluted to varying concentrations (10, 25, 50 and 100%) using deionized water; and cowpea (*Vigna* *unguiculata*), maize (*Zea mays* L.) and tomato (*Lycopersicon esculentum*) seed germination was evaluated. The 100% extract concentration represented pure extract, while 10, 25 and 50% concentration represented 90, 75 and 50 mL distilled water addition, respectively. Table 3.2 below shows the pH and EC of the compost extracts.

Table 3.2: The pH and electrical conductivity (EC) of the different extracts of compost types

Compost type	**Extract concentration (%)**	**pH (H_2O)**	**EC (dS m^{-1})**
INC1	10	8.86	0.54
	25	9.50	0.88
	50	10.10	2.30
	100	9.83	9.36
UNC1	10	9.33	0.50
	25	10.05	0.87
	50	10.30	2.63
	100	10.03	9.03
INC1.5	10	9.73	0.64
	25	10.14	1.67
	50	10.40	2.85
	100	10.19	10.23
UNC1.5	10	9.49	0.63
	25	9.93	1.72
	50	10.30	2.47
	100	10.03	9.79

INC1 and INC1.5 denote inoculated composts with pile size of 1.0 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1.0 m and 1.5 m, respectively

Ten seeds of each crop were placed in 90-mm diameter petri dishes lined with a filter paper and moistened with 5 mL extract of each of the various compost concentrations and deionized water as a control. Hence, the various compost types and the extract concentrations per petri dish constituted treatment factors. Maize seeds were soaked in 250 mL deionized water overnight prior to sowing to minimize the lag-phase in seedling germination (Nadeem et al. 2017), while the seeds of cowpea and tomato were directly sown without prior soaking. Triplicate petri dishes containing treatment factors were placed in an Electro-Thermostatic incubator (Model: CNW ETI-9052) whose temperature was maintained at 25°C. The seeds that germinated after five days were counted and recorded, while the length of the primary root was measured using a measuring ruler. The value of GI was calculated according to Priac et al. (2017) using equation 3.1 below:

$$GI = \{(RLS \times GSS)/(RLC \times GSC)\} \text{……………………………..………………(equation 3.1)}$$

whereby: RLS = root length in compost extract; RLC = root length in control; GSS = number of germinated seeds in extract; and GSC = number of germinated seeds in control.

3.2.5 Data analysis

Data on the WSW composts physico-chemical properties, GI, TPC and the content of fibre fractions were subjected to analysis of variance (ANOVA) using Statistical 10.0 computer software program. The differences among treatment means were separated by Fisher's protected least significant difference (LSD) test at $p \leq 0.05$. Simple Pearson correlation analysis was performed among percent seed germination, percent root length, GI, pH, and EC to establish their relationship.

3.3 Results

3.3.1 Dynamics of composts temperature during the composting process

Figure 3.2 depicts the compost pile and ambient temperatures measured during the 19 weeks of (co-) composting period. The figure reveals that the 1.0 m compost heaps experienced extended thermophilic phase (above 45°C) up to 13 days after the first turning, whereas the 1.5 m compost heaps stayed in this phase for only the first seven days after the initial turning. The highest temperature measured was greater than 60°C in the 1.0 m compost piles, but less than 60°C in 1.5 m piles after the first turning, while the ambient temperature ranged from 11.2°C to 25.6°C throughout the (co-)composting period.

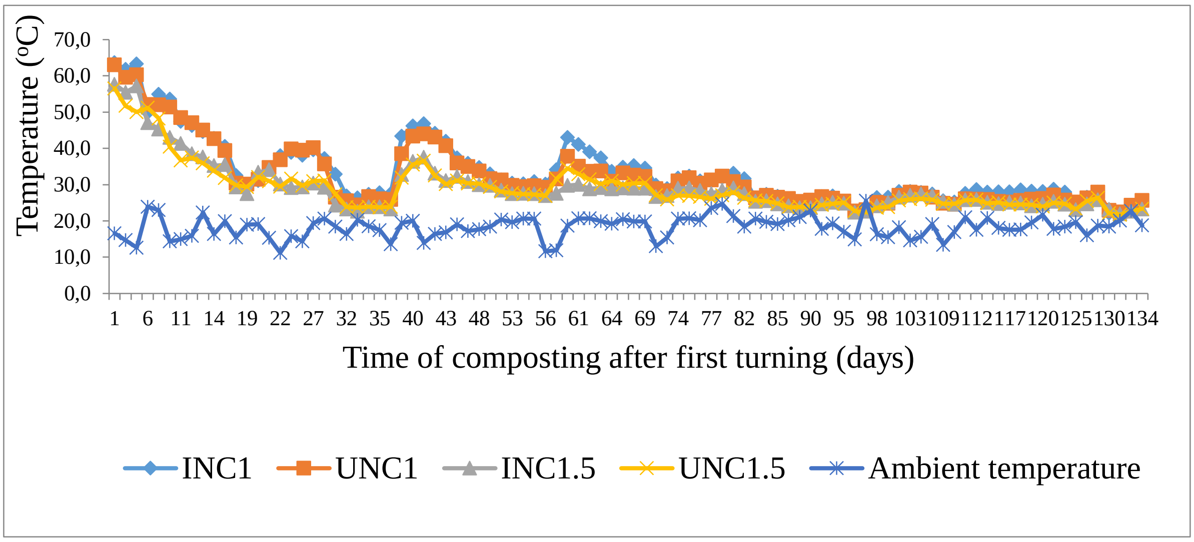

Figure 3.2: Compost piles temperature and ambient temperature during composting.

3.3.2 Physico-chemical characteristics of the winery solid waste materials and composts

The results of the WSW materials showed that perlite was very strongly alkaline with a pH value of 9.42, while the other waste materials were acidic in nature with the DE being ultra-acidic with pH value of 2.11 (Table 3.3). The EC of waste materials ranged from 0.10 dS m^{-1} in GS to 4.52 dS m^{-1} in perlite. The DE had a much lower C content (6.8%) than the remaining waste materials that had generally high C contents (>30%). The total N content ranged from 0.26% in DE to 4.19% in perlite, while the total P content ranged from 0.23 g kg^{-1} in DE to 3.45 g kg^{-1} in perlite. The perlite contained relatively high K content (140 g kg^{-1}), while the Na content ranged from 1.62 g kg^{-1} in GPC to 3.38 g kg^{-1} in perlite.

Table 3.3: Physico-chemical properties of winery solid waste materials used in composting

Parameters	**Raw materials**				
	Perlite	**DE**	**GS**	**MSS**	**GPC**
pH (KCl)	9.42	2.11	6.43	5.84	5.98
EC (dS m^{-1})	4.52	2.68	0.10	1.04	0.69
Bulk density (g cm^{-3})	0.47	0.46	0.27	0.34	0.16
VS (%)	67	20	98	89	90
WHC (g H_2O g^{-1})	3.24	1.72	3.84	2.08	3.83
C (%)	31.3	6.8	32.5	42.8	33.6
N (%)	4.19	0.26	0.36	2.8	0.76
P (g kg^{-1})	3.45	0.23	0.84	2.22	1.35
K (g kg^{-1})	140	2.75	3.08	21	2.09
Na (g kg^{-1})	3.38	1.74	1.82	1.84	1.62
Mg (g kg^{-1})	2.52	1.45	4.05	4.70	5.74
Ca (g kg^{-1})	31	14	38	40	50
B (mg kg^{-1})	860	650	650	740	780
S (%)	0.26	0.12	0.11	0.21	0.04
Mn (mg kg^{-1})	31	68	11	49	602
Fe (mgkg^{-1})	180	220	95	270	345
Cu (mg kg^{-1})	0.40	0.40	0.40	1.20	0.80
Zn (mg kg^{-1})	0.05	0.02	0.38	0.08	0.40
Cr (mg kg^{-1})	1.20	1.20	0.80	1.20	2.40
Al (g kg^{-1})	1.12	1.23	0.52	0.98	5.04
TPC (mg GAE g^{-1} DW)	1.77	0.94	1.64	1.44	1.60
ADF (%)	nd	nd	60	64	62
ADL (%)	nd	nd	39	55	36
NDF (%)	nd	nd	66	72	77

DE = diatomaceous earth; GS = grape stalks; MSS = mixture of grape seeds and skins; GPC = grapevine pruning canes; WHC = water holding capacity; EC = electrical conductivity; VS = volatile solids; WHC = water holding capacity; TPC = Total phenolic content; NDF = neutral detergent fibre; ADF = acid detergent fibre; ADL = acid detergent lignin; nd = not determined

Table 3.4 shows the results of the physico-chemical properties and fibre fractions of the composts. There was no significant difference in the bulk density, VS content and WHC among the various compost types. The composts bulk density ranged from 0.34 g cm^{-3} (INC1) to 0.39 g cm^{-3} (UNC1). The WHC ranged from 3.24 g water g^{-1} compost in both INC1 and NIC1.5 to 3.76 g water g^{-1} compost in INC1.5.

Table 3.4: Physico-chemical characterization of the WSW composts produced

Parameter	**Compost type**					
	INC1	**UNC1**	**INC1.5**	**UNC1.5**	**LSD$_{(0.05)}$**	**CV (%)**
pH (KCl)	9.69	9.68	9.76	9.75	0.21	1.19
EC (dS m^{-1})	9.36	9.03	10.23	9.79	1.62	9
Bulk density (g cm^{-3})	0.34	0.39	0.36	0.36	0.07	10
VS (%)	50	49	53	54	7	7
WHC (g H_2O g^{-1})	3.24	3.46	3.76	3.24	0.78	12
Total C (%)	19	17	19	18	3	9
Total N (%)	2.56	2.10	2.29	2.29	0.48	11
NO_3-N (g kg^{-1})	3.30	2.18	2.32	2.09	1.49	32
NH_4-N (g kg^{-1})	0.07b	0.09a	0.09a	0.09a	0.01	9
TMN (g kg^{-1})	3.37	2.27	2.41	2.18	1.49	31
Total P (g kg^{-1})	6.04	4.87	5.72	5.27	1.68	16
Bray-2 P (g kg^{-1})	2.75b	2.90ab	2.83ab	3.12a	0.29	5
C:N ratio	7.45	8.29	8.45	8.08	1.08	7
C:P ratio	33	36	34	35	11	17
Total K (g kg^{-1})	251a	165b	215ab	195ab	73	19
Available K (g kg^{-1})	60	59	64	63	9	8
Total Na (g kg^{-1})	5.03	5.29	6.20	5.29	1.21	12
Total Mg (g kg^{-1})	6.14a	4.20ab	4.58ab	4.01b	2.07	23
Total Ca (g kg^{-1})	55	41	45	40	16	19
Total B (g kg^{-1})	1.14	0.72	0.89	0.81	0.45	27
Total S (%)	0.27	0.19	0.25	0.19	0.13	32
Total Fe (mg kg^{-1})	1931	2196	3106	2194	1222	32
Total Mn (mg kg^{-1})	96	64	53	53	44	35
Total Cu (mg kg^{-1})	1.20a	0.80b	0.80b	0.80b	0.37	22
Total Zn (mg kg^{-1})	0.53	0.40	0.40	0.40	0.21	27
Total Cr (mg kg^{-1})	2.26	0.80	1.20	0.80	1.52	64
Total Al (g kg^{-1})	5.94a	3.22ab	3.29ab	2.63b	3.04	43
TPC (mg GAE g^{-1} DW)	1.62	1.74	1.72	1.61	0.39	13
NDF (%)	37	38	34	39	5	8
ADF (%)	50	51	49	47	7	8
ADL (%)	38	37	36	35	8	11

Means with the same letter(s) within a row are not significantly different at 5% probability level; where no letters are shown indicate no significant differences; INC1 and INC1.5 denote inoculated composts with pile size of 1.0 m and 1.5 m, respectively; UNC1and UNC1.5 denote uninoculated composts with pile size of 1.0 m and 1.5 m, respectively; EC = electrical conductivity; VS = volatile solids; WHC = water holding capacity; TPC = Total phenolic content; NDF = neutral detergent fibre; ADF = acid detergent fibre; ADL = acid detergent lignin; LSD = Least significant difference; CV = coefficient of variation

The VS content ranged from 49% (NIC1) and 54% (NIC1.5). The pH (KCl) values 9.68 to 9.76 for the composts revealed alkalinity, while the EC values of 9.03 to 10.23 dS m^{-1} suggested moderate variation albeit high salt contents among the composts. None of the C/N ratio, total C, N and measured minerals including metal content was significantly affected by compost pile size or its interaction with EM inoculation. However, EM inoculation and variation in compost types exerted significant effects on the total K, Mg, Al, and Cu content. The C/N ratio ranged from 7.45 (INC1) to 8.45 (INC1.5), total C ranged from 17% (UNC1) to 19% (INC1 and INC1.5), while total N varied between 2.10% (UNC1) and 2.56% (INC1). The total P content ranged from 4.87 g kg^{-1} (UNC1) to 6.04 g kg^{-1} (INC1), while the total K content in INC1 (251 g kg^{-1}) was significantly higher than in UNC1 (165 g kg^{-1}). Generally, the inoculated 1.0 m heap compost had quantitatively higher total C, N and P contents than the uninoculated 1.0 m compost pile, while the 1.5 m inoculated pile compost similarly had quantitatively higher total C, P, K and Na contents than the uninoculated compost pile.

Total micronutrients content of the composts ranged from 0.80 to 1.20 mg kg^{-1} for Cu, 1931 to 3106 mg kg^{-1} for Fe, 53 to 96 mg kg^{-1} for Mn, 0.40 to 0.53 mg kg^{-1} for Zn, and 0.72 to 1.14 mg kg^{-1} for B. The total Cr content ranged from 0.8 mg kg^{-1} (UNC1 = UNC1.5) to 2.26 mg kg^{-1} (INC1) whereas the As, Cd, Hg, Ni, and Pb concentrations were below the detection limits. The contents of NH_4-N and Bray-2 P differed significantly across the two compost pile sizes, while EM inoculation only exerted a significant effect on the composts Bray-2 P content. The inoculated 1.0 m compost pile had significantly lower amounts of NH_4-N than the remaining compost types. The contents of TMN, Bray-2 P and exchangeable K in the composts ranged from 2.18 to 3.37 g kg^{-1}, 2.75 to 3.12 g $kg^{-1}$and 59 to 64 g kg^{-1}, respectively. None of EM inoculation, compost pile size and their interaction showed significant effects on TPC and fibre fractions. The TPC ranged from 1.61 to 1.74 mg GAE g^{-1} DW, while fibre fractions in the composts ranged from 34 to 39%, 47 to 51% and 35 to 38%, respectively, for NDF, ADF and ADL. The results of the present study revealed that EM inoculation during composting had inconsequential effect on the TPC content relative to the value in original waste materials. Nevertheless, the TPC content was reduced by nearly 7% with EM inoculation in 1.0 m compost pile but increased by 7% in the 1.5 m pile.

3.3.3 Phyto-toxicity test of the WSW composts

The GI values of each of the three crop species at 10 and 25% extract concentrations were statistically similar, while the 50 and 100% concentrations gave statistically similar GI for cowpea (Figure 3.3). Extract concentration of 50% and above resulted in significantly reduced GI values in the three crops. The GI of maize and tomato showed a general decreasing trend with increasing compost extract concentration, while the cowpea GI at 25% extract concentration was marginally greater than the 10% concentration. There was no significant difference in the percent seed germination of cowpea seeds across the different compost types and extract concentrations, but the increasing extraction concentrations of the various compost types resulted in significant inhibition of maize and tomato seed germination attributes (Table 3.5). The mean maize root length across the various extract concentrations was higher than those of cowpea and tomato. The GI values ranged from 101 to 102% for cowpea, 97 to 105% for maize and 58 to 77% for tomato. Tomato seed GI obtained from inoculated 1.0 m compost pile was the highest and differed significantly from the GI value obtained from inoculated 1.5 m compost pile. The GI of all three crops at 50% extract concentrations and beyond were significantly reduced compared to the lower extract concentrations (Table 3.5; Figure 3.3).

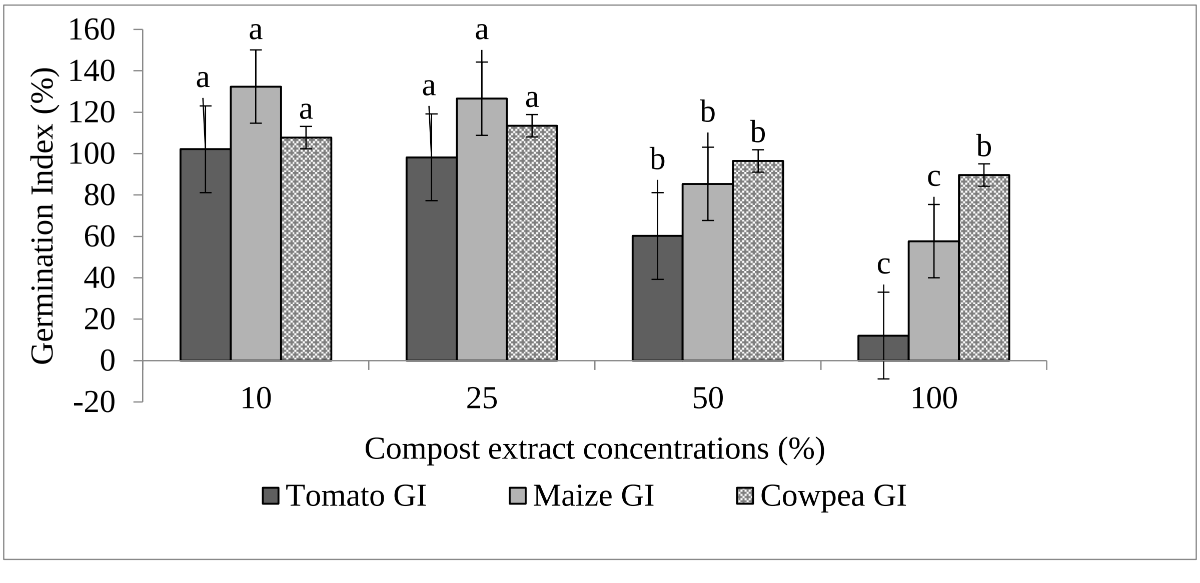

Figure 3.3: Effect of extract concentration on the GI of tomato, maize and cowpea across the compost types. Columns labelled with the same letter for each crop type are not significantly different at p≤0.05. The bars indicate standard errors of composts extract concentration.

Table 3.5: Interaction effect of compost type and compost extract concentration on seed germination, root growth, and germination index of cowpea, tomato and maize

Compost type	Extract concentration (%)	Seed germination (%)			Root length (%)			Germination index (%)		
		Cowpea	**Maize**	**Tomato**	**Cowpea**	**Maize**	**Tomato**	**Cowpea**	**Maize**	**Tomato**
INC1	10	100	87abcd	85ab	109abcd	132ab	149a	109abc	116abc	126a
	25	100	83abcd	81abc	110abc	148a	140ab	110abc	123ab	110ab
	50	100	80abcd	69abcd	92bcde	135ab	77ef	92bcde	106bcd	57cd
	100	100	50f	54def	97abcde	96d	25g	97abcde	48e	14ef
Mean		100	75	72	102	128	98	102	98	77A
UNC1	10	100	93ab	69abcd	106abcd	149a	125abc	106abcd	139ab	85bc
	25	100	93ab	77abcd	114a	152a	117bcd	114ab	143a	90bc
	50	100	90abc	85ab	88de	91d	93def	88cde	81cde	79bcd
	100	100	60ef	42ef	98abcde	97d	29g	98abcde	59e	13ef
Mean		100	84	68	101	122	91	101	105	67AB
INC1.5	10	100	97a	85ab	105abcd	155a	107cde	105abcd	149a	89bc
	25	100	83abcd	65bcde	114ab	134ab	131abc	114ab	114abc	88bc
	50	100	73cde	65bcde	103abcd	106bcd	68f	103abc	79de	46de
	100	97	73cde	38f	90cde	85d	24g	87de	62e	11f
Mean		99	82	63	103	120	83	102	101	58B
UNC1.5	10	100	97a	92a	110abc	130abc	117bcd	110abc	126ab	109ab
	25	100	90abc	73abcd	116a	140a	142ab	116a	126ab	105ab
	50	100	77bcde	73abcd	103abcd	99cd	81ef	103abcd	76de	60cd
	100	97	70de	58cdef	79e	90d	19g	77e	62e	10f
Mean		99	83	74	102	115	90	101	97	71AB
$LSD_{(0.05)}$		3	18	26	22	32	30	22	35	34
CV(%)		2	14	22	13	16	20	13	21	30

Means with the same letter(s) within the same column are not significantly different at 5% probability level; where no letters are shown indicate no significant differences; INC1 and INC1.5 denote inoculated composts with pile size of 1.0 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1.0 m and 1.5 m, respectively; LSD = Least significant difference; CV = coefficient of variation

The results of the correlation analysis between seed germination, root length, germination index, pH and EC are presented in Table 3.6. The pH of the compost extracts correlated negatively and significantly with the percent root length and percent GI of maizeand tomato, while the EC correlated negatively and significantly ($p<0.001$) with all the measured growth parameters of all crops.

Table 3.6: Results of correlation analysis between seed germination, root length, germination index, pH (H_2O), and electrical conductivity (EC)

Parameters	pH	EC
pH	1	
EC	0.35*	1
Cowpea seed germination	-0.11ns	-0.38**
Maize seed germination	-0.24ns	-0.66***
Tomato seed germination	-0.26ns	-0.66***
Cowpea root length	-0.22ns	-0.47***
Maize root length	-0.41**	-0.68***
Tomato root length	-0.50***	-0.87***
Cowpea germination index	-0.23ns	-0.50***
Maize germination index	-0.40***	-0.76***
Tomato germination index	-0.49***	-0.84***

*significant at $p<0.05$; **significant at $p<0.01$; ***significant at $p<0.001$, ns = not significant at $p<0.05$

3.4 Discussion

The non-significant effect of EM inoculation on the compost's measured physico-chemical parameters suggested that EM inoculation had no direct benefits on these quality indices. Albeit, it exerted indirect beneficial effects on hastening compost maturity and promoted compost sanitization through the extended thermophilic phase. This may be attributed to the rapid proliferation of EMs and microbial loading through the addition of molasses and high heat generation, which may have facilitated the decomposition of complex substrates including those rich lignin and cellulose (Jusoh et al. 2013). During the thermophilic phase, plant pathogens are destroyed (Hargreaves et al. 2008) while weed seeds and insect larvae are similarly killed (Chongrak & Koottatep 2017). The non-significant effect of variation in compost pile size on the measured physico-chemical properties of the WSW composts observed in this study resonates with earlier research by Sandra (2008). The recorded bulk densities for the composts were nearly 66% below the 1.0 g cm^{-3} maximum permissible limit prescribed by the Indian Fertilizer Control (Singh & Nain 2014). However, the considerably higher WHC of the composts above their actual weight observed in this study is in consonance with the previous studies (El-Nagerabi et al. 2011), which suggest their potential use in highly drained sandy soils to conserve water for plant growth. The strongly alkaline nature of the cured composts may be attributed to the high pH and higher amount of the perlite used than the other waste materials. Hence, the cautious use of any of these composts and the extracts as soil amendments to avoid extremely high soil pH and promote optimal plant nutrients availability for plant root growth (IPNI 2010). In this regard, the use on acidic soils may serve an additional role as liming material for increasing soil pH value. Similarly, utilization based on the experimentally optimum application rates is critical. The EC of compost as a quality parameter reflects its salinity content that largely influences its suitability for crop growth (Gómez-Brandón et al. 2008). The EC range of 1.0 to 10.0 dS m^{-1} in the cured composts is considered ideal (Composting Council 2010), while a threshold value of 1.0 dS m^{-1} is desirable for nursery substrate (Chong & Purvis 2004). Although the measured EC values are generally higher than the prescribed standard limit of 4.0 dS m^{-1} (El-Nagerabi et al. 2011; Singh & Nain 2014), they are lower than the range of 13.6 to 19.1 dS m^{-1} regarded as high as cited by Martínez-Nieto et al. (2011). Such high EC values may inhibit good water and nutrients absorption by salinity sensitive crops such as maize and tomato notwithstanding the variations in sensitivity. Based on the composts’ measured EC values, it is pertinent to apply caution in its utilization either as nursery substrate or soil amendments. This is because of the possible inducement of salt and/or organic acid stress in most plant seedlings (Liu et al. 2014), which may hinder plant growth (El-Nagerabi et al. 2011). Possible N and P release from the WSW composts into soil solution following application is expected due to their lower C/N ratios, which are below 20:1 (Gaskell et al. 2011). The less than 20:1 C/N ratio of the composts affirms the complete curing (Mangkoedihardjo 2006), while the greater than 12% total C content suggests that they are rich in C (Singh & Nain 2014) and could be a good C source for microorganisms (Gougoulias et al. 2014). The considerably high TMN, Bray-2 P and K contents in the composts with NO_3-N content constituting nearly 97% of TMN, further necessitates meticulousness in its usage to prevent any environmental pollution hazards, particularly NO_3-N contamination of ground water. The significant reduction in Bray-2 P caused by EM inoculation suggests lower activity of P solubilizing microorganisms and the increased consumption of P by other microorganisms introduced by the application of EM inoculant (Alori et al. 2017). The fact that these composts were free from metals (As, Cd, Hg, Ni and Pb) makes them potentially beneficial for direct application onto crop fields. Furthermore, the Cr contents in the composts were far below the prescribed acceptable threshold levels for India, European Union, United States, Germany, Belgium, Canada, and Sweden (CIWMB 2009; Mandal et al. 2014; Singh & Nain 2014).

The measured NDF and ADF contents in the WSW composts were generally lower than that from the raw waste materials, suggesting the degradation of these fibre fractions during composting. This resonates with the findings reported by Fazaeli and Masoodi (2006). The lower lignin (ADL) content in the composts could promote rapid nutrient mineralization when used as nutrient source in the soil (Dimambro et al. 2007). According to Cascant et al. (2016), besides reducing the volume of the final product, composting also gradually decreases the concentration of phenolic compounds. The observed decrease in TPC in EM inoculated 1.0 m pile and increase in 1.5 m EM inoculated pile may be attributed to the intensive microbial activity as shown by the longer stay of the 1.0 m compost in the thermophilic phase (>45°C) than the 1.5 m compost (Hachicha et al. 2006). Ghaly et al. (2011) attributed the lower degradation of phenolic compounds in the microbial inoculated compost to lower temperature and shorter thermophilic phase in comparison with uninoculated compost. The significantly reduced GI values of the three crops at extract concentrations greater than 50% suggest the presence of phyto-toxic compounds that impeded seed germination and root growth. However, the phyto-toxic effect instigated by the high Na content was lower in cowpea, and worst in tomato, which is more salinity-sensitive. The higher than 100% root length and GI values recorded at various extract concentrations for all the three crops also suggest that the composts serve as both phyto-nutrients and phyto-stimulants (Barral & Paradelo 2011). The greater than 80% mean GI value of cowpea and maize across the extract concentrations indicates the absence of phyto-toxicity (Emino & Warman 2004) and confirms that unlike tomato, these crops more tolerant and are less salinity sensitive. The observed risks of phytotoxicity of the composts and their extract (Martinez-Nieto et al. 2011) can be mitigated through various strategies. For instance, soil application at experimentally determined optimum rates could result in a dilution effect (Liu et al. 2014) or by restricting the use of these composts to acid soils to help increase the soil pH. Carballo et al. (2009) recommended the dilution of bovine manure teas with very high EC to reduce their phyto-toxicity. The significant but negative correlation observed between EC and growth parameters affirms that lowering the EC through dilution can reduce the salinity problem of the WSW composts.

3.5 Conclusions and recommendations

This study revealed that EM inoculation and compost pile size exerted inconsequential effects on WSW compost quality parameters. However, the addition of EM inoculant during composting provided the indirect benefits of an extended thermophilic phase that was much longer in the 1.0 m compost pile size, thus, promoting compost sanitization. Notwithstanding the potential fertilizer value of the WSW compost produced, the high EC values resulting from high soluble salts concentration specifically Na, constitutes risk for crops and soils. Although maize and tomato demonstrated varying degrees of phyto-toxicities particularly for the above 50% extract concentration, cowpea was completely devoid of phyto-toxicity to the different composts extract concentrations. Interestingly, the phyto-toxicity recorded in maize and tomato can be eliminated using lower application rates. The germination test for the three crop species also revealed the phyto-nutrient and phyto-stimulant nature of the compost extracts with root length and GI values greater than 100%. The low Cr concentrations and apparent absence of other heavy metals in the WSW composts eliminates the risks of their usage on croplands. Experimental studies to determine safe and optimum application rates of the WSW compost are hereby recommended.

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CHAPTER 4

In-field assessment of soil pH changes and mineralization of phosphorus and potassium following addition of winery solid waste compost in sandy loam Ferric Luvisol

Abstract

This study quantifies the amount and describes the patterns of phosphorus (P) and exchangeable potassium (K) release from winery solid waste (WSW) compost in sandy loam soil across two seasons. Treatments consisted of equivalent rates of 0, 5, 10, 20 and 40 t ha^{-1} of compost mixed with 900 g soil in Ziplock bags buried at 30 cm depth. The 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 increased soil pH by up to 9.5% while the remaining rates gave significantly higher soil pH values at the beginning of incubation in comparison to the un-amended soil. Net mineralized P and K contents measured were significantly ($p<0.05$) affected by compost rate and incubation period interaction. The compost rate exerted a significant ($p<0.05$) effect on the net mineralized and cumulative K released. Over the 126 days of the incubation period, mineralized P ranged from -62 to 86 mg kg^{-1} whereas mineralized K varied between 41 and 2047 mg kg^{-1}. While K mineralization from 5 and 10 tha^{-1} rates displayed no consistent pattern throughout the incubation period, a steady increase in K mineralization was recorded from 20 t ha^{-1} until 42 DAI. A steep increase in K mineralization from 40 t ha^{-1} rate occurred between 21 and 42 DAI accompanied by immediate sustained steady decrease until 105 DAI cutting across the summer and winter seasons. Conversely, momentary P immobilization from 5, 20 and 40 t ha^{-1} rates occurred, this was followed by mineralization until 84 DAI and resulted in a substantial cumulative net mineralized P content. Cumulative mineralized P and K contents were highest under the 40 t ha^{-1} and ranged from 62 to 207 mg kg^{-1} and 1272 to 9206 mg kg^{-1}, respectively, from the compost depending on application rate. The high net P and K mineralized contents suggest that WSW compost may act as P and K sink. However, its cautious use as soil amendment is crucial for mitigating potential resultant risks of soil pH increases, nutrient imbalance, toxicity and antagonistic effects of P and K on other plants nutrients.

Keywords: mineralized potassium; mineralized phosphorus; winery solid waste compost

4.1 Introduction

Grape growing and processing for winemaking results in significant amounts of solid wastes and wastewater. Winery solid organic waste materials include grapevine prunings and grape marc consisting of pressed skins, stalks, seeds, and pulps (Nerantzis & Tataridis 2006; Oliveira & Duarte 2016). The over-production and persistent increase of winemaking perpetuates the inappropriate disposal of these materials on agricultural land (Domínguez et al. 2014; Van Schoor 2005). Although the grape marc can be used as a nutrient-rich organic soil amendment, its direct application to soil can have negative effects on the environment (Domínguez et al. 2014; Sebaaly et al. 2017). Domínguez et al. (2014) suggested the use of vermicomposting waste treatment technology to minimize or eliminate the agronomic problems associated with the application of the raw grape marc to soil. 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 waste enables the wine sector to comply with environmental management system such as ISO 14000, which encourages the recycling of wastes (Oliveira & 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 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 an 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 & Murphy 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.

4.2 Materials and methods

4.2.1 Description of study site

A field incubation study was conducted during the 2018 summer and winter seasons at the North-West University Agriculture Farm (25°48’ S, 25°38’ E), Mafikeng, South Africa. The South African Weather Service (2018) provided data on the mean monthly minimum and maximum temperatures for Mafikeng during these seasons. 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).

4.2.2 Winery solid waste compost and soil used in this study

The WSW compost (INC1) used in this study was produced with effective microorganisms (EMs) inoculation and had an initial pile height of 1.0 m. The full details of the production process and physico-chemical characterization of this compost are provided in chapter 3. Briefly, the INC1 was produced through an aerobic-thermophilic composting process and had a pH (KCl) value of 9.69, 19% total C, 6.04 g kg^{-1} total P, and 251 g kg^{-1} total K. The surface soil (0-15 cm depth) used in this study was collected from the North-West University Agriculture Farm. Subsequent to soil collection, the soil was air-dried and passed through an 8-mm sieve to remove stones and plant debris. The physico-chemical properties of the soil were analyzed prior to the commencement of the study following standard laboratory procedures. 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 using an international classification under the FAO/UNESCO system.

4.2.3 Incubation and quantification of nutrients mineralized

The study was conducted during a 126-day period under field conditions using a buried-bag procedure (Figure 4.1; 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. The bags were zipped and buried at 30 cm depth. Destructive sampling was performed by removing one buried bag per treatmentat 0, 7, 21, 42, 63, 84, 105 and 126 DAI. At each sampling period, approximately 50 g of soil were sub-sampled from each bag and oven dried at 105°C for 24 hours to determine the gravimetric moisture content (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. The standard laboratory analyses procedures prescribed by the NASAWC (1990) were used to determine the pH (KCl), extractable P (Ambic-1) and exchangeable K (1 M NH_4OAc). 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 was recorded over the 126 days incubation duration.

Figure 4.1: (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.

4.2.4 Data analysis

Data on pH, moisture content, net and cumulative net contents of P and K were subjected to analysis of variance (ANOVA) using Statistical 9.4 computer software program 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.

4.3 Results and discussion

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

The net P and K contents were significantly ($p < 0.0001$) influenced by interaction effect of compost rate and incubation period (Figures 4.2). The net P content ranged from -62 to 86 mg kg^{-1} while the net mineralized K content varied between 41 and 2047 mg kg^{-1} over the 126 days incubation period. Initial P immobilization was observed from 5, 20 and 40 t ha^{-1} rates followed by a net P mineralization up to 84 DAI. Microbes might have taken up the released P at the beginning of incubation (Fening et al. 2010). Enwezor (1966) reported a similar finding. Waksman (1924) as (cited by Enwezor 1966) has shown that luxury absorption of P occurs when microorganisms grow in media of high P content. Phosphorus immobilization may also be due to excessive amounts of soluble and exchangeable Ca (555 mg kg^{-1}) in the soil due to reaction of $CaCO_3$ with orthophosphate anions to form a precipitate (Fuentes et al. 2006). Park et al. (2004) suggested that high levels of total P in soil amended with compost increased fixed-P form with Ca, Fe and Al. 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). This finding contradicts an earlier report by Gagnon et al. (2012), which states that the net P immobilization of 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 leass than 200.

Although there were no significant changes in the amounts of the net P and K released from 63 to 84 DAI, a general decrease of the net mineralized P was observed until 105 DAI in which maximum P immobilization occurred for 5, 10 and 40 t ha^{-1} rates. The maximum P immobilization for 20 t ha^{-1} occurred at the beginning of incubation. Although a considerable net P mineralization occurred at the end of incubation following immobilization at 105 DAI, studies by Akhtar and Alam (2001) and Boukhalfa-Deraoui et al. (2015) showed that soil

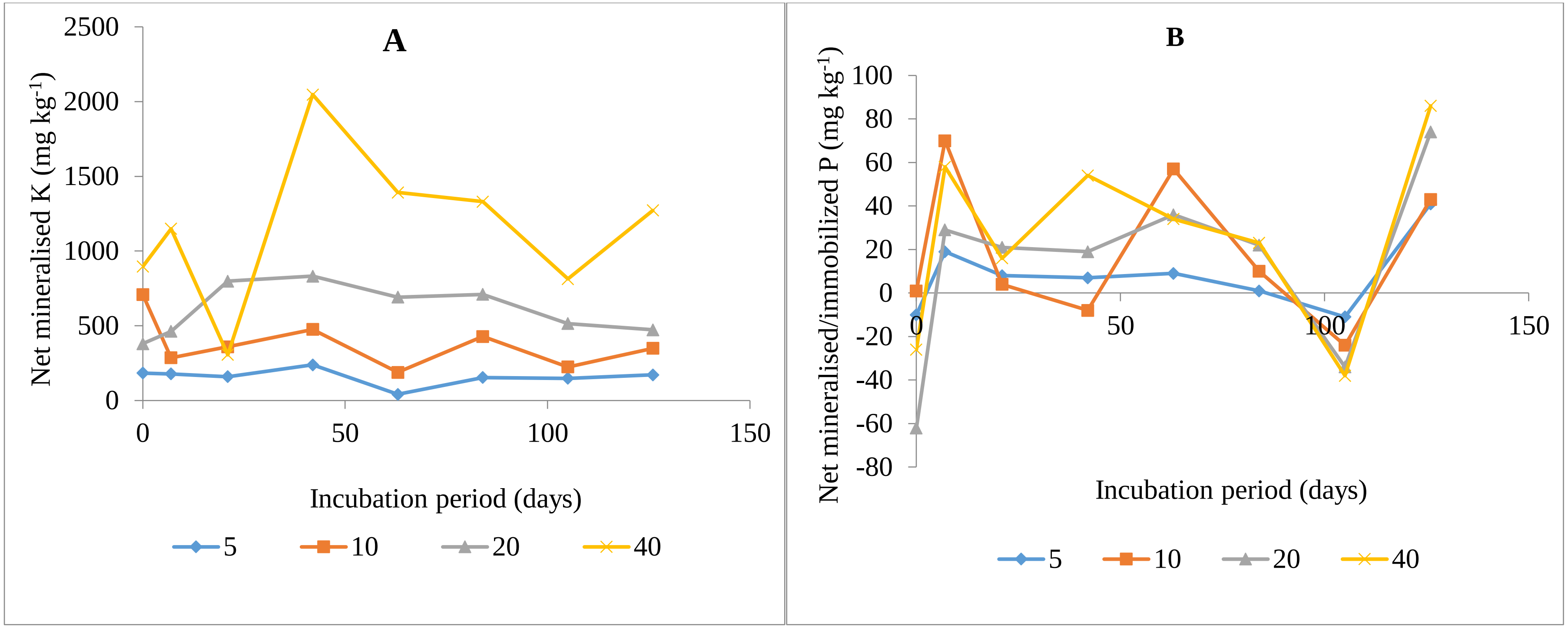

Figure 4.2: Effect of different rates of winery solid waste compost on (A) P mineralization (LSD = 47; CV = 203%) and (B) K mineralization over the incubation period of 126 days (LSD = 255; CV = 32%).

P availability decreased following application of organic and inorganic P sources with increasing time of incubation. 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 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 net mineralized P was highly variable (CV > 35%), while the net mineralized K was moderately variable with coefficient of variation of 15-35% (Wilding 1985).

4.3.2 Effect of compost rates on the net and cumulative P and K mineralized

Significant ($p<0.0001$) compost rate effects were observed only on the net and cumulative K mineralized (Figure 4.3B and D, respectively). The net and cumulative P are represented in Figure 4.3 A and C, respectively, and K released were lowest under the 5 t ha^{-1} rate but highest under the 40 t ha^{-1} rate. Cumulative net mineralized P ranged from 62 to 207 mg kg^{-1} while the cumulative net mineralized K varied between 1272 and 9206 mg kg^{-1}. The high net P and K mineralized may be associated with the high available P and K contents of WSW (Table 3.4, Chapter 3) and indicated the possible potential of WSW compost as P and K source. However, its cautious use as a soil amendment is necessary to avoid soil nutrient imbalance, toxicity and the possible antagonistic effects of P and K on other plants nutrients. Excessive P application can lead to plant toxicity with 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) have described how excess P in the soil causes Zn deficiency. The over application of K to the soil increases cation competition resulting in reduced uptake of NH_4, Ca and Mg by plants (Gransee & Führs 2013). The net mineralized K was higher than the threshold level of 62 mg kg^{-1} (Uzohu et al. 2007), and 80 to 120 mg kg^{-1} acceptable sufficiency level for maize (FSSA 2007). The net K content from

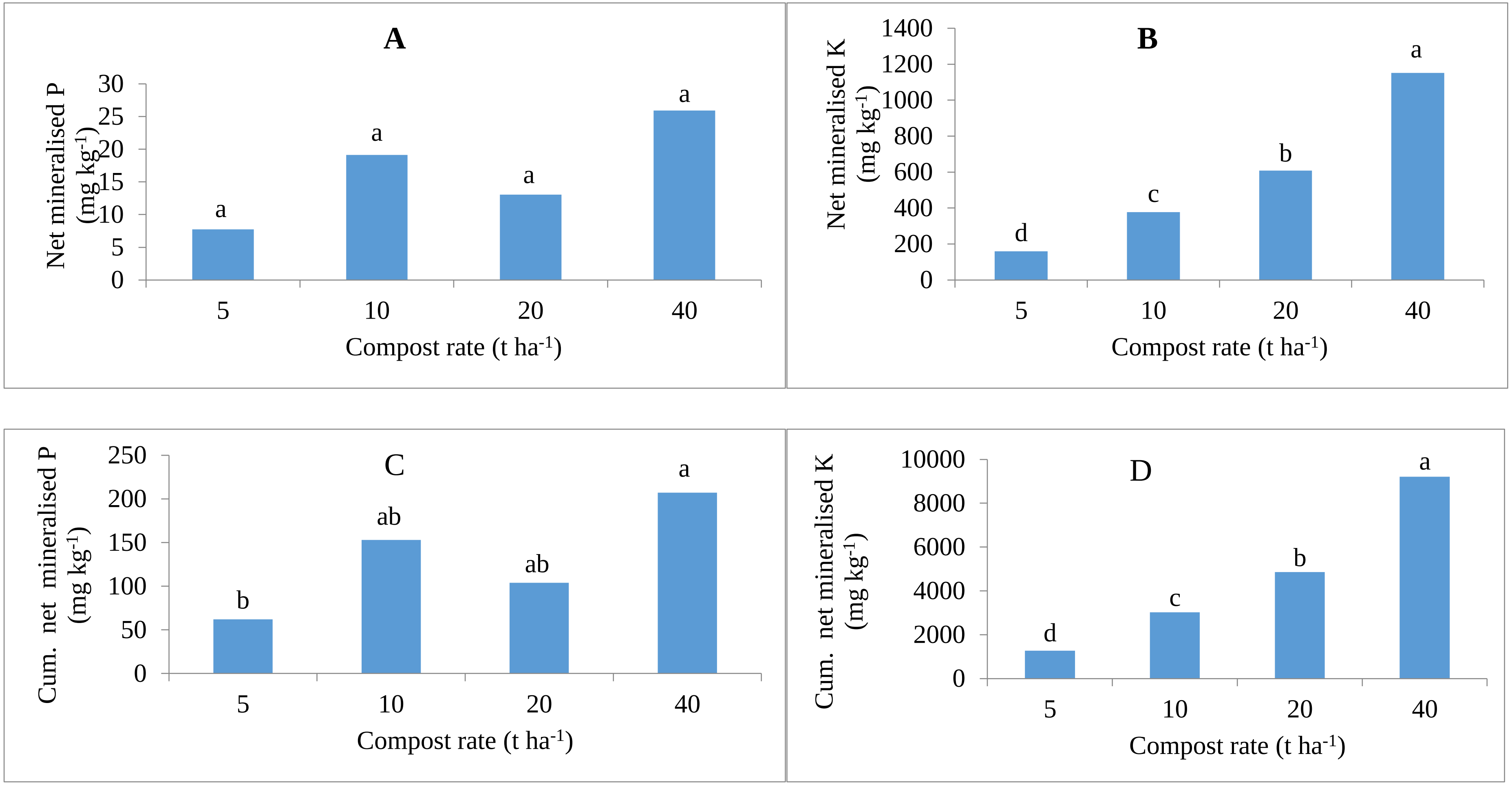

Figure 4.3: Effect of compost rate on the contents (A) net mineralized P (LSD = 22.13; $p<0.4026$; CV = 272%), (B) net mineralized K (LSD = 55; $p<0.0001$; CV = 55%), (C) cumulative net mineralized P (LSD = 105, $p<0.0538$, CV = 51%), and (D) cumulative net mineralized K across the incubation period (LSD = 769; $p<0.0001$; CV = 11%).

the 5 t ha^{-1} rate was approximately two times higher than the threshold level for maize while the remaining rates were approximately 6 to 18 times higher. The use of rates below 5 t ha^{-1} may be recommended when this compost is used as a K source in maize production. This finding of high K mineralization in this compost is in consonance with the results of earlier research (Kutu & Masowa 2018). Net and net cumulative mineralized P, net mineralized K across the incubation were mostly variable (CV > 35%) while the net cumulative mineralized K was least variable (CV < 15%) (Wilding 1985).

4.3.3 Interaction effect of compost rate and incubation period on soil pH and moisture content

Plant nutrient availability is regulated by the soil pH, which controls the chemical forms of the different nutrients and influences their chemical reactions (Oshunsanya 2019). The interaction of compost rate and incubation period had significant effects on soil pH and moisture content (Table 4.1). Soil pH ranged from 7.28 (0 t ha^{-1}; 0 DAI) to 8.18 (40 t ha^{-1}; 42 DAI). Compared to the untreated soil within each sampling day, the 40 t ha^{-1} rate significantly increased the soil pH by up to 9.50% throughout the incubation period while the remaining compost rates gave significantly higher soil pH values only at the beginning of incubation. This rise in soil pH after the addition of compost may be attributed strongly alkaline nature of this compost. Ebid et al. (2007) also recorded a rise in soil pH following the 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 very acidic soil may be helpful in increasing the soil pH. Soil pH generally increased with the increasing compost rate. However, the increases in pH were not always proportionate to the compost rates within each sampling day. There were no significant changes in soil pH from treatments with 0, 5, 20 and 40 t ha^{-1} throughout the incubation period. A similar observation was noted from a treatment with 10 t ha^{-1} compost, with the exception that the soil pH value recorded at 63 DAI was significantly lower as compared to that recorded at the beginning of the incubation and at 21 DAI.

Table 4.1: Interaction effect of compost rate and incubation period on pH (KCl) and percent gravimetric soil moisture content

	Incubation period (days)								
	Summer season				**Winter season**				
Rate (t ha^{-1})	**0**	**7**	**21**	**42**	**63**	**84**	**105**	**126**	***Mean***
					pH (KCl)				
0	7.28l	7.54ghijkl	7.57ghijkl	7.47ijkl	7.40ijkl	7.53ghijkl	7.35kl	7.62fghijkl	7.47
5	7.65efghijk	7.67defghijk	7.67defghijk	7.54ghijkl	7.44ijkl	7.62fghijkl	7.38jkl	7.61fghijkl	7.57
10	7.82bcdefgh	7.72defghij	7.83bcdefg	7.63fghijk	7.44ijkl	7.63fghijk	7.48hijkl	7.67defghijk	7.65
20	7.64efghijk	7.81bcdefgh	7.84bcdefg	7.65efghijk	7.73cdefghi	7.68defghijk	7.63fghijk	7.69defghij	7.71
40	7.86abcdefg	8.07abc	8.08ab	8.18a	7.97abcde	7.94abcdef	7.99abcd	7.97abcde	8.01
					Gravimetric moisture content (%)				
0	15.6fgh	19.2abcd	18.1abcdefg	17.8bcdefgh	16.9cdefgh	17.8bcdefgh	16.0efgh	15.8efgh	17.2
5	16.7cdefgh	18.2abcdefg	19.0abcde	17.2cdefgh	15.1gh	14.8h	20.9ab	18.0bcdefgh	17.5
10	16.2defgh	17.7bcdefgh	18.3abcdef	16.8cdefgh	15.8efgh	18.0bcdefgh	21.2a	16.3cdefgh	17.5
20	16.4cdefgh	18.6abcdef	17.4cdefgh	15.9efgh	17.9bcdefgh	16.9cdefgh	19.5abc	17.0cdefgh	17.5
40	17.6cdefgh	17.0cdefgh	17.3cdefgh	17.4cdefgh	17.5cdefgh	17.6cdefgh	17.3cdefgh	15.8efgh	17.2

pH: least significant difference value = 0.3399, $p<0.0001$, coefficient of variance = 1.57%; Gravimetric moisture content: least significant difference value = 3.1883, $p<0.0001$; coefficient of variance = 6.51%

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 4.2). Angelova et al. (2013) and Abreu-Jr et al. (2003) have previously established positive correlations of pH with P and K contents of the soil. The moisture content ranged from 14.8% (5 t ha^{-1}; 84 DAI) to 21.2% (10 t ha^{-1}; 105 DAI). Except at 105 DAI whereby the 5, 10 and 20 t ha^{-1} rates resulted in greater soil moisture contents, the different compost rates statistically exerted similar effects on soil moisture content within each sampling day. The 5 and 10 t ha^{-1} rates gave significantly higher soil moisture content than the 40 t ha^{-1} rate at 105 DAI. Negative and non-significant ($p<0.05$) correlations were given by the soil moisture content with the net and cumulative net mineralized P and K (Table 4.2). This indicated that the excessive soil moisture may negatively affect the mineralization of P and K from the WSW compost by influencing the microbial activity since soil microorganisms 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 & Wyszkowska 2016). In this regard, Torbert and Wood (1992) have proven that microbial activity decreased with the increase of water-filled pore space.

Table 4.2: Results of correlation analysis between net mineralized P and K, cumulative net mineralized P and K, soil pH and moisture content

Soil properties	pH	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)

4.4 Conclusions and recommendations

Soil nutrient management remains a crucial aspect of the maintenance of soil health and for sustainable crop production. Amending sandy loam soil with the winery solid waste compost 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 significant increase in soil pH following the application of 40 t ha^{-1} compost throughout the incubation period raises serious soil health concerns about the use of this compost on high pH soils. The 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 trials to evaluate different application rates lower than 5 t ha^{-1} under different climatic and soil conditions are therefore recommended.

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CHAPTER 5

Optimizing winery solid waste compost application rate for maize growth and dry matter yield, and effect on soil chemical properties

Abstract

A 4x7x2 factorial experiment was conducted under tunnel house conditions to determine the experimentally optimum rates of the winery solid waste (WSW) compost based on two mathematical models. The trial comprised of four WSW compost types applied at various rates (0, 5, 10, 20, 40, 80 and 100 t ha^{-1}) on two soils (Hutton and Glenrosa form soils) with different inherent characteristics. The results showed a general increase in stem girth, plant height, number of leaves per plant, dry matter yield (DMY) and distinct relative agronomic effectiveness following increasing compost rates. The different compost types and compost rates gave significantly higher shoot N, P, K, Na and Zn uptake than the untreated control. Microbial inoculation and variation of WSW compost with pile size did not induce significant effects on the maize performance and soil chemical properties. The WSW compost application of 80 t ha^{-1} and above resulted in an excessive increase in exchangeable soil-Na content by up to 175% that harmed the maize seedlings. The optimum rates predicted by the linear-plus-plateau model ranged from 11.78 to 26.03 t ha^{-1}, but varied between 28.16 and 39.53 t ha^{-1} with the quadratic model. The higher optimum WSW compost rate predicted by the quadratic model with few exceptions resulted in marginal increase in DMYs, unlike that predicted by the linear-plus-plateau model. This suggests the preference of the linear-plus-plateau model in predicting the optimum WSW compost rate for maize dry matter production.

Keywords: compost; dry matter yield; linear-plus-plateau model; quadratic model; soil nutrients; winery solid waste

5.1 Introduction

The decline in soil fertility and productivity are part of the major problems contributing to food and nutrition insecurities not only in South Africa, but also across sub-Saharan Africa. For instance, nearly 40% of the soil in these countries are low in nutrient capital reserves (<10% weatherable minerals), 25% suffer from aluminium toxicity, and 18% have a high leaching potential (Tully et al. 2015). The estimated net annual nutrients losses in SSA during 1993-1995 is 7629900 metric tons with South Africa losing 110900 metric tons (Henao & Baanante 1999). Nutrients depletion and organic matter decline in soils occurs due to continuous cultivation and inappropriate farming methods in these countries (Onduru et al. 2008). These factors are further exacerbated by smallholder farmers' poor management practices including little to none, or sub-optimal fertilizer uses (Kutu 2012). The depletion of soil nutrients is often swiftly ameliorated through the application of inorganic fertilizers. However, limited access to and high costs of inorganic fertilizers are some of the major constraints restricting the reliance on its use by smallholder farmers in SSA (Onduru et al. 2008; Kihara et al. 2016). The integrated use of chemical and organic sources such as manures and composts is widely recognized as a way of sustainably increasing crop productivity (Baghdadi et al. 2018). This strategy improves soil organic matter, soil structure, water holding capacity, nutrient cycling and cation exchange capacity and soil's biological activity (Mahmood et al. 2017). According to Erhart and Hartl (2010), regular compost addition also improves soil's conductivity against pests and diseases.

Wine production results in the generation of enormous amounts of by-products such as in organic wastes, wastewater, emission of greenhouse gases, and inorganic residues (Teixeira et al. 2014). The organic wastes produced during winemaking include grape pomace (seeds, pulp and skins, grape stems, and grape leaves), while the inorganic wastes include diatomaceous earth, bentonite clay, and perlite (Teixeira et al. 2014). Products resulting from the composting of these wastes have an immense potential to be used as sources of nutrients and organic matter (García-Martínez 2009; Masowa et al. 2018). Several studies have indicated the positive effects of the application of composted winery and distillery waste on various crops (García-Martínez 2009; Masowa et al. 2016; Raquel et al. 2018). However, there is a paucity of information regarding the determination of optimum application rates of WSW compost for judicious use on croplands. This is pertinent because the application of adequate amounts of nutrients is indispensable to the improvement of crop production (Alonso et al. 2016) as nutrients uptake takes place in optimal conditions when nutrients are adequately provided in balanced quantities in relation to the needs of plants (Sala et al. 2015). Mathematical models have been used to describe the response of crops to fertilization (Cerrato & Blackmer 1990; Bullock & Bullock 1994; Mahd 2008). Cerrato & Blackmer (1990) indicated that the reason for selecting one model over the others deserves more attention than it has received in the past when making decisions concerning amounts of fertilizer required for profitable crop production. Based on the foregoing, this study aimed to determine the optimum application rate of the WSW compost and their effects on maize performance and soil chemical properties. It was hypothesized that the predicted optimum WSW compost rate based on the use of a suitable mathematical model will improve maize performance and soil chemical properties.

5.2 Materials and methods

5.2.1 Description of study site

The pot experiment was conducted during the 2017/18 summer cropping season under tunnel house over a period of 7 weeks at the North-West University experimental Farm (25°48’ S, 25°38’ E), Mafikeng, South Africa. The maximum temperature of 28°C in the tunnel during the day was maintained using thermostatically activated fans and a wet wall cooling system.

5.2.2 Description of WSW compost production processes and compost analysis

The aerobic-thermophilic production process of the WSW compost types, and their physico-chemical properties have been presented in chapter 3. The WSW compost types produced comprised inoculated compost with an initial heap height (hereafter referred to as pile size) of 1 m (INC1), inoculated compost with pile size of 1.5 m (INC1.5), uninoculated compost with pile size of 1 m (UNC1), and uninoculated compost with pile size of 1.5 m (UNC1.5). The compost piles were prepared by mixing the filter materials and waste plant materials at the ratio of 40:60 on percent volume basis. The effective microorganisms (EM) inoculants was used for microbial inoculation. The pH (KCl) values of the composts ranged from 9.68 to 9.76 while the electrical conductivity varied between 9.03 and 10.23 dS m^{-1}. The measured total contents of N, P, K and Na in composts ranged from 1.23 to 1.80%, 4.87 to 6.04 g kg^{-1}, 2.10 to 2.56% and 5.03 to 6.20 g kg^{-1}, respectively.

5.2.3 Experimental design, treatments, and procedure

The pot study comprised of a 4×7×2 factorial experiment fitted in a randomized complete block design with the treatment factors comprising of four WSW compost types, with each applied at seven rates (0, 5, 10, 20, 40, 80 and 100 t ha^{-1} dry weight) in two different soils. Each treatment combination was replicated four times. Surface soils (0-15 cm) were collected from the cropland of the North-West University experimental Farm located in Mafikeng (25°48’ S, 25°38’ E) and from the farmer’s field in Ventersdorp (26.2774°S, 26.7614°E) both located in the North-West Province of South Africa. The soil from Mafikeng is classified as Hutton form, while the soil from Ventersdorp soil is classified as red apedal Glenrosa form based on the Soil Classification Working Group (1991). For the purpose of this study, the soils from Mafikeng and Ventersdorp will hereafter be referred to as Hutton and Glenrosa soils, respectively. Surface soil sample was collected to determine its physical and chemical properties prior to the commencement of the trial. The results showed that Hutton soil had 5.1% clay (hydrometer method), 0.42% organic C (Walkley-Black method), pH (H_2O) of 6.77, 6.95 mg kg^{-1} total mineral-N (0.5 M K_2SO_4), 80 mg kg^{-1} P (Bray-1), 235 mg kg^{-1} exchangeable K, 10 mg kg^{-1} exchangeable Na, 555 mg kg^{-1} Ca and 293 mg kg^{-1} Mg (1 N NH_4OAc). A sample of Glenrosa soil test values of 6.3% clay, 1.13% organic C, 6.06 pH (H_2O), 19.35 mg kg^{-1} total mineral-N, 75 mg kg^{-1} Bray-1 P, 168 mg kg^{-1} exchangeable K, exchangeable Na content of 5 mg kg^{-1}, and exchangeable Ca and Mg contents of 648 and 228 mg kg^{-1}, respectively (NASAWC 1990).

The air-dried soils were passed through a 6 mm sieve to remove stones and plant roots. Following this, the plastic pots (30 cm diameter) were filled with 12 kg of soil. Each compost type was mixed with the soil based on the calculated weight of soil used per pot and an assumption of weight of soil (2 million kg) per hectare furrow slice (Masowa et al. 2016). The holes at the bottom of each pot were blocked using a cotton wool to prevent soil losses. Pots were watered with municipal water, thereafter, allowed to equilibrate for 5 hours prior to sowing three seeds of maize (*Zea mays* L.) cv. WE6206B in each pot. Maize seedlings in each pot were thinned down to two seedlings after one week of seedling emergence. The pots received uniform irrigation throughout the period of plant growth. The trial was terminated at 7 weeks after planting by harvesting plant shoots.

5.2.4 Data collection

The morphological and chlorophyll content data were collected prior to harvesting the shoots. Chlorophyll content was measured around the midpoint of a healthy and longest leaf using a portable CCM-200 *plus* chlorophyll content meter (Opti-Sciences Inc, USA). The morphological data collected include the number of functional leaves per plant, plant height and stem diameter. The functional leaves per plant were counted manually. Plant height was measured using a measuring tape from the soil surface up to the tip of the highest leaf (Ayub et al. 2012). The stem diameter was measured 10 cm from the soil surface using a Vernier calliper and thereafter converted to girth using the equation 5.1 (Ukonze et al. 2016):

Stem girth = stem diameter × π (*pi*)…………………………………………… (Equation 5.1)

Maize shoots harvested from the soil surface using a sharp knife were washed with deionized water and oven-dried at 70°C to a constant weight for DMY determination. The computation of the relative agronomic effectiveness (RAE) followed the equation adapted from Law-Ogbomo et al. (2012):

RAE (%) = $(DMY_T - DMY_C)/(DMY_C)$……...………………………………… (Equation 5.2) whereby: DMY_T = maize dry matter yield from compost treated pots, DMY_C = maize dry matter yield from control pots.

For the determination of the total contents of shoot N, P, K, Na and Zn, shoots were ground to pass through 0.85 mm using a mill. Total N was determined titrimetrically following digestion of 1 g of sample in a sulfuric-salicylic acid mixture (Estefan et al. 2013). One gram of shoots from each pot was ashed at 500°C for 2 h in a furnace and then P, K, Na and Zn were extracted following procedures described by Okalebo et al. (2002). Afterwards, the total P content was determined following the vanadomolybdate yellow colorimetric method (Jackson 1964), while the concentrations of K, Na, and Zn in the aliquots were determined using an atomic absorption spectrophotometer. The nutrient uptake was estimated by multiplying the grain or biomass nutrient content with the dry matter yield (Upadhyay et al. 2012).

Post-harvest soil samples were collected, air-dried, and ground to pass through a 2 mm sieve, then analyzed for pH (H_2O), exchangeable Na content and electrical conductivity following procedures described by NASAWC (1990).

5.2.5 Data analysis

Data on plant growth, chlorophyll content, DMY, tissue nutrient analysis and soil chemical properties were subjected to analysis of variance (ANOVA) using the statistical analysis system (SAS) software 9.4. The differences among treatment means were separated by the Duncan Multiple Range test at $p<0.05$. The analysis of the correlations between maize growth parameters, dry matter yield, shoot nutrient content and uptake, and soil chemical properties was done using the IBM SPSS Statistics software (Version 23). Linear-plus-plateau and quadratic polynomial models were fitted to the DMY data using the NLIN and PROC REG procedures of SAS software 10.0, respectively, to determine the optimum application rate and DMY (Cerrato & Blackmer 1990; Moswatsi et al. 2013). The quadratic model is defined by equation 5.3 below:

$$Y = a + bX + cX^2 \quad \text{(Equation 5.3)}$$

whereby: Y = dry matter yield (g pot^{-1}); X = application rate (t ha^{-1}); a (intercept); b (linear coefficient); and c (quadratic coefficient) (Moswatsi et al. 2013).

The linear-plus-plateau is defined by equation 4 below:

$Y = a + bX$……………………………………………….………… (Equation 5.4)
If X is less than C
$Y = P$………………………………………………………………….. (Equation 5.5)
if X is greater and equal C

whereby: Y = dry matter yield (g pot^{-1}); X = application rate (t ha^{-1}); a (intercept); b (linear coefficient); b (linear coefficient), C (critical rate of fertilization, which occurs at the intersection of the linear response and the plateau lines), and P (plateau yield) are constants obtained by fitting the model to the data (Cerrato & Blackmer 1990).

5.3 Results

5.3.1 Treatments and their interaction effects on growth attributes, chlorophyll content, DMY and RAE

Significant interaction effect of soil type, compost type and compost rate on the number of functional leaves per plant and RAE was observed (Table 5.1). The mean number of functional leaves per plant ranged from 7.75 (untreated control) to 11.62 (INC1 at 40 t ha^{-1}) under the Hutton soil, and from 9.62 (untreated control) to 13 (UNC1 and INC1.5 applied at 40 t ha^{-1}) under the Glenrosa soil. In most cases, the 20 and 40 t ha^{-1} rates gave significantly higher mean number of functional leaves per plant than the 5 and 10 t ha^{-1} rates. However, the 20 and 40 t ha^{-1} rates were statistically at par in their effects on the number of functional leaves per plant. Except for INC1 at 5 t ha^{-1} under the Hutton soil, the remaining treatments gave significantly higher values of mean number of functional leaves per plant in comparison to the control of each soil type. The RAE values ranged from 34% with INC1 (5 t ha^{-1}) to 165% with UNC1 (40 t ha^{-1}) under the Hutton soil, and from 34% with UNC1.5 (5 t ha^{-1}) to 80% with INC1.5 (40 t ha^{-1}) under the Glenrosa soil. The RAE values obtained from the 20 t ha^{-1} rate were significantly higher than those recorded at 5 and 10 t ha^{-1} under Hutton soil. Similar results were recorded from the 40 t ha^{-1} rate except under the INC1 treatment in which the 10 t ha^{-1} rate was statistically at par with it under the Hutton soil. An increase in the application rate of each compost type from 20 to 40 t ha^{-1} within each soil type did not result in significant difference in the RAE value.

Table 5.1: Interaction effect of soil type, compost type and compost rate on the number of functional leaves per plant and relative agronomic effectiveness

Treatments	**Application rate (t ha^{-1})**	**NFLP**		**RAE (%)**	
		Hutton soil	**Glenrosa soil**	**Hutton soil**	**Glenrosa**
INC1	5	8.00hi	11.00de	34f	50ef
	10	9.87f	11.00de	81de	53ef
	20	11.12de	12.00bc	142abc	67ef
	40	11.62cd	12.75ab	153ab	74def
UNC1	5	8.62gh	11.00de	51ef	43ef
	10	9.75f	11.37cde	72def	52ef
	20	10.75e	12.00bc	127abc	67ef
	40	11.25cde	13.00a	165a	68ef
INC1.5	5	9.25fg	10.75e	56ef	40ef
	10	9.62f	11.25cde	70def	42ef
	20	11.00de	12.50ab	124bc	67ef
	40	11.00de	13.00a	111cd	80ed
UNC1.5	5	9.12fg	10.87de	46ef	34f
	10	9.50f	11.25cde	78de	46ef
	20	11.00de	11.62cd	119bc	69ef
	40	10.87de	12.75ab	122bc	71def
Control	0	7.75i	9.62f	-	-
p-value		0.032		<0.001	
CV (%)		4.55		32.75	

Means with same letter(s) for each variable are not significantly different at 5% probability level. INC1 and INC1.5 denote inoculated composts with 1 m and 1.5 m pile size, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively; NFLP = number of functional leaves per plant; RAE = relative agronomic effectiveness; CV = coefficient of variance

The interaction effect of soil type and application rate significantly influenced the number of functional leaves per plant (Figure 5.1A) and DMY (Figure 5.1B). The highest value of mean number of functional leaves per plant was recorded from 40 t ha^{-1} rate (12.88) under the Glenrosa soil, while the lowest value was obtained from the untreated control (7.75) under the Hutton soil. The DMY given by the 20 and 40 t ha^{-1} rates in each soil type were statistically at par and higher than that given by the remaining rates.

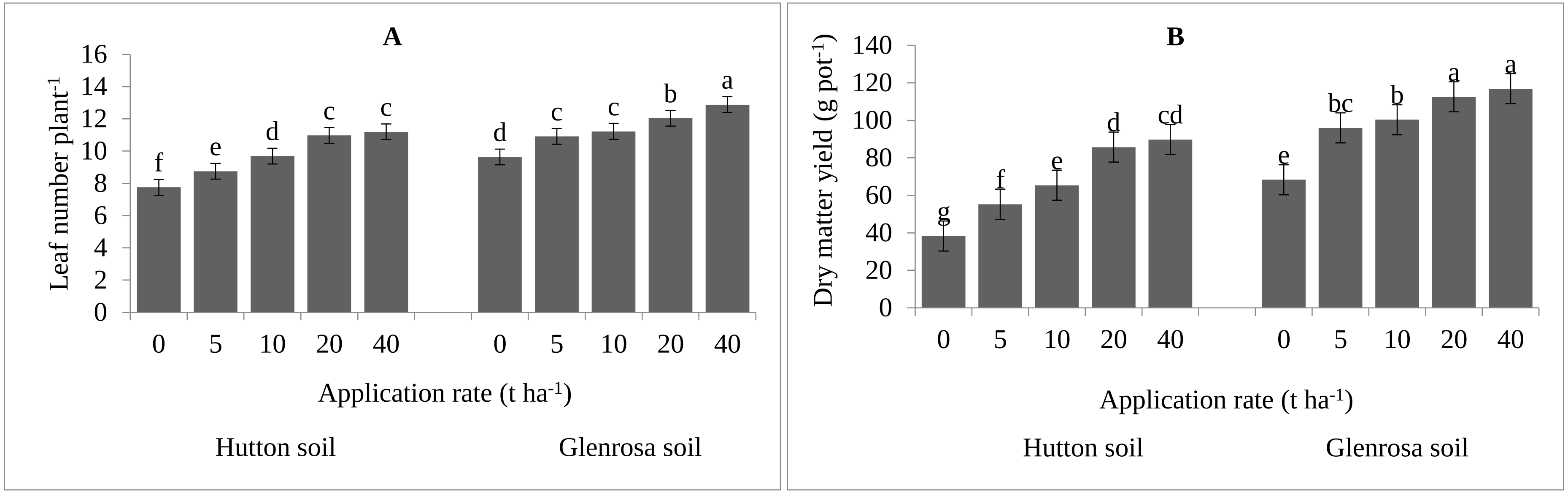

Figure 5.1: Interaction effect of soil type and application rate on the (A) number of functional leaves per plant ($p < 0.001$) and (B) dry matter yield ($p = 0.011$). The bars indicate standard error of treatment mean.

The measured plant growth attributes and DMY were significantly influenced by the soil type, compost type and application rate while chlorophyll content and RAE were influenced by the compost type and application rate (Table 5.2). Plants grown on Hutton soil had higher mean number of functional leaves per plant, but had thicker stems, taller stalks and higher DMY when grown on Glenrosa soil. The different composts significantly improved the number of functional leaves per plant, chlorophyll content, stem girth, plant height and DMY relative to the control. The compost types did not differ with each other in their effects on maize growth parameters, DMY, chlorophyll content and RAE. In general, the chlorophyll content, mean number of functional leaves per plant, plant height, DMY and RAE increased with increasing compost rates.

Table 5.2: Effect of soil type, compost type and compost application rate on maize growth, dry matter yield, chlorophyll content and relative agronomic effectiveness

Treatments	**NFLP**	**LCC (CCI)**	**Stem girth (mm)**	**Plant height (cm)**	**DMY (g pot^{-1})**	**RAE (%)**
Soil type						
Hutton soil	11.63a	5.22a	58b	117b	71b	97a
Glenrosa soil	10.00b	5.90a	64a	135a	104a	58b
p-value	<0.001	0.069	<0.001	<0.001	<0.001	<0.001
Compost type						
INC1	10.92a	5.73a	62a	128a	92a	82a
UNC1	10.96a	5.48a	61a	128a	91a	81a
INC1.5	11.04a	5.81a	61a	127a	88a	74a
UNC1.5	10.87a	5.08a	61a	126a	88a	73a
Control	8.68b	3.5b	53b	104b	53b	-
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.462
Compost rate (t ha^{-1})						
0	8.68e	3.50c	53c	104d	53d	-
5	9.82d	4.02c	60b	119c	75c	44c
10	10.45c	4.22c	60b	121c	82b	62b
20	11.5b	5.53b	63a	131b	99a	98a
40	12.03a	8.33a	64a	140a	103a	106a
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with same letter(s) within a column and treatment are not significantly different at 5% probability level. INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively; NFLP = number of functional leaves per plant; LCC = leaf chlorophyll content; DMY = dry matter yield; RAE = relative agronomic effectiveness

5.3.2 Treatments and their interaction effects on nutrient content and uptake of maize shoots

The effect of soil type, compost type and compost application rate on nutrient content of maize shoots is indicated in Table 5.3. Shoots of plants grown on Hutton soil had significantly lower total N and P contents of but higher total Na and Zn contents than those of plants grown on

Glenrosa soil. The total N, K and Na contents in maize shoot were significantly affected by compost type relative to the control treatment. However, total N, K and Na contents were not significantly affected by compost type. The total contents of N, K and Zn increased with the increasing rates.

Table 5.3: Effect of soil type, compost type and compost application rate on maize shoots nutrient content

Treatments	**N**	**P**	**K**	**Na**	**Zn**
			(%)		**(mg kg^{-1})**
Soil type					
Hutton soil	0.54b	0.16b	2.68a	0.09a	25a
Glenrosa soil	0.65a	0.22a	2.78a	0.06b	17b
p-value	<0.001	<0.001	0.072	<0.001	<0.001
Compost type					
INC1	0.62a	0.18a	2.77a	0.08a	22a
INC1.5	0.60a	0.18a	2.77a	0.07a	21a
UNC1	0.63a	0.19a	2.78a	0.08a	22a
UNC1.5	0.58a	0.19a	2.79a	0.07a	20a
Control	0.45b	0.20a	1.93b	0.04b	19a
p-value	0.001	0.142	<0.001	0.040	0.467
Compost rate (t ha^{-1})					
0	0.45c	0.20a	1.93d	0.04c	19b
5	0.46c	0.19ab	2.17c	0.07b	18b
10	0.49c	0.19ab	2.34c	0.06bc	18b
20	0.62b	0.19ab	2.84b	0.08ab	21b
40	0.86a	0.18b	3.77a	0.09a	27a
p-value	<0.001	0.433	<0.001	0.002	<0.001

Means with the same letter(s) within a column and treatment are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively

The interaction effect of compost type and application rate significantly affected the shoot N, K and Zn contents (Table 5.4). In comparison to the untreated control, the 20 and 40 t ha^{-1} rates of all compost types significantly increased the shoot N content. The shoot N content recorded from the 40 t ha^{-1} of compost was significantly higher than that obtained from the other compost rates. The application of all compost types at 20 and 40 t ha^{-1}, and UNC1 and UNC1.5 at 10 t ha^{-1} increased the shoot K content when compared to the untreated control. The 40 t ha^{-1} rate gave the highest shoot K content, followed by the 20 t ha^{-1} rate. Treatments with the INC1, INC1.5 and UNC1 applied at 40 t ha^{-1} gave significantly higher shoot Zn content than the untreated control.

Table 5.4: Interaction effect of compost type and application rate on maize shoot nutrient content

Compost type	Compost rate (t ha^{-1})	N (%)	K (%)	Zn (mg kg^{-1})
INC1	5	0.48ef	2.23de	21cde
	10	0.51def	2.27de	18e
	20	0.60cd	2.74bc	22bcde
	40	0.89ab	3.84a	28ab
INC1.5	5	0.44f	2.14de	19cde
	10	0.48ef	2.31de	19de
	20	0.68c	2.98b	21bcde
	40	0.83ab	3.67a	26abc
UNC1	5	0.45f	2.17de	18e
	10	0.49ef	2.31d	19de
	20	0.64c	2.83bc	21bcde
	40	0.93a	3.81a	29a
UNC1.5	5	0.46f	2.13de	16e
	10	0.48ef	2.48cd	18e
	20	0.57cde	2.81bc	21bcde
	40	0.80b	3.75a	25abcd
Control	0	0.45f	1.93e	19de
p-value		<0.001	<0.001	<0.001

Means with the same letter(s) within a column are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively

The soil type and compost type interaction showed significant effect on the contents of shoot N, P, Na and Zn (Figure 5.2A-D). The compost types exerted similar effects on shoot N and Na content in each soil type. However, all the compost types increased shoot Na content under the Glenrosa soil, whereas only INC1 and UNC1.5 gave significantly higher shoot Na content under Hutton soil when compared to the untreated control. The different WSW compost types and the untreated control under the Glenrosa soil gave significantly higher shoot P content than under the Hutton soil. The untreated control treatment of each soil type gave the shoot Zn content that was statistically comparable to that given by the different compost types. The contents of N, P, K, Na and Zn in maize shoots were significantly affected by the interaction effect of soil type and application rate (Figure 5.3A-E). For each soil type, the 40 t ha^{-1} gave highest shoot N content than the other compost rates. An insignificant decrease in shoot P content with increasing compost rate was observed under the Hutton soil. The shoot K content showed a pattern of increase with increasing compost rate. The 40 t ha^{-1} rate gave significantly higher shoot K content than the other rates in each soil type. The shoot Zn content recorded from the 40 t ha^{-1} rate was significantly higher than those recorded from the 5 and 10 t ha^{-1} rates under the Hutton soil.

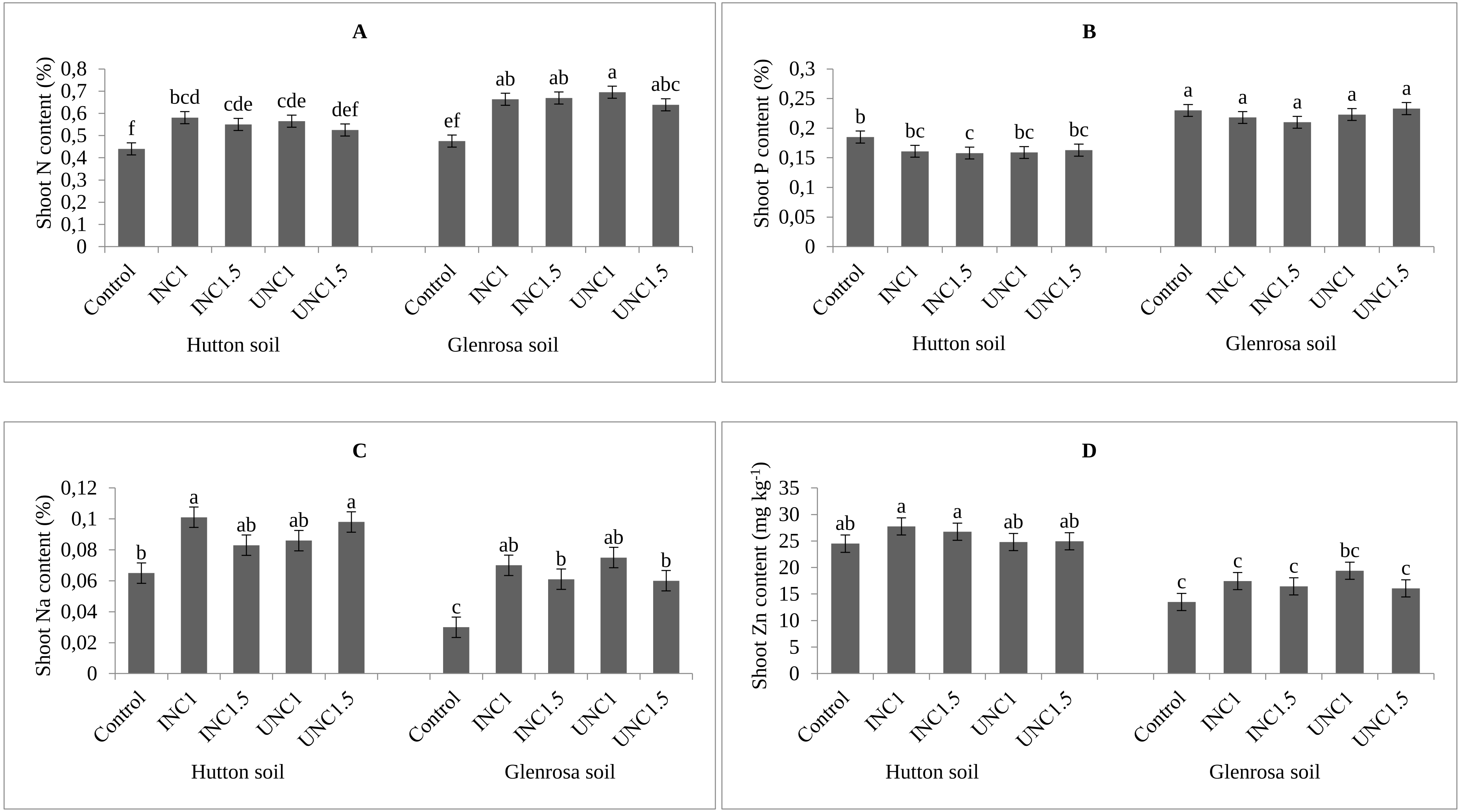

Figure 5.2: Soil type and compost type interaction effect on the contents of shoot (A) nitrogen ($p < 0.001$), phosphorus ($p <0.001$), (C) sodium ($p = 0.001$) and (D) zinc ($p <0.001$). The bars indicate standard error of treatment mean.

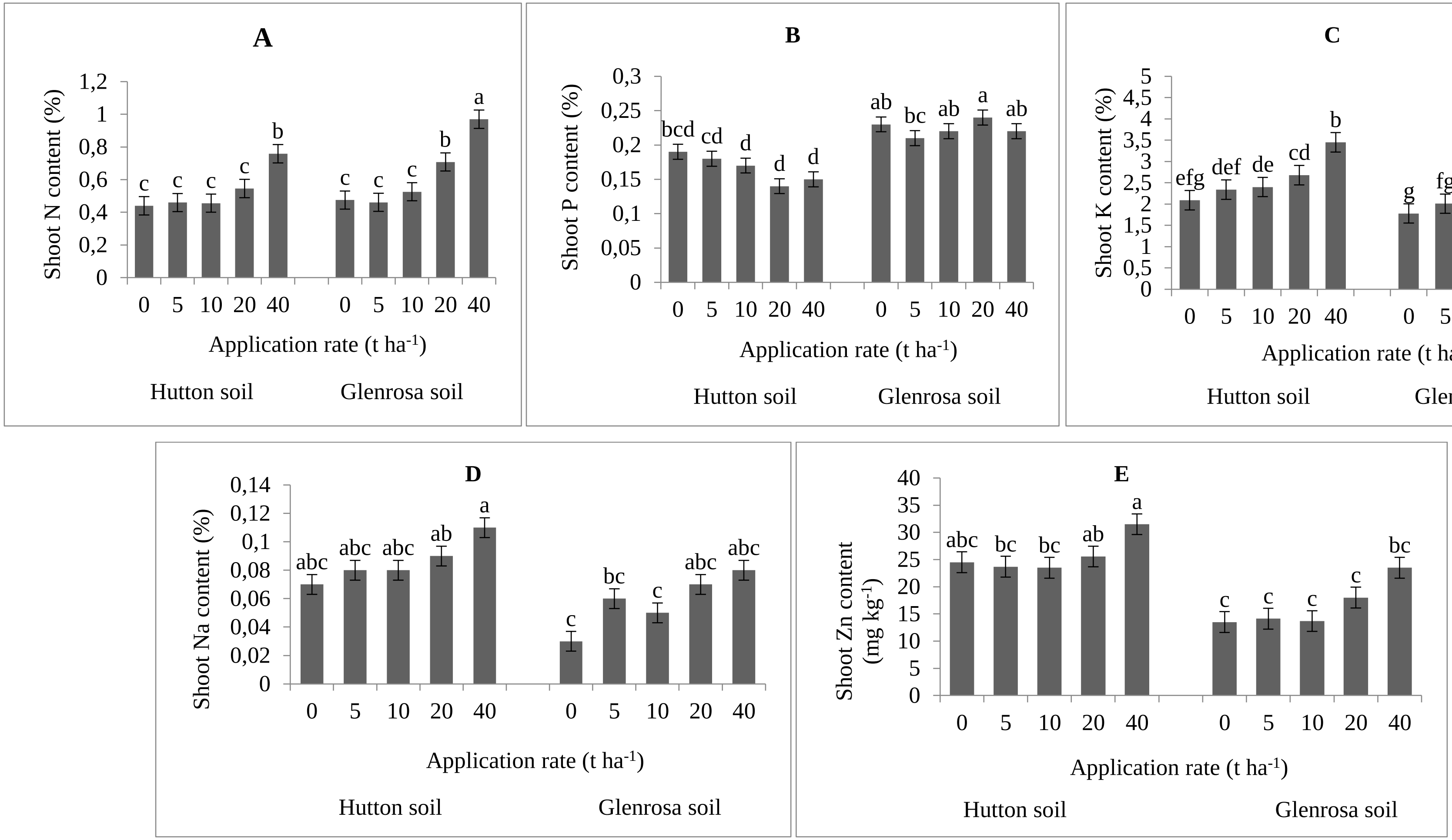

Figure 5.3: Interaction effect of soil type and application rate on the contents of shoot (A) nitrogen, (B) phosphorus, (C) potassium, (D) sodium and (E) zinc ($p < 0.001$). The bars indicate the standard errors of treatment mean.

The effect of soil type, compost type and compost application rate on maize shoot nutrient uptake is indicated in Table 5.5. The uptake of N, P and K was significantly higher in shoots of plants grown on Glenrosa than on Hutton soil. The compost type significantly affected uptake of N, P, K, Na and Zn by maize shoot relative to the control treatment. However, N, P, K, Na and Zn uptake were not affected by compost type. In general, the uptake of N, K and Zn increased with the increasing rates.

Table 5.5: Effect of soil type, compost type and compost application rate on maize shoots nutrient uptake

	N	P	K	Na	Zn
Treatments	(g pot^{-1})				(mg pot^{-1})
Soil type					
Hutton soil	0.41b	0.11b	1.98b	0.06a	1.90a
Glenrosa soil	0.70a	0.23a	2.98a	0.06a	1.81a
p-value	<0.001	<0.001	<0.001	0.775	0.399
Compost type					
INC1	0.59a	0.17a	2.63a	0.07a	2.03a
INC1.5	0.56a	0.16a	2.52a	0.06a	1.84a
UNC1	0.60a	0.17a	2.61a	0.07a	2.02a
UNC1.5	0.53a	0.18a	2.53a	0.06a	1.77a
Control	0.24b	0.11b	1.00b	0.02b	0.92b
p-value	<0.001	<0.001	<0.001	0.001	0.001
Compost rate (t ha^{-1})					
0	0.24d	0.11c	1.00e	0.02c	0.92d
5	0.34c	0.14b	1.60d	0.05b	1.32c
10	0.41c	0.16b	1.93c	0.05b	1.45c
20	0.63b	0.19a	2.83b	0.08a	2.11b
40	0.90a	0.19a	3.93a	0.09a	2.77a
p-value	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter(s) within a column and treatment are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively

The interaction of soil type and compost type showed significant effect on the shoot uptake of N, P and K (Figure 5.4A-C). The different compost types (within each soil type) were statistically comparable to each other in their effects on shoot N uptake and gave significantly higher shoot N uptake than the untreated control. Comparable results were observed for P and K uptake. The shoot N, P, K, Na and Zn uptake showed a trend of increase with increasing compost rates under the Hutton soil (Figure 5.5A-E). The same trend was observed under the Glenrosa soil except for P and Na uptake in which the values of P and Na uptake from 40 and 10 t ha^{-1} rates were lower than those recorded from the 20 and 5 t ha^{-1} rates, respectively.

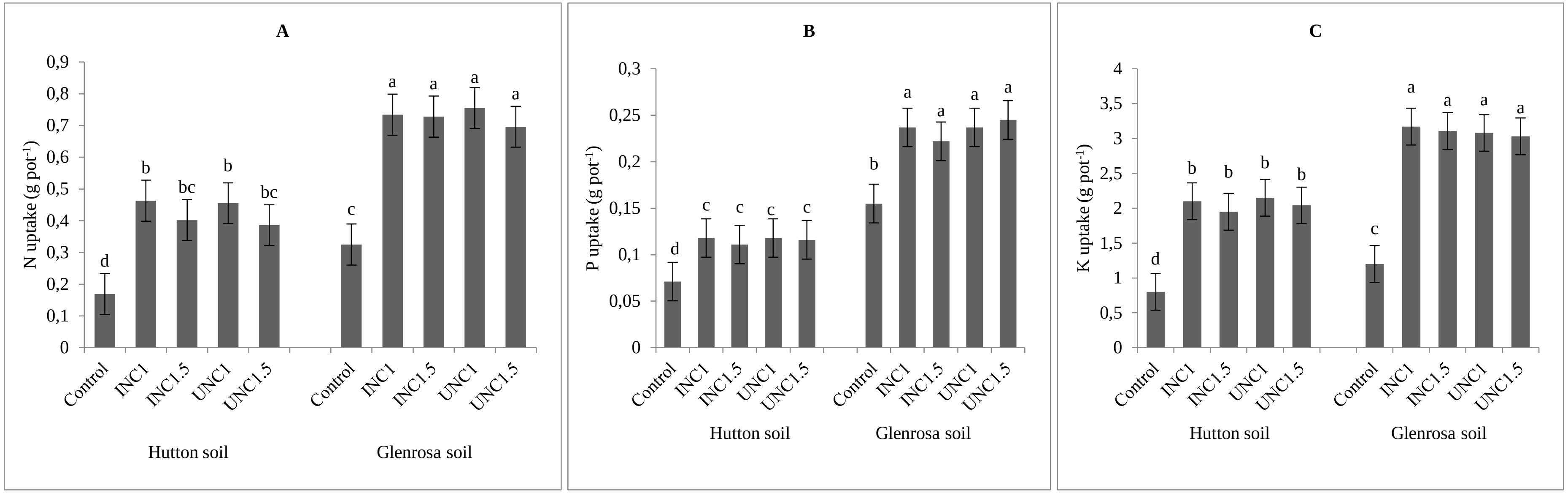

Figure 5.4: Interaction effect of soil type and compost type on the shoot (A) nitrogen, (B) phosphorus and (C) potassium uptake ($p < 0.001$). The bars indicate the standard error of treatment mean.

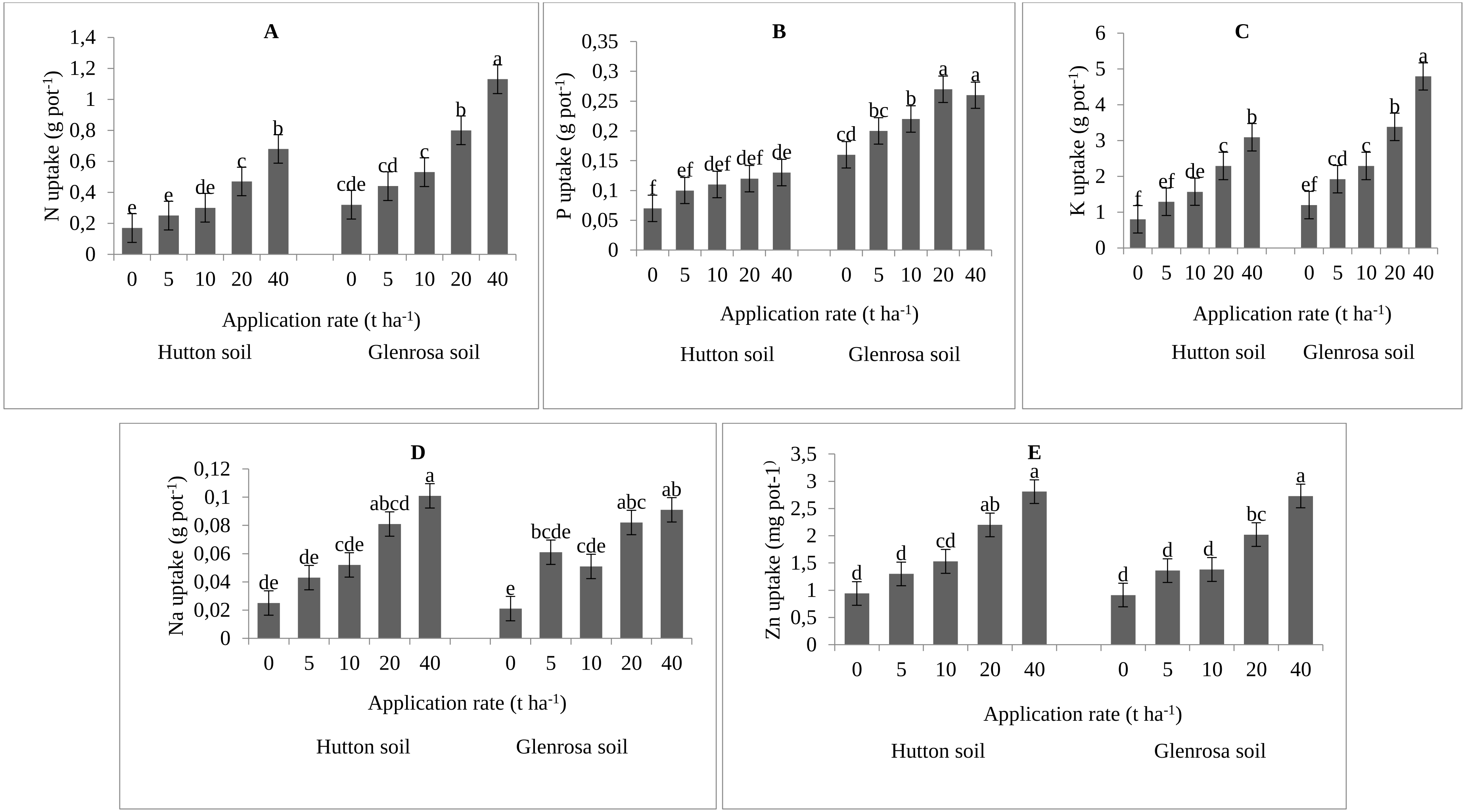

Figure 5.5: Interaction effect of soil type and application rate on the uptake of (A) nitrogen, (B) phosphorus, (C) potassium, (D) sodium and (E) zinc ($p < 0.001$). Bars indicate the standard error of treatment mean.

The interaction effect of compost type and application rate on the shoot N, P K, Na and Zn uptake was significant (Table 5.6). The 40 t ha^{-1} of UNC1 gave the highest shoot N uptake that was statistically at par with that recorded from the 40 t ha^{-1} of INC1. The shoot N uptake was significantly increased following the application of INC1, UNC1 and UNC1.5 at 10, 20 and 40 t ha^{-1} and INC1.5 at 20 and 40 t ha^{-1} with reference to the untreated control. The shoot K uptake from the 40 t ha^{-1} of compost was highest, followed by the 20 t ha^{-1} of compost. The application of compost at 20 and 40 t ha^{-1} resulted in significantly higher uptake of Na and Zn uptake than the untreated control.

Table 5.6: Interaction effect of compost type and application rate on maize shoot nutrient uptake

Compost	**Application rate**	**N**	**P**	**K**	**Na**	**Zn**
	(t ha^{-1})		**(g pot^{-1})**			**(mg pot^{-1})**
INC1	5	0.36	0.15	1.63	0.056	1.44
	10	0.44	0.16	1.93	0.055	1.51
	20	0.62	0.18	2.81	0.103	2.24
	40	0.95	0.20	4.16	0.100	2.95
INC1.5	5	0.34	0.14	1.61	0.048	1.38
	10	0.38	0.15	1.83	0.047	1.42
	20	0.68	0.20	2.95	0.071	2.07
	40	0.84	0.16	3.70	0.084	2.46
UNC1	5	0.34	0.15	1.63	0.054	1.32
	10	0.41	0.16	1.92	0.053	1.49
	20	0.65	0.19	2.81	0.076	2.09
	40	1.00	0.19	4.09	0.113	3.17
UNC1.5	5	0.33	0.14	1.53	0.052	1.15
	10	0.40	0.17	2.04	0.052	1.39
	20	0.57	0.19	2.76	0.078	2.04
	40	0.83	0.20	3.78	0.088	2.48
Control	0	0.24	0.11	1.00	0.023	0.92
p-value		<0.001	<0.001	<0.001	<0.001	<0.001
SEM		0.035	0.008	0.137	0.0036	0.086

Means with the same letter(s) within a column are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively; SEM = standard error of mean

Shoot N, P, and K contents as well as the shoot uptake of N and K were significantly influenced by the interaction of soil type, compost type and compost rate (Table 5.7). The highest values of shoot N, P and K contents (1.09%, 0.250% and 4.28%, respectively) were obtained from the treatments with the 40 t ha^{-1} of UNC1, UNC1.5, and INC1 respectively, under the Glenrosa soil. The highest values of shoot N, P and K contents (1.09%, 0.250% and

Table 5.7: Interaction effect of soil type, compost type and compost rate on maize shoots nutrient content and uptake

Treatments	Rate	Nutrient content (%)			Nutrient uptake (g pot^{-1})	
	(t ha^{-1})	N	P	K	N	K
Hutton soil						
INC1	5	0.48	0.195	2.52	0.24	1.27
	10	0.46	0.170	2.30	0.30	1.53
	20	0.55	0.135	2.53	0.50	2.30
	40	0.84	0.145	3.42	0.80	3.28
UNC1	5	0.44	0.185	2.35	0.25	1.34
	10	0.48	0.165	2.37	0.30	1.51
	20	0.57	0.145	2.78	0.49	2.36
	40	0.78	0140	3.38	0.77	3.37
INC1.5	5	0.45	0.170	2.23	0.26	1.29
	10	0.45	0.160	2.38	0.28	1.51
	20	0.53	0.150	2.73	0.44	2.30
	40	0.78	0.150	3.44	0.61	2.69
UNC1.5	5	0.47	0.175	2.27	0.25	1.24
	10	0.45	0.175	2.58	0.29	1.71
	20	0.54	0.145	2.69	0.44	2.20
	40	0.65	0.155	3.55	0.54	2.99
Control	0	0.44	0.185	2.09	0.16	0.79
Glenrosa soil						
INC1	5	0.48	0.205	1.96	0.49	1.99
	10	0.57	0.210	2.25	0.58	2.32
	20	0.66	0.225	2.96	0.74	3.32
	40	0.95	0.230	428	1.11	5.03
UNC1	5	0.47	0.205	2.01	0.44	1.92
	10	0.51	0.225	2.27	0.52	2.32
	20	0.72	0.240	2.90	0.81	3.26
	40	1.09	0.220	4.25	1.23	4.82
INC1.5	5	0.44	0.200	2.06	0.41	1.94
	10	0.52	0.215	2.25	0.49	2.15
	20	0.84	0.245	3.24	0.93	3.61
	40	0.89	0.180	3.91	1.06	4.71
UNC1.5	5	0.46	0.215	2.01	0.41	1.82
	10	0.52	0.225	2.39	0.51	2.36
	20	0.62	0.240	2.94	0.69	3.32
	40	0.97	0.250	3.96	1.11	4.57
Control	0	0.48	0.230	1.78	0.32	1.20
p-value		0.003	0.006	<0.001	0.032	0.009
SEM		0.023	0.005	0.085	0.035	0.137

Means with the same letter(s) within a column are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5 m, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively; SEM = standard error of mean

4.28%, respectively) were obtained from the treatments with the 40 t ha^{-1} of UNC1, UNC1.5 and INC1 respectively, under the Glenrosa soil. Shoot N contents from all the treatments with 5, 10 and 20 t ha^{-1} were statistically equivalent under the Hutton soil. The 20 and 40 t ha^{-1} rates gave significantly higher K contents under both soils in comparison with the control. In several instances, the different rates were statistically similar in their effects on shoot P content. The

40 t ha^{-1} of UNC1 under the Glenrosa soil gave the highest shoot N uptake (1.23 g pot^{-1}) that was statistically equivalent to that obtained from the 40 t ha^{-1} of other compost types under the Glenrosa soil. Treatments with the 10 and 20 t ha^{-1} of compost were statistically the same in their effects on shoot N uptake in both soils. A similar finding was observed for treatments with 5 and 10 t ha^{-1} of compost. The 20 and 40 t ha^{-1} rates gave significantly higher uptake of N than the control in both soils. The 10 t ha^{-1} of INC1 also significantly increased N uptake than the control only under Glenrosa soil. The highest value of shoot K uptake (5.03 g pot^{-1}) was obtained from the treatment with INC1 at 40 t ha^{-1} under the Glenrosa soil. The application rates greater than 5 t ha^{-1} significantly increased the K uptake as compared to the untreated control under the Hutton soil, whereas all the compost rates under the Glenrosa soil gave significantly higher K uptake than the untreated control. Treatments with 40 t ha^{-1} of compost were statistically similar in their effects on the shoot N and K uptake under the Glenrosa. In general, the total contents and uptake of N and K increased with the increasing rates.

5.3.3 Treatments and their interaction effects on soil pH, exchangeable Na content and electrical conductivity

The interaction effect of soil type, compost type and compost rate was significant on soil pH (Table 5.8) and insignificant on the electrical conductivity and exchangeable Na content. Soil pH values recorded from the 80 and 100 t ha^{-1} rates were significantly higher than those recorded from the untreated control of both soils except under the application of 80 t ha^{-1} of INC1 under the Glenrosa soil. The UNC1 at 100 t ha^{-1} presented the highest soil pH value (9.20) under the Hutton soil, whereas the 10 t ha^{-1} of INC1 gave the lowest soil pH value (7.67) under the Glenrosa soil. The application of 80 and 100 t ha^{-1} of compost in each soil type increased the soil pH with reference to the untreated controls.

Soil type and compost rate significantly influenced soil pH, electrical conductivity, and exchangeable Na content while compost type significantly affected only soil pH and exchangeable Na content (Table 5.9). Soil pH, electrical conductivity and exchangeable Na content were significantly higher in Hutton soil in comparison with the values obtained from the Glenrosa soil. There were no significant differences among the compost types in their effects on soil pH, electrical conductivity, and exchangeable Na content. Compost application significantly increased soil pH and the exchangeable Na content in comparison with the control. Similar increases in the soil electrical conductivity were recorded under the application of INC1.5, UNC1 and UNC1.5 in comparison with the control. The 100 t ha^{-1} rate gave the highest soil pH value (8.78), followed by the 80 t ha^{-1} rate (8.63). Significantly higher soil pH values were given by all application rates higher than 20 t ha^{-1} with reference to the untreated control. Soil pH values recorded under the 5, 10, 20 and 40 t ha^{-1} were statistically equivalent. The 80 and 100 t ha^{-1} gave significantly higher values of the soil electrical conductivity (4.04 and 7.63 mS cm^{-1}, respectively) and Na content (202 and 209 mg kg^{-1}, respectively) as when compared to the remaining rates that did not differ with each other in their effects.

Table 5.8: Interaction effect of soil type, compost type and compost rate on soil pH

		pH (H_2O)	
Compost type	**Application rate (t ha^{-1})**	**Hutton soil**	**Glenrosa soil**
INC1	5	8.09	7.70
	10	7.94	7.67
	20	8.02	7.80
	40	8.03	7.91
	80	8.77	8.04
	100	8.60	8.70
UNC1	5	8.01	7.75
	10	7.95	7.80
	20	8.10	7.74
	40	8.09	7.91
	80	8.74	8.56
	100	9.02	8.65
INC1.5	5	8.07	7.68
	10	8.05	7.79
	20	8.03	7.77
	40	8.15	7.91
	80	8.65	8.80
	100	9.07	8.79
UNC1.5	5	7.96	7.75
	10	7.97	7.77
	20	8.14	7.80
	40	8.08	7.83
	80	9.05	8.51
	100	9.20	8.23
Control	0	7.91	7.71
p-value		0.003	
SEM		0.044	

Means with the same letter(s) are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively; SEM = standard error of mean

Table 5.9: Effect of soil type, compost type and compost rate on soil pH, electrical conductivity (EC) and exchangeable Na content

Treatments	**pH (H_2O)**	**EC (mS cm^{-1})**	**Na (mg kg^{-1})**
Soil type			
Hutton soil	8.30a	2.74a	128a
Glenrosa soil	8.02b	1.74b	107b
p-value	<0.001	<0.001	<0.001
Compost type			
INC1	8.10a	2.01ab	121a
INC1.5	8.22a	2.27a	119a
UNC1	8.19a	2.14a	126a
UNC1.5	8.18a	2.22a	110a
Control	7.81b	1.63b	76b
p-value	<0.001	0.238	0.028
Compost rate (t ha^{-1})			
0	7.81d	1.63b	76b
5	7.87cd	1.78b	82b
10	7.86cd	1.63b	75b
20	7.92cd	1.56b	67b
40	7.98c	1.69b	80b
80	8.63b	4.04a	202a
100	8.78a	7.63a	209a
p-value	<0.001	<0.001	<0.001
CV (%)	1.81	32.37	24.88

Means with the same letter(s) within a column and treatment are not significantly different at 5% probability level; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively; CV = coefficient of variance

Soil pH, electrical conductivity and exchangeable Na content were not significantly influenced by the interaction of soil type and compost type, and that of compost type and application rate. Amongst the measured soil properties, only the electrical conductivity was significantly influenced by the soil type and application rate interaction (Figure 5.6). The 80 and 100 t ha^{-1} rates did not differ from each other in their effects on the soil electrical conductivity in both soils. The values of the soil electrical conductivity recorded from the 40 t ha^{-1} rate and below were statistically lower than those recorded from the 80 and 100 t ha^{-1} rates under the Glenrosa soil. The 80 t ha^{-1} gave significantly higher values of soil electrical conductivity than the 20 t ha^{-1} rate, whereas the 100 t ha^{-1} resulted in higher values of the soil electrical conductivity than the rates below the 80 t ha^{-1} under the Hutton soil.

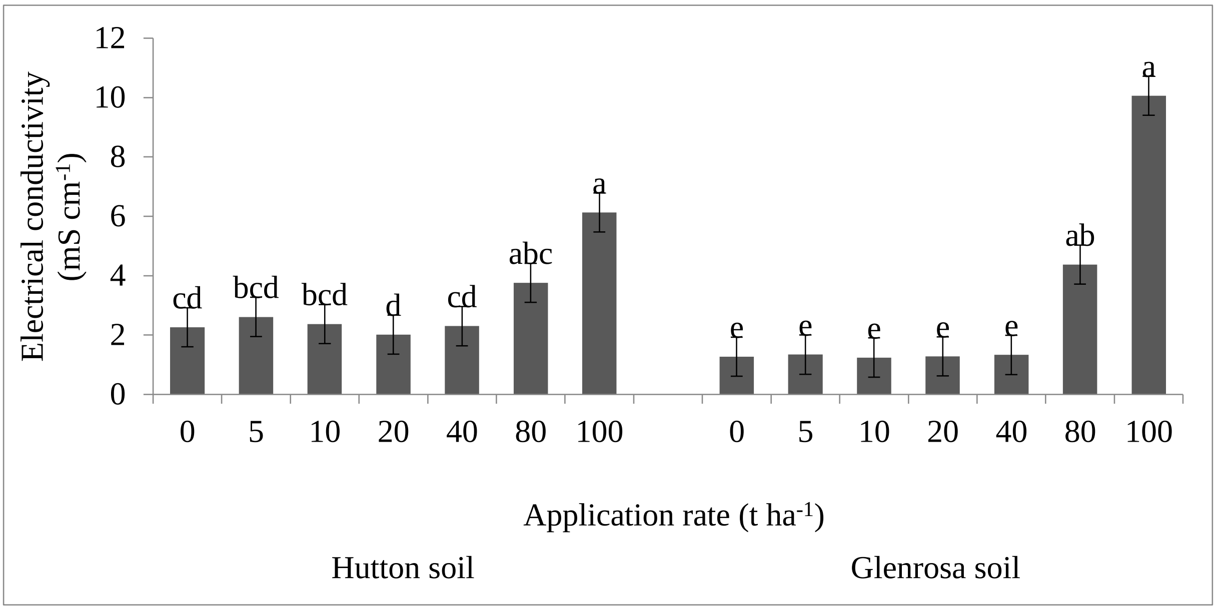

Figure 5.6: Interaction effect of soil type and application rate on the soil electrical conductivity ($p < 0.001$). The bars indicate standard error of treatment mean.

5.3.4 Correlations among the measured growth parameters, chlorophyll content, dry matter yield, nutrient content, and uptake, and soil chemical properties

The correlations among maize growth parameters, chlorophyll content, DMY, tissue nutrient content and uptake, and soil chemical properties for both Hutton and Glenrosa soils (Table 5.10). The DMY had significant and positive correlations with the chlorophyll content and measured growth parameters. The correlations of chlorophyll content and DMY with shoot P content were negative and significant in Hutton soil, but positive and insignificant in Glenrosa soil. The DMY, chlorophyll content, number of functional leaves per plant and plant height showed significant and positive correlations with shoot N, K, Na and Zn contents and uptake, and P uptake under both soil types. The stem girth showed comparable results with the exception that it showed positive and non-significant correlations with maize shoot tissue Kand Zn contents in Hutton soil. Soil pH demonstrated significant and positive correlations with the measured growth parameters and DMY on Glenrosa soil. For Hutton soil, soil pH correlated positively and significantly with number of leaves per plant, plant height, chlorophyll content and DMY. Soil pH gave significant and positive correlations with the contents of shoot N and K, and with the uptake of N, P, K and Zn under Hutton soil. Soil pH gave significant and positive correlations with shoot N, K, Na, and Zn contents and uptake for Glenrosa soil. Soil Na content had significant and negative correlations with the number of leaves per plant, Na uptake and P uptake in Hutton soil. Shoot N content and

Table 5.10: Results of correlation analysis among maize growth parameters, chlorophyll content, dry matter yield, shoot nutrient content and uptake, and soil chemical properties in Hutton and Glenrosa soils

		NFLP	**LCC**	**SG**	**PH**	**DMY**	**Soil pH**	**EC**	**Soil Na**	**N content**	**N uptake**	**P content**	**P uptake**	**K content**	**K uptake**	**Na content**	**Na uptake**	**Zn content**	**Zn uptake**
Hutton	**NFLP**	1																	
	LCC	0.630**	1																
	SG	0.639**	0.467**	1															
	PH	0.907**	0.742**	0.649**	1														
	DMY	0.937**	0.706**	0.630**	0.942**	1													
	Soil pH	0.360*	0.471**	0.283	0.372*	0.379*	1												
	EC	0.337	-0.104	-0.117	0.171	0.285	0.069	1											
	Soil Na	-0.344*	0.200	0.031	-0.207	-0.307	0.110	-0.887**	1										
	N content	0.693**	0.829**	0.440**	0.767**	0.728**	0.402*	0.090	-0.069	1									
	N uptake	0.840**	0.831**	0.546**	0.906**	0.903**	0.402*	0.184	-0.184	0.944**	1								
	P content	-0.810**	-0.626**	-0.555**	-0.786**	-0.856**	-0.251	-0.189	0.193	-0.534**	-0.717**	1							
	P uptake	0.875**	0.573**	0.593**	0.877**	0.903**	0.379*	0.316	-0.353*	0.692**	0.832**	-0.570**	1						
	K content	0.684**	0.625**	0.317	0.720**	0.675**	0.408*	0.259	-0.248	0.881**	0.837**	-0.411*	0.743**	1					
	K uptake	0.877**	0.733**	0.504**	0.914**	0.916**	0.404*	0.303	-0.310	0.889**	0.966**	-0.698**	0.890**	0.905**	1				
	Na content	0.450**	0.384*	0.313	0.458**	0.474**	0.027	0.141	-0.242	0.618**	0.572**	-0.288	0.536**	0.671**	0.611**	1			
	Na uptake	0.761**	0.589**	0.485**	0.772**	0.809**	0.199	0.267	-0.345*	0.779**	0.840**	-0.604**	0.803**	0.783**	0.869**	0.885**	1		
	Zn content	0.380*	0.361*	0.235	0.393*	0.370*	0.238	0.120	-0.141	0.707**	0.589**	-0.102	0.495**	0.737**	0.600**	0.720**	0.673**	1	
	Zn uptake	0.816**	0.638**	0.532**	0.835**	0.849**	0.344*	0.269	-0.306	0.873**	0.924**	-0.598**	0.863**	0.852**	0.936**	0.709**	0.909**	0.793**	1
Glenrosa	**NFLP**	1																	
	LCC	0.899**	1																
	SG	0.839**	0.720**	1															
	PH	0.941**	0.911**	0.865**	1														
	DMY	0.890**	0.746**	0.924**	0.911**	1													
	Soil pH	0.685**	0.661**	0.520**	0.621**	0.507**	1												
	EC	-0.037	-0.126	-0.038	-0.076	-0.047	0.188	1											
	Soil Na	0.242	0.333	0.205	0.254	0.191	-0.018	-0.739**	1										
	N content	0.869**	0.916**	0.680**	0.869**	0.688**	0.635**	-0.069	0.309	1									
	N uptake	0.923**	0.933**	0.767**	0.929**	0.796**	0.643**	-0.082	0.311	0.986**	1								
	P content	0.155	0.079	0.145	0.132	0.118	-0.160	-0.153	0.162	0.326	0.287	1							
	P uptake	0.734**	0.569**	0.758**	0.735**	0.797**	0.268	-0.107	0.209	0.685**	0.741**	0.689**	1						
	K content	0.903**	0.925**	0.728**	0.883**	0.732**	0.709**	-0.109	0.317	0.960**	0.966**	0.256	0.673**	1					
	K uptake	0.940**	0.934**	0.794**	0.933**	0.825**	0.698**	-0.108	0.313	0.945**	0.976**	0.230	0.726**	0.988**	1				
	Na content	0.467**	0.439**	0.589**	0.476**	0.443**	0.390*	0.228	-0.125	0.378*	0.403*	-0.080	0.277	0.415*	0.428*	1			
	Na uptake	0.606**	0.572**	0.704**	0.622**	0.597**	0.460**	0.175	-0.051	0.508**	0.547**	-0.021	0.419*	0.549**	0.575**	0.978**	1		
	Zn content	0.679**	0.779**	0.643**	0.740**	0.553**	0.535**	-0.108	0.248	0.845**	0.823**	0.281	0.559**	0.814**	0.790**	0.632**	0.706**	1	
	Zn uptake	0.809**	0.852**	0.779**	0.864**	0.733**	0.597**	-0.097	0.255	0.892**	0.903**	0.255	0.677**	0.880**	0.886**	0.631**	0.737**	0.971**	1

**Correlation was significant at the 0.01 level; *Correlation was significant at the 0.05 level; NFLP = number of functional leaves per plant; LCC = chlorophyll content; SG = stem girth; PH = plant height; DMY = dry matter yield; EC = electrical conductivity uptake showed positive and significant correlations with the shoot K, Zn and Na contents and uptake, and with the shoot P uptake in both soils. Shoot P content gave significantly negative correlations with the shoot N and K contents, and with the shoot N, P, K, Na and Zn uptake in Hutton soil. Shoot P content Glenrosa soil had a significant and positive correlation with the shoot P uptake. The correlations of shoot P uptake with shoot K, Na, Zn contents and uptake were positive in both soils. Shoot K content and uptake showed positive and significant correlation and with the shoot Na and Zn contents and uptake in both soils. Shoot Na content and uptake were positively and significantly correlated with each other, and with the shoot Zn content and uptake under both soil types. There was a significant and positive correlation between shoot Zn content and uptake.

5.3.5 Determination of optimum WSW compost application rate and dry matter yield

The quadratic model predicted higher optimum rates for each compost type in comparison to the linear-plus-plateau model but with DMY that was nearly similar to those predicted by the linear-plus-plateau model (Table 5.11). The optimum rates predicted by linear-plus-plateau model ranged from 11.78 to 26.03 t ha^{-1}, while those predicted by quadratic model ranged from 28.16 to 39.53 t ha^{-1}. In general, greater R^2 values were obtained under Hutton soil unlike the Glenrosa soil. For each compost type, both models provided significant R^2 values that were either equal or nearly equal.

Table 5.11: Predicted compost application rates and dry matter yield

Treatments	**Linear-plus-plateau model**			**Quadratic model**		
	Rate (t ha^{-1})	**DMY (g pot^{-1})**	***R*^{2}**	**Rate (t ha^{-1})**	**DMY (g pot^{-1})**	***R*^{2}**
Hutton soil						
INC1	21.34	95.41	0.93***	32.96	98.69	0.93***
UNC1	26.03	99.74	0.92***	39.53	99.69	0.92***
INC1.5	16.24	81.96	0.78***	28.35	87.60	0.79***
UNC1.5	20.06	84.53	0.79***	30.78	88.87	0.80***
Glenrosa soil						
INC1	11.78	115.00	0.64**	29.29	122.69	0.62*
UNC1	12.00	112.97	0.76***	28.16	120.81	0.74***
INC1.5	23.18	120.63	0.71***	33.52	121.90	0.74***
UNC1.5	14.23	114.69	0.83***	29.96	121.07	0.83***

***significant at $p<0.0001$; **significant at $p=0.0002$; *significant at $p=0.0003$; INC1 and INC1.5 denote inoculated composts with pile size of 1 m and 1.5, respectively; UNC1 and UNC1.5 denote uninoculated composts with pile size of 1 m and 1.5 m, respectively

5.4 Discussion

5.4.1 Maize growth and shoot N, P, K, Na, and Zn contents and uptake

The positive results regarding the number of functional leaves per plant, stem girth, plant height, chlorophyll content and DMY following application of WSW compost soil can be attributed to the soil ameliorative effects of compost. Compost or organic wastes improve the soil structure, water retention, cation exchange capacity, soil aeration, and microbiological activity (Demir & Gülser 2015). It also increases the availability of plant nutrients, particularly N, P (Tambone et al. 2007) and K (Kabil et al. 2015). The general increase in the measured growth parameters following the increase in compost rate attributes to the increased availability of soil nutrients. This remark is supported by the general increase in the total contents and uptake of N, K and Zn with the increasing compost rate observed in this study. This is further substantiated by the recorded significant and positive correlations of the number of functional leaves per plant, chlorophyll content, plant height and DMY with shoot N, K, Na and Zn contents and uptake, including the P uptake. Masowa et al. (2016) reported a similar finding only on the maize growth parameters and DMY. The finding that the various compost types across the soil types and application rate exerted similar effects on maize growth parameters, chlorophyll content and DMY indicated that varying WSW compost with EM inoculation and pile size does not influence their agronomic potential. A similar finding was also reported regarding the shoot uptake and contents of N, P, K, Na and Zn.

It is evident that the inherently high availabile N in the Glenrosa soil resulted in higher stem girth, plant height and DMY in comparison with the Hutton soil across the compost rate and application rate. However, the higher availability of N in the Glenrosa soil did not increase the number of functional leaves per plant and chlorophyll content than in the Hutton soil. The general and significant increase in the measured growth parameters, chlorophyll content and DMY evinced by 20 and 40 t ha^{-1} rates as compared to the 5 and 10 t ha^{-1} rates may be attributed to the increase in the availability of soil nutrients shown by the higher N, K and Zn uptake under these rates. Adejumo et al. (2010) also noted the highest plant height, DMY, leaf area and grain yield at higher dose (40 t ha^{-1}) of municipal solid waste compost. The significant and positive correlation of DMY with the measured growth parameters affirms the DMY as one of the measures of plant growth (Laekemariam & Gidago 2013). Carpici & Celik (2010) observed a positive and significant correlation between maize dry forage yield and plant height. Similarly, Kumar and Singh (2004) reported a significant and positive correlation of maize dry forage yield per plant with plant height, number of leaves per plant, and stem diameter.

The higher N availability in the Glenrosa soil could also be responsible for the higher shoot uptake of N, P and K than in the Hutton soil across the compost type and application rate. Nitrogen also mediates the utilization of P, K and other elements in plants (Onasanya et al. 2009) and their optimal amounts in the soil cannot be utilized efficiently if plants are N deficient (Mikkelsen & Hartz 2008). The general increase in the total contents and uptake of N, K and Zn with the increasing compost rate could be linked to the increase in the availability of these nutrients in the soil with increasing compost rate.

5.4.2 Soil pH, electrical conductivity, and exchangeable Na content

Soil pH, electrical conductivity and exchangeable Na content were analyzed because the seedlings in pots treated with composts at 80 and 100 t ha^{-1} died after showing signs of salt stress one week after emergence. The significant increase in soil pH and Na content, is attributable to the very strongly alkaline condition of the WSW compost types and their high Na content. The use of these composts on soils with high pH and Na content should be restricted because high soil pH negatively affects the availability of important nutrients such as P (Boysan & Cimrin 2006), while Na content could prove toxic to soil and plants. Furthermore, introducing more Na into such soils may affect the K uptake of plants (Wakeel 2013). However, lowering compost application rates may minimize their effects on increasing soil pH as shown by the insignificant change in soil pH of treated soil with composts at 40 t ha^{-1} rates and below. The significant increase of up to 175% in the exchangeable Na content recorded from the 80 and 100 t ha^{-1} rates coupled with the high soil pH may have been responsible for the death of seedlings. In comparison with the control, the high values of electrical conductivity induced by the 80 and 100 t ha^{-1} rates in several instances indicate the increased concentration of dissolved salts in the soil (Jones et al. 1992). High salt concentration of soil or nutrient solution negatively affects the uptake and utilization of mineral nutrients by plants (Fageria et al. 2011).

5.4.3 Optimum dry matter yield and compost application rate

Except for the UNC1 in Hutton soil, quantitatively higher optimum compost rates predicted by the quadratic model were associated with marginal yield increases when compared to the yield predicted by the linear-plus-plateau model. Quadratic model has often led to the over estimation of fertilizer recommendations derived from crop responses to fertilizer (Bullock & Bullock 1994; Hochmuth et al. 2011) if the maximum point on the curve is taken as the best fertilization rate (Mahd 2008). For each compost type, both models gave R^2-values that were equal or nearly equivalent. Hence, the use of R^2 statistic to select the best model for predicting the optimum rate and DMY is limited in this study. In fact, the use of the predicted optimum DMY may be a viable option for selecting the best model. Therefore, the linear-plus-plateau model is more preferable than the quadratic model for predicting optimum WSW compost rate for maize dry matter production. The predicted optimum rates ranging from 11.78 to 39.53 t ha^{-1} were within the range of those used in practice which range from 10 to 40 t ha^{-1} (fresh weight) (Elherradi et al. 2005). When compared to the rates of manure, the predicted rates were higher than the recommended annual rates of 8-20 t ha^{-1} for semi-arid areas and higher than 10 t ha^{-1}, which is recommended for high rainfall areas (Ncube et al. 2007). The current predicted optimum rates of the WSW compost types contradict the earlier optimum rate of 87 t ha^{-1} predicted by Masowa et al. (2016) for maize grown in sandy soil under greenhouse conditions. This suggests that the optimum rates for these composts are site-specific and dependent on soil characteristics. Alivelu et al. (2006) recommended the site or season specific knowledge of crop nutrient requirements and nutrient supply from soil in order to achieve maximum yields.

5.5 Conclusions and recommendations

The WSW compost has enormous potential for the improvement of maize growth and dry matter production. The effects of WSW compost on maize performance increased with increasing compost rates. Apparently, the differences in WSW compost associated with pile size and EM inoculation does not influence the compost agronomic effectiveness because the compost types across the soil types and rate exerted similar effects on the measured growth parameters, and the contents and uptake of N, P, K, Na and Zn. The 80 and 100 t ha^{-1} rates significantly increased exchangeable soil-Na content by up to 175%, which may be the reason for the death of the seedlings. The quadratic model predicted quantitatively higher optimum rates associated with marginally higher DMYs compared to the DMYs predicted by the linear-plus-plateau model. Therefore, the linear-plus-plateau model is preferable to the quadratic model for predicting the optimum rates of WSW compost for maize dry matter production. The use of R^2-value to select the best model for predicting the optimum rate and DMY is limited in this study because R^2 values of both models for each compost type were (nearly) equal. Based on these findings, follow-up field experiments are recommended to validate the predicted rates.

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CHAPTER 6

Maize growth and yield indices as affected by combined application of inorganic fertilizers and winery solid waste compost under field conditions

Abstract

Maize growth and yield indices were assessed following application of combined nitrogen (N) and phosphorus (P) from inorganic fertilizer (INPF) and winery solid waste (WSW) compost over two summer cropping seasons under field conditions. Variable ratios of INPF and WSW compost with and without effective microorganisms (EMs) inoculation (0:0, 75:25, 50:50, 25:75 and 0:100, w/w) were combined to supply proportionate N and P amount. A mixture of the recommended inorganic fertilizer rates of 200 kg N ha^{-1} and 90 kg P ha^{-1} was included as a standard control. The results revealed a significant ($p<0.05$) compost type x application rate interaction effect on plant height and leaf area index during the 2018 season, as well as on number of functional leaves per plant and stem girth at tasselling stage during the 2018/19 season. In most instances, the measured growth and yield indices showed no differential response to compost types but the different mix ratios of compost and INPF gave higher growth and yield indices compared to the untreated control. The combined application of uninoculated compost (UNC1) and INPF at 75:25 ratio gave the highest number of functional leaves per plant (15.5) in 2018/19 season. Sole application of inoculated compost (INC1) gave the highest values of stem girth (9.5 cm) and plant height (278 cm) at crop physiological maturity in 2018 and 2018/19, respectively. The recorded leaf chlorophyll content of 18.5 and 23.0 CCI, respectively from INC1 and INPF treatments across the application rates were significantly higher than 14.4 CCI from untreated control in 2018/19. The measured cob length of 21.54, 21.77 and 20.40 cm, respectively from INC1, UNC1 and INPF treatments during the 2018/19 season were statistically comparable. The positive and significant correlations between the growth and yield indices shows that the use of any mix ratio of compost and INPF that favourably affects the growth parameters will likely enhance the yield components. In conclusion, the promising results indicate that the application of WSW compost alone or in combination with the INPF has the potential to improve maize growth and yield indices by increasing the nutrient availability to crop through enhanced organic matter decomposition and mineralization processes.

Keywords: maize, growth indices, winery solid waste compost, yield components

6.1 Introduction

The world population is estimated to exceed 9 billion people by the year 2050, and with about 70% extra food production required to satisfy global demands (Kumar & Kalita 2017). Urban population is also expected to escalate with human diets increasingly shifting from staples to processed food fortified with meat and dairy products thereby resulting in a greater demand for intensive crop production (Long et al. 2015). Appropriate measures must be implemented to tackle this envisaged increase in global food demand. Although many identified problems in crop production such as climate change, agricultural resource scarcity and environmental degradation due to declining soil quality, a combination of improved crop and improved agronomical practices were suggested by Fan et al. (2012) to tackle the expected increased food demand.

Maize (*Zea mays* L.) is a major staple food crop grown in diverse agro-ecological zones and under diverse farming systems. Its consumption in South Africa (SA) and many parts of sub-Saharan Africaas a staple food vary according to food preferences and socio-economic backgrounds (Macaule 2015), and its popularity has gradually increased since the early part of the 20th century (Isaacson 2004). In SA, the North-West Province represents the major producing area of white maize where around 20% of all the commercial maize is grown (DAFF 2012). A potential decline in maize and wheat yields is projected in SA by 2050 due to drier conditions with up to 6.4% possible increase in irrigation demands (UNU-WIDER 2016). Due to the effectiveness of irrigation as a tool for increasing yield potential on cropped lands the increasing demand for irrigation is already posing a problem in SA (Sosibo et al. 2017). This is because maize production particularly demands considerable amounts of water (Lv et al. 2011) and nutrients in comparison to other agronomic crops (Usadadiya et al. 2013). In this respect, Sosibo et al. (2017) argue that it is critical for farmers to refine management practices of soil fertility due to inevitable increases of nutrient demand and removal as farmers intensify crop production and target higher yields. Similarly, Nambiar and Abrol (1992) as cited by Choudhary et al. (2013) have viewed combined use of organic and inorganic fertilizers as promising not only for the maintenance of higher productivity, but also for enhanced stability to crop production.

A preliminary study revealed that the application of WSW compost could be a useful source of K and zinc for maize (Masowa et al. 2016). However, the N and P contents in maize shoots from the compost treatments were lower than the critical level of N and P. This suggests supplementary N and P needs through the use of higher concentrations of soluble N and P fertilizers when this compost is used. The study hypothesized that the combined application of WSW compost and inorganic NP fertilizers would lead to improved maize plant growth and yield indices than the sole application of either the WSW compost or inorganic fertilizers.

6.2 Materials and methods

6.2.1 Description of study site

Field trials were conducted during the 2018 and 2018/19 summer cropping seasons at the North-West University Agriculture Farm (25°48’ S, 25°38’ E), Mafikeng, South Africa. The physico-chemical properties of the Mafikeng soil were given previously in chapter 5. Mafikeng has a typical semi-arid tropical Savannah climate with summer mean annual rainfall of 571 mm (Materechera & Medupe 2006). Table 6.1 shows the rainfall and temperature data recorded during the first (2018) and second (2018/19) planting of the field trial.

Table 6.1: Monthly rainfall and temperature data for the North-West University Agriculture Farm, Mafikeng for the duration of experimental period (SAWS 2018, 2019)

2018 season	**Climate data**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
	Rainfall (mm)	108.8	90	27.6	26.0	0
	Maximum temperature (°C)	29.7	29.6	27	25.2	23.5
	Minimum temperature (°C)	17.4	15.4	12.5	7	3.9
2018/19 season	**Climate data**	**Dec**	**Jan**	**Feb**	**March**	**Apr**
	Rainfall (mm)	90.6	30.2	133.4	36.2	122.8
	Maximum temperature (°C)	34.8	34.5	31.5	33.7	26.6
	Minimum temperature (°C)	19.6	18.9	17.5	17.1	13.7

6.2.2 Experimental design and procedures

The inoculated (INC1) and uninoculated (UNC1) WSW compost types were initially evaluated through a 7 weeks tunnel house maize pot trial at 0, 5, 10, 20 and 40 kg ha^{-1} application rates to predict their optimum rate based on maize dry matter yield using a quadratic model (Chapter 5). Thereafter, the INPF and obtained optimum rate of each compost type were combined at different ratios (0:0, 75:25, 50:50, 25:75 and 0:100, w/w) to supply proportionate N and P amount for the field trial. Inorganic K fertilizer was excluded from the fertilizer programme due to the high amount of available K in WSW compost. The optimum inorganic NP fertilizer rate (200 kg N ha^{-1} and 90 kg P ha^{-1}) was included as a standard control (Soropa et al. 2012). All treatments in the trials were laid out as split-plot arrangement fitted in a randomized complete block design with three replicates. The compost type was the main plot while the compost rate was the sub-plot. Each sub-plot measured 4 m x 3.6 m. The plots were 1 m apart, while the blocks were 1.5 m apart. The WSW compost was spread uniformly on each plot as per treatment and worked lightly into the soil using hand hoe at one week before seed sowing to ensure thorough mixing with the soil. Broadcasting of the inorganic NP fertilizer treatment at planting but with N split-applied with 50% at planting, and the remaining amount applied at the V10 stage to promote nutrients accumulation (Ransom 2013). The sources of N and P were limestone ammonium nitrate (28% N) and single superphosphate (10.5% P), respectively. Intra-row distance between the plants was 25 cm while inter-row distance was 70 cm, resulting in six maize rows per plot. The inter-row spacing of maize seeds generally ranges from 70 to 100 cm, while the intra row spacing varies between 20 and 30 cm (Desta 2015). Two maize seeds were sown per hole followed by thinning to one plant per stand at one week after emergence. Weeding and irrigation were kept uniform on the field for all treatments throughout the period of plant growth. Spraying of Insectido™ (5 EC) on plants was done during tasselling stage to control the occurrence of aphids.

6.2.3 Data collection

6.2.3.1 Measurement of growth parameters

Data collection on the growth indices at tasselling and physiological maturity stages was conducted using four randomly selected plants from the central four rows of each plot. The measurement of the chlorophyll content (CCI) of the flag leaf using a portable CCM-200 *plus* chlorophyll content meter (Opti-Sciences Inc, USA) occurred during the tasselling stage. The measured growth indices include number of functional leaves per plant, stem girth, plant height and leaf area index (LAI). Manual counting of functional plant leaves was performed at tasselling stage while the plant height was measured of using a steel meter tape from the ground level to the tip of the flag leaf (Ayub et al. 2002). The leaf length was measured using a steel tape from the leaf base at the stem to the leaf tip, while the leaf width was at the region of the leaf with the maximum width. Thereafter, the equation 6.1 provided by Makinde and Ayoola (2010) was employed for the computation of the leaf area. Computation of LAI involved dividing the calculated leaf area per plant by the ground area per plant as described by Iqbal et al. (2015).

Leaf area = {0.75 × (Leaf length × Leaf width)…………………………….… (Equation 6.1)

The stem diameter was measured 10 cm from the soil surface using a Vernier calliper at tasselling stage and physiological maturity and thereafter converted to stem girth using the equation 6.2 (Ukonze et al. 2016):

Stem girth = {stem diameter × π (*pi*)}………………………………………. (Equation 6.2)

6.2.3.2 Yield components

Data collection on yield components at harvest was done using four tagged plants as described in sub-section 6.3.2.1. These include the number of cobs plant^{-1}, cob weight, cob length, number of grains cob^{-1}, grain weight cob^{-1}, and 1000-seed weight (TSW). Cob length was measured using a meter tape from the base to the tip of the cob. Recording of cob weight was done after dehusking, while the number of grains cob^{-1}, grain weight and TSW were determined after shelling.

6.2.4 Data analysis

The measured data on the maize growth indices and yield components were subjected to analysis of variance and separation of differences between treatment means involved Fisher's protected least significant difference (LSD) test at 5% level of significance using a SAS software version 9.4. Simple Pearson's correlation analysis was run for the measured maize growth indices at physiological maturity and yield components.

6.3 Results and discussion

6.3.1 Treatments and their interaction effects on maize growth indices at tasselling stage

Table 6.2 presents the effect of compost type and application rate on chlorophyll content and number of functional leaves per plant. Compost type and application rate had significant effects on measured chlorophyll content at tasselling stage in 2018/19. The INC1 and INPF treatments across the application rates gave significantly higher chlorophyll content (18.5 and 23.0 CCI, respectively) than untreated control (14.4 CCI) in 2018/19. Notwithstanding the compost type, sole compost application (i.e. 100:0 compost and INPF mix ratio) resulted in significant increase in chlorophyll content compared to the untreated control. Siavoshi and Laware (2013) attributed the increased photosynthetic pigment of rice following sole and combined application of NPK and organic fertilizers to the improved soil physical and chemical properties and optimum nutrients available in fertilizers. The leaf chlorophyll concentration showed close relationship to plant N concentration (Sharifai et al. 2012; Peng et al. 2017; Mendoza-Tafolla et al. 2019).

An increase or decrease in the number of leaves per plant has a direct bearing on the yield of crops (Laekemariam & Gidago 2013). This is because the number of leaves on a plant determines the photosynthetic activity of a plant, which in turn influences the growth and yield of the crop (Yigermal et al. 2019). Compost types had a significant effect on the number of functional leaves per plant at tasselling stage in 2018/19. Compared to the untreated control, plants that received variable mix ratios of compost and INPF produced significantly higher number of functional leaves per plant in 2018/19. Relatively, the compost application rate had a significant effect on the number of functional leaves per plant in both seasons. Treatments with sole INPF and 75:25 compost and INPF mix ratio gave significantly higher mean number of functional leaves per plant in 2018.

Table 6.2: Effect of compost type and application rate on chlorophyll content and number of functional leaves per plant at tasselling stage

	Chlorophyll content (CCI)		**NFLP**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**
Compost type				
INC1	17a	18.5b	14.42a	14.38b
UNC1	16a	18.2bc	14.25a	15.22a
INPF	17a	23.0a	14.83a	15.00ab
Control	16a	14.4c	14.08a	11.75c
$LSD_{(0.05)}$	4	3.90	0.58	0.71
p-value	0.702	0.001	0.152	<0.001
CV (%)	16	43	2.97	10.13
Application rate (WSWC:INPF)				
0:0	16a	14.4b	14.08cd	11.75b
25:75	18a	18.1ab	14.50abc	14.69a
50:50	15a	18.8ab	14.29bcd	15.13a
75:25	17a	15.3b	14.54ab	14.56a
100:0	17a	21.1a	14.00d	14.81a
INPF	17a	23.0a	14.83a	15.00a
$LSD_{(0.05)}$	2.18	5.04	0.4237	0.9637
p-value	0.173	0.008	0.001	<0.001
CV (%)	23	38.9	5.16	9.57
Compost x application rate interaction				
F-test probability	ns	ns	ns	***

Means with same letter(s) within the same column and treatment factor are not significantly different at 5% probability level. CCI = chlorophyll content index; NFLP = number of functional leaves per plant; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation; WSWC = winery solid waste compost; ns = not significant at 5% probability level; ***significant at 0.1% probability level

Compost x application rate interaction had a significant effect on the number of functional leaves per plant during the 2018/19 season (Figure 6.1). The highest mean number of functional leaves per plant of 15.5 was obtained from the 75:25 mix ratio of UNC1-INPF. The 75:25 mix ratio of INC1-INPF gave significantly lower mean of number of functional leaves per plant than the other compost-INPF combinations except the 25:75 and 100:0 of INC1-INPF in 2018/19. The different mix ratios of compost and INPF gave significantly higher mean number of functional leaves per plant than the untreated control only in 2018/19. This might be due to the increase in nutrient availability following the application of sole INPF and the integrated use of compost and INPF. Highest maize leaf number induced by the application of inorganic fertilizer alone or in combination with the compost has also been reported by several other researchers (Laekemariam & Gidago 2013; Ndukwe et al. 2014; El-Gawad & Morsy 2017).

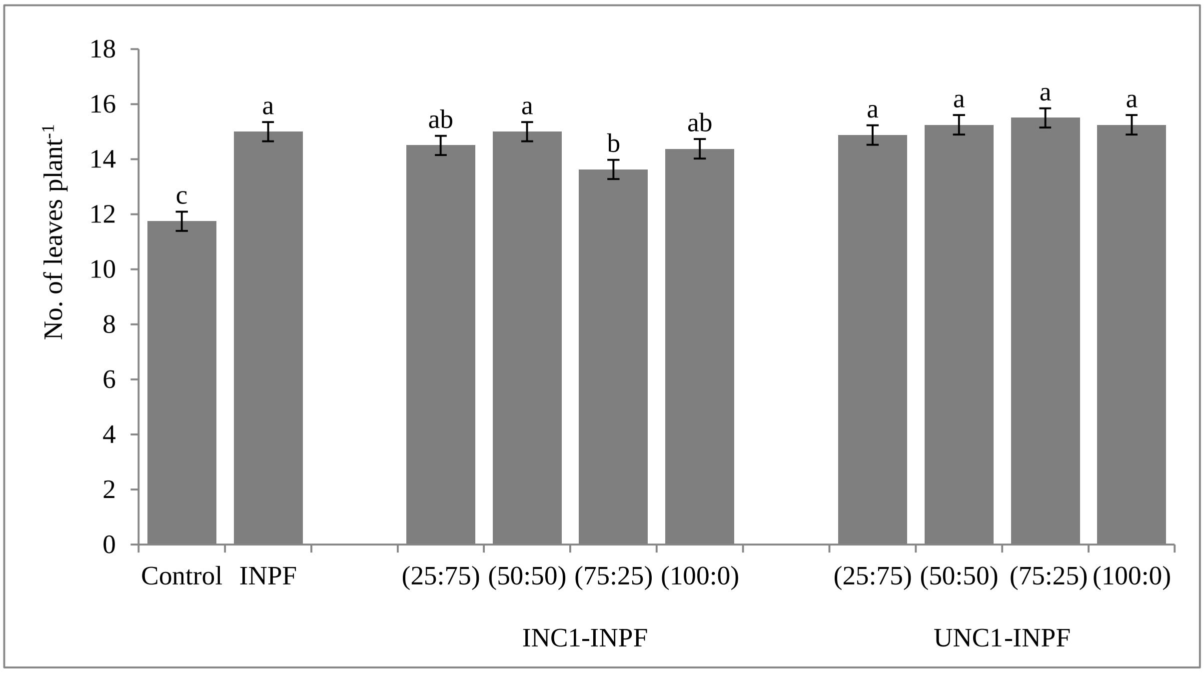

Figure 6.1: Interaction effect of compost type and application rate on the number of functional leaves per plant during the 2018/19 season ($p < 0.001$; LSD = 1.2143; CV = 8.38). The bars show standard error of treatment mean.

The treatments effects on plant height, stem girth and LAI at tasselling stage are shown in Table 6.3. The compost type significantly affected plant height in both seasons. Plant heights with compost and INPF treatments across the mix ratios were statistically similar, but higher than that recorded from the untreated control in 2018/19. The compost treatments gave taller plants than the untreated control but significantly shorter plants than those from the INPF treatment across the application rates in 2018. Plants in plots treated with the application of different mix ratios of compost and INPF across the compost types were significantly taller than those in untreated plots in 2018. In a similar manner, the UNC1 gave plants with thicker stems than the INC1, INPF and untreated control in 2018/19. Compost application rate had a significant effect on stem girth in 2018. Only the 25:75 compost-INPF mix ratio was statistically at par with the untreated control in its effect on the stem girth in 2018. The stem girth of plants from sole compost application (10.26 cm) was significantly higher than that of plants from the compost-INPF combination of 25:75 (9.47 cm) and 50:50 (9.83 cm) in 2018.

Table 6.3: Effect of compost type and application rate on plant height, stem girth and leaf area index at tasselling stage

	Plant height (cm)		**Stem girth (cm)**		**LAI**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type						
INC1	253b	280a	9.84a	6.96b	0.43a	0.32bc
UNC1	251b	284a	9.91a	7.71a	0.43a	0.34ab
INPF	274a	279a	9.89a	7.26b	0.43a	0.31c
Control	205c	263b	9.11a	7.15b	0.36b	0.35a
LSD$_{(0.05)}$	17	11	0.65	0.36	0.03	0.019
p-value	<0.001	0.001	0.103	0.001	0.001	<0.001
CV (%)	5	8	4.87	10.14	4.74	11.63
Application rate (WSWC:INPF)						
0:0	205d	263a	9.11d	7.15a	0.36c	0.31a
25:75	259b	282a	9.47cd	6.93a	0.42b	0.33a
50:50	254bc	284a	9.83bc	7.24a	0.43ab	0.33a
75:25	246c	279a	9.94ab	7.52a	0.43ab	0.33a
100:0	248c	283a	10.26a	7.65a	0.44a	0.33a
INPF	274a	279a	9.89abc	7.26a	0.43ab	0.35a
LSD$_{(0.05)}$	8.35	14.88	0.420	0.590	0.017	0.030
p-value	<0.001	0.065	<0.001	0.187	<0.001	0.110
CV (%)	6	8	7.55	11.52	7.24	12.71
Compost x application rate interaction						
F-test probability	***	ns	ns	*	**	ns

Means with the same letter(s) within the same column and treatment are not significantly different at 5% probability level. LAI = leaf area index; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation; WSWC = winery solid waste compost; ns = not significant at 5% probability level; *, **, ***significant at 5%, 1% and 0.1% probability level, respectively

Leaf area index is an important plant growth character since the effectiveness of photosynthesis depends on large and deficient assimilating area, adequate supply of solar and carbon dioxide and favourable environmental conditions (El-Gawad & Morsy 2017). Compost type had a significant effect on LAI in both seasons. The low LAI values observed in this study is indicative of an early maturing maize cultivar with lower leaf area per plant (Sangoi 2001; Fromme et al. 2019). This also indicates that the plant population density (70834 plants ha^{-1})

used in this study could be low for the cultivar leading to reduced LAI value (Sangoi 2001; Maddonni & Otegui 2004). The LAI values from treatments with compost and INPF across the application rates were statistically at par with each other but significantly higher than that recorded from the untreated control in 2018. All treatments with compost-INPF combinations gave LAI values that were statistically similar with those recorded from the INPF. This increased LAI of maize following application of combined application of WSW compost and INPF could be attributed to better growth and development of leaves with corresponding improvements in net carbon dioxide assimilation (Endris 2019). This finding further indicates that the increase in soil nutrient availability with the combined application of WSW compost and INPF improved growth.

Compost x application rate interaction had a significant effect on plant height in 2018 (Figure 6.2A), stem girth during the 2018/19 season (Figure 6.2B) and LAI in 2018 (Figure 6.3). The plant height values ranged from 205 cm with the untreated control to 274 cm with the sole INPF treatment in 2018. Maize plant from plots that received combined INC1-INPF at 50:50 ratio (266 cm) had significantly higher heights than those of INC1-INPF at 75:25 ratio (239 cm) and UNC1-INPF at 50:50 (242 cm) in 2018. Combined application of compost-INPF treatment resulted in increased plant height due to the increased availability of plant nutrients required for plant growth and development. The stem girth ranged from 6.67 cm with the untreated control to 8.16 cm with UNC1-INPF (100:0). The UNC1-INPF (100:0) gave rise to plants with thicker stems than the other compost-INPF combinations except UNC1-INPF (50:50; 75:25) in 2018/19. Treatments with UNC1-INPF (50:50; 75:25) gave the thicker plant stems than the untreated control in 2018/19. The sole application of uninoculated compost (100:0) resulted in plants with thicker stems than the untreated control and the sole application of INPF in 2018/19, thus, suggesting better improvement in soil properties and improved nutrition of the plants (Tambone et al. 2007). Both the sole or combined application of WSW compost and INPF resulted in increased LAI in 2018 possibly due to increased availability and uptake of nutrients, which prompted improved crop growth. A similar study by Pandit et al. (2018) showed that nutrient stress alleviation following the application of organic amendment positively influences plant growth.

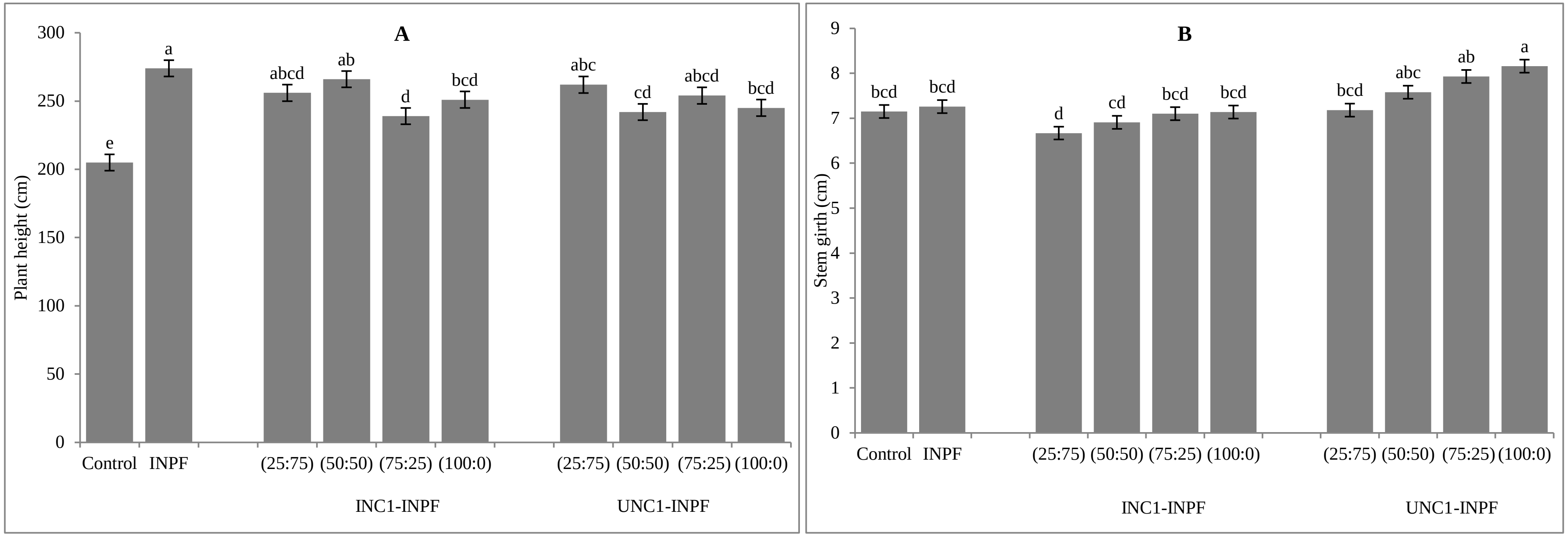

Figure 6.2: Interaction effect of compost and application rate on (A) plant height at tasselling stage in 2018 ($p < 0.001$; LSD = 22; CV = 5.03) and (B) plant stem girth at tasselling stage during the 2018/19 season ($p = 0.022$; LSD = 0.8385; CV = 11.50). The bars show the standard error of treatment mean.

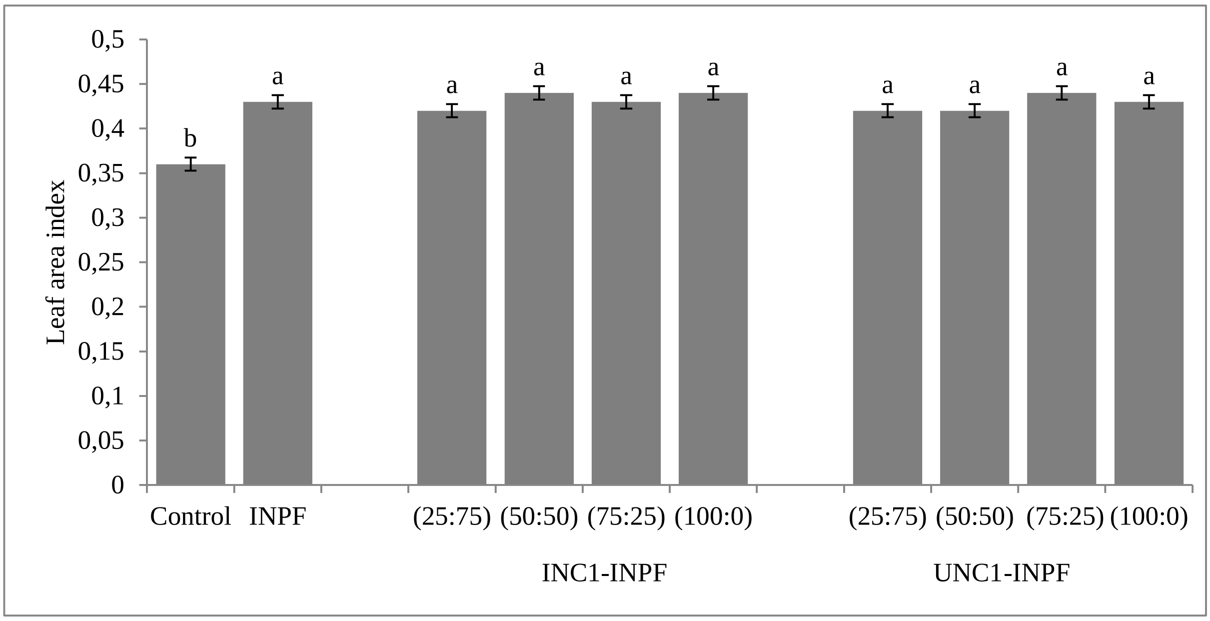

Figure 6.3: Interaction effect of compost type and application rate on LAI in 2018 at tasselling stage (p = 0.008; LSD = 0.03; CV = 4.74). The bars indicate the standard error of treatment mean.

6.3.2 Treatments and their interaction effects on plant growth parameters at physiological maturity

Compost type and application rate significantly affected plant height in 2018/19 and stem girth in both planting seasons (Table 6.4). Plants from plots treated with compost and INPF across the application rates had statistically similar plant heights in 2018/19. In comparison with the untreated control, compost and INPF treatments across the application rates significantly increased the plant height in 2018/19. The 50:50 combined WSW compost and INPF and sole compost across resulted in significant ($p<0.005$) increase in plant height than that obtained from the untreated control in 2018/19. Maize plant stem girth in plots that received compost and INPF was higher across the compost mix ratios than in untreated control plants in both seasons. Plants from the INC1 treatment across the application rates had significantly lower stem girth than those from the INPF treatment. Treatments with 50:50, 75:25 and 100:0 compost-INPF combinations across the two compost types had plants with significantly higher stem girth than that of untreated control plants in 2018. The 100:0 compost-INPF combination across the compost types also gave a significantly higher value of stem girth than the sole INPF treatment in 2018. With the exception of the 25:75 compost-INPF mix ratio, the remaining compost-INPF combinations resulted in plants with statistically similar stem girth as those from the sole INPF treatment in 2018/19. Compared to the untreated control, the INPF and mix ratios (100:0 and 75:25) of compost and INPF across the compost types resulted in plants with thicker stems in 2018/19.

Table 6.4: Effect of compost type and application rate on plant growth parameters at crop physiological maturity

	Plant height (cm)		**Stem girth (cm)**		**LAI**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type						
INC1	302a	270a	8.89a	7.21b	0.49a	0.36a
UNC1	303a	268a	8.98a	7.31ab	0.50a	0.35a
INPF	307a	275a	8.72a	7.59a	0.52a	0.36a
Control	295a	257b	8.01b	6.86c	0.50a	0.35a
$LSD_{(0.05)}$	19	8.35	0.63	0.2816	0.05	0.018
p-value	0.757	0.001	0.032	<0.001	0.520	0.484
CV (%)	5	5	5	6.78	8.0	8.60
Application rate (WSWC:INPF)						
0:0	295a	257b	8.01d	6.86c	0.50a	0.35a
25:75	308a	267ab	8.45cd	7.09bc	0.49a	0.34a
50:50	306a	274a	8.85bc	7.20abc	0.50a	0.36a
75:25	295a	265ab	9.00ab	7.35ab	0.49a	0.35a
100:0	301a	273a	9.43a	7.41ab	0.49a	0.37a
INPF	307a	275a	8.72bc	7.59a	0.52a	0.36a
$LSD_{(0.05)}$	15	11.93	0.4918	0.4246	0.0401	0.025
p-value	0.303	0.033	<0.001	0.019	0.561	0.181
CV (%)	4	5	5	7.18	6.79	8.72
Compost x application rate interaction						
F-test Probability	ns	*	*	ns	ns	***

Means with the same letter(s) within the same column and treatment are not significantly different at 5% probability level; LAI = leaf area index; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation; WSWC = winery solid waste compost; ns = not significant at 5% probability level; *, ***significant at 5% and 0.1% probability level, respectively

The interaction effect of compost type and application rate was significant on plant height in 2018/19 (Figure 6.4). Plant height ranged from 257 cm with the untreated control to 278 cm with INC1-INPF (100:0) in 2018/19. Plants from treatments with INC1-INPF (25:75; 100:0), UNC1-INPF (50:50) and sole INPF treatment were statistically similar in height but were significantly taller than the plants from the untreated control plants in 2018/19. The finding that the compost-INPF combinations resulted in plant height values that were statistically at par with that recorded from the sole INPF treatment in 2018/19 indicates that enhanced crop growth is achievable with the combined application of WSW compost and INPF thereby reducing the cost of crop fertilization through the use of INPF alone. The improvement in plant height showed an increase in available nutrients for plant uptake following the application of WSW compost and inorganic fertilizers. This is consonance with similar findings by Oad et al. (2004) following the combined application of farmyard manure and urea. Saleem et al. (2017) also reported an increase in maize plant height following the combined application of organic amendments (farmyard manure, poultry manure, and biochar) and zinc fertilizer.

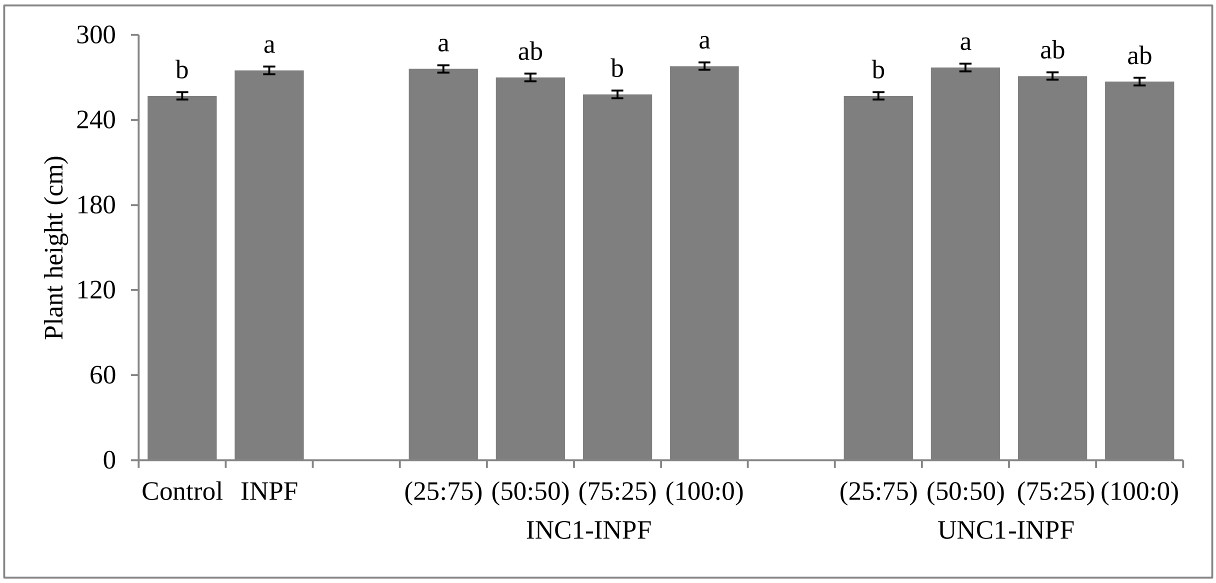

Figure 6.4: Interaction effect of compost type and application rate on plant height at physiological maturity in 2018/19 (p = 0.039; LSD = 16.12; CV = 5). The bars indicate the standard error of treatment mean.

The interaction effect of compost type and application rate on stem girth was significant only in 2018 (Figure 6.5). Sole compost application produced significantly highest stem girth in 2018, albeit not statistically different from the stem girth obtained from the compost-INPF treatments. This suggests the beneficial effect of the application of WSW compost alone or in combination with INPF for the improvement of plant growth. Afe et al. (2015) also reported an increase in stem girth of maize plant following the application of combined application of organic and inorganic NPK fertilizer. The increase in stem girth indicates the availability of more nutrients for plant growth following the combined application of organic and inorganic fertilizers (Akande et al. 2011).

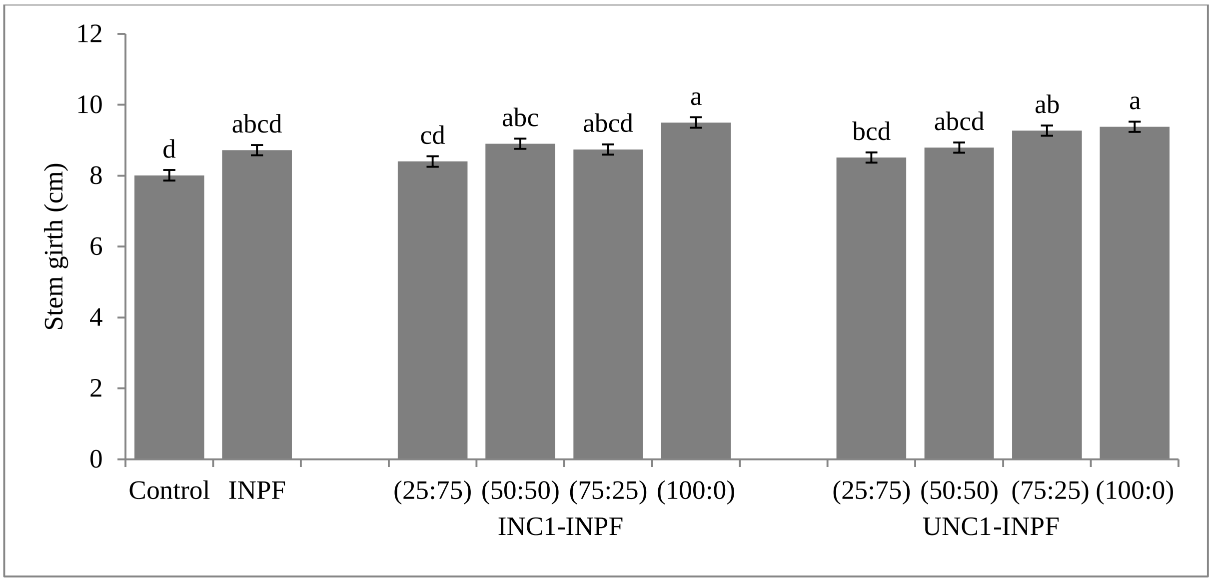

Figure 6.5: Interaction effect of compost type and application rate on plant stem girth at physiological maturity in 2018 (p = 0.024; LSD = 0.80; CV = 5). The bars indicate the standard error of treatment mean.

The interaction effect of compost type and application rate on LAI was significant in 2018/19 (Figure 6.6). The mean LAI values ranged from 0.31 with the UNC1-INPF (25:75) to 0.39 with INC1-INPF (100:0) during the 2018/19 season. Compared to the untreated control, only INC1-INPF (100:0) resulted in significantly higher LAI, while UNC1-INPF (25:75) gave a significantly lower LAI value in 2018/19. Sole application of inoculated compost gave a significantly higher LAI value than INC1-INPF (25:75; 75:25), and UNC1-INPF (25:75; 50:50; 100:0). The LAI value recorded from UNC1-INPF (75:25) was significantly higher than that recorded from treatments with UNC1-INPF (25:75; 100:0) and INC1-INPF (75:25). The INC1-INPF (25:75) had a significantly higher LAI value than UNC1-INPF (25:75). Treatment containing equal proportion (50:50) of INC1 and INPF gave LAI value that was significantly higher than that recorded from the 75% of inoculated compost and in INC1-INPF (75:25) and UNC1-INPF (25:75).

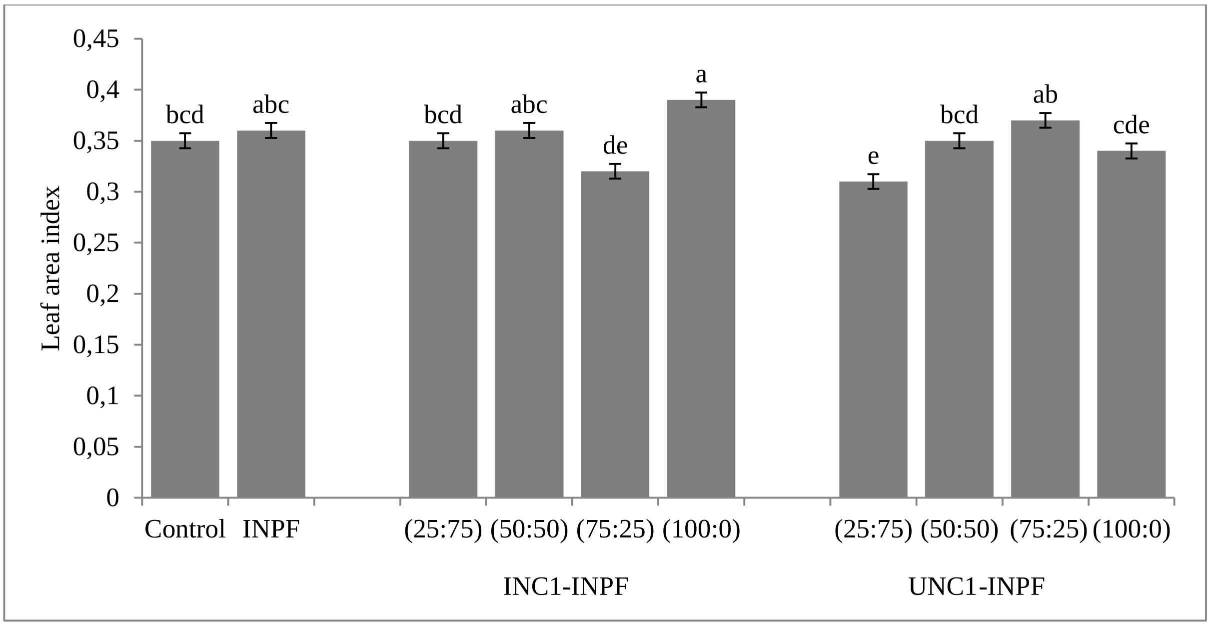

Figure 6.6: Interaction effect of compost type and application rate on LAI at physiological maturity in 2018/19 (p = 0.001; LSD = 0.0308; CV = 7.49). The bars present the standard error of treatment mean.

6.3.3 Treatments and their interaction effects on maize yield components

The effects of the treatments on the measured yield components are indicated in Table 6.5. Cob length substantially contributes to maize grain yield by influencing both numbers of grains cob^{-1} and kernel size (Yigermal et al. 2019). Cobs from the treated plots were significantly longer than those from the untreated control across the application rates in 2018/19. This increase in cob length is attributable to the improved nutrient availability to plants through the enhanced organic matter decomposition and mineralization processes (Dzomeku & Illiasu 2018). The various compost application rates resulted in significantly higher cob length in 2018/19. Nonetheless, there was no significant difference in the measured cob length between the different compost-INPF mix ratios the across compost types. Similarly, there was no observed significant difference in grain number cob^{-1}, grain weight cob^{-1} and TSW among the compost types in both planting seasons. Sole compost application across the compost types resulted in significantly higher grain cob weight than the untreated control and 25:75 compost-INPF mix ratio whereas the 50:50 compost-INPF mix ratio resulted in higher cob grain weight than the untreated control in 2018. This may be due to increased nutrient availability and better soil properties following the application of these treatments. Compost type and application rate interaction effect on the measured yield indices was not significant.

Table 6.5: Effect of compost type and application rate on yield components at crop harvest

	Cob length (cm)		**Cob weight (g)**		**GWC (g)**		**GNC**		**TSW (g)**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type										
INC1	22.40	21.54a	158	106	140	74	547	518	256	141
UNC1	22.04	21.77a	149	113	134	77	539	538	248	143
INPF	21.97	20.40a	147	108	132	76	553	472	239	144
Control	22.16	18.33b	136	92	118	59	523	474	225	126
LSD$_{(0.05)}$	1.58	1.41	26	24	22	18	49	76	34	20
p-value	0.870	<0.001	0.347	0.353	0.256	0.161	0.707	0.226	0.279	0.225
CV (%)	5.24	8.34	13	28	12	30	6.63	18.32	10	17
Application rate (WSWC:INPF)										
0:0	22.16	18.33b	136	92	118c	59	523	474	225	126
25:75	21.72	21.38a	139	113	126bc	80	539	550	233	146
50:50	22.34	21.93a	157	116	140ab	81	549	524	255	150
75:25	22.02	21.40a	150	97	134abc	65	523	502	254	129
100:0	22.80	21.90a	167	112	149a	78	562	535	265	142
INPF	21.97	20.40ab	147	108	132abc	76	553	472	239	144
LSD$_{(0.05)}$	1.25	2.08	22	35	19	25	40	110	29	28
p-value	0.590	0.012	0.086	0.674	0.043	0.415	0.256	0.617	0.067	0.408
CV (%)	4.75	8.42	13	28	12	29.13	6.18	18.31	9.85	16.95
Compost x application rate interaction										
F-test probability	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means with the same letter(s) within the same column and treatment are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; GWC = grain weight cob^{-1}; GNC = grain number cob^{-1}; TSW = thousand seed weight; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation; WSWC = winery solid waste compost; ns = not significant at 5% probability level

6.3.4 Correlations among the maize growth parameters and yield components

Table 6.6 show the results of correlation analysis among maize growth parameters and yield components. The TSW had positive and highly significant correlations with plant height, stem girth, LAI, cob length, cob weight and grain weight cob^{-1} but it had positive and significant correlation with grain number cob^{-1}. Grain number cob^{-1} showed highly significant and positive correlations with cob length, cob weight and grain weight cob^{-1} whereas grain weight cob^{-1} gave positively and highly significant correlations with plant height, stem girth, LAI, cob length and cob weight. The correlation of cob weight with plant height, stem girth, LAI and cob length was highly significant. Cob length showed highly significant correlation with plant height and stem girth, but it gave significant correlation with LAI. These positive and significant correlations between the growth parameters and yield components demonstrate that the yield components are greatly affected by these measured growth parameters. Thus, the application of any WSW compost and INPF combination that increases the growth parameters will likely enhance yield components and ultimately boost grain or biomass yield.

Table 6.6: Results of correlation analysis among maize growth parameters and yield components

Parameters	**PLHT**	**SG**	**LAI**	**CL**	**CW**	**GWC**	**GNC**	**TSW**
PLHT	1							
SG	0.88**	1						
LAI	0.94**	0.90**	1					
CL	0.59**	0.57**	0.48*	1				
CW	0.87**	0.89**	0.83**	0.74**	1			
GWC	0.92**	0.94**	0.91**	0.67**	0.98**	1		
GNC	0.55*	0.49*	0.42	0.75**	0.71**	0.63**	1	
TSW	0.91**	0.94**	0.94**	0.62**	0.95**	0.99**	0.54*	1

PLHT = plant height; SG = stem girth; LAI = leaf area index; CL = cob length; CW = cob weight; GWC = grain weight per cob; GNC = grain number per cob; TSW = thousand seed weight; *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

6.4 Conclusions and recommendations

The findings of this study showed that the application of winery solid waste compost either alone or in combination with INPF holds immense potentials for the improvement of maize growth and yield components by increasing the plant nutrient availability through enhanced organic matter decomposition and mineralization processes. The findings revealed a significantly comparable performance of maize plant growth and yield indices following combined WSW compost and inorganic NP fertilizers application relative to the sole application of either the WSW compost or inorganic fertilizers. Similarly, the differences in compost types exerted no significant effects on the maize growth and yield indices thereby suggesting that microbial inoculation during composting had no influence on the agronomic potential of the resulting WSW compost product. There was no observed significant difference in maize growth and yield indices among the different mix ratios of compost and INPF across the compost types. In general, the 50:50 mix ratio of WSW compost and INPF outperformed the other mix ratios in improving the maize growth and yield indices. The positive and significant correlations between the growth parameters and yield components indicated that the yield components are greatly affected by these measured growth parameters. Therefore, the use of any mix ratio of WSW compost and INPF that improves the growth parameters will likely enhance yield components and ultimately boost grain or biomass yield. Thus, the conducting of long-term field trials under diverse soil and climatic conditions are recommended.

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CHAPTER 7

Yield, protein content, nutrient content and uptake of maize as influenced by sole and complementary application of inorganic fertilizers and winery solid waste compost produced with and without effective microorganisms inoculation

Abstract

The effect of combined application of inorganic nitrogen (N) and phosphorus (P) fertilizers (INPF) and winery solid waste (WSW) compost on maize yield and nutrient content and uptake was evaluated during the 2018 and 2018/19 summer cropping seasons. Treatments consisted of INPF and a tunnel house established optimum rate of each of the two WSW compost types combined at different ratios (0:0, 75:25, 50:50, 25:75 and 0:100, w/w) to supply proportionate N and P amount. Recommended inorganic fertilizer rates of 200 kg N ha^{-1} and 90 kg P ha^{-1} were mixed and included as a standard control. The results showed that the interaction of compost type and application rate had no significant effects on total biomass yield (TBY), grain yield (GY), harvest index (HI) and relative agronomic efficiency. The compost type had significant effects on GY and HI in 2018/19. The TBYs obtained from the treatments with 50:50, 75:25 and 100:0 compost-INPF combinations were 19693, 18835 and 20618 kg ha^{-1} respectively, and were significantly higher than 16161 kg ha^{-1} for the untreated control across the compost types in 2018. The 25:75 and 50:50 compost-INPF combinations gave GYs of 6649 and 6246 kg ha^{-1} respectively, which were significantly higher than 4557 kg ha^{-1} obtained from the untreated control in 2018/19. The INPF treatment resulted in significantly higher contents of grain N (1.53%) and crude protein (9.51%) than the untreated control (1.25% N, 7.80% crude protein) in 2018/19. The biomass P uptake recorded from the sole INPF (19 kg ha^{-1}) was significantly higher than that recorded from INC1 (13 kg ha^{-1}), UNC1 (13 kg ha^{-1}) and untreated control (12 kg ha^{-1}) in 2018/19. Grain yield correlated significantly and positively with the soil NH_4 and P contents indicating that these nutrients contributed to the final GY. The selection of the compost-INPF combinations for the production of high yields should also be focused on the compost-INPFcombinations that enhance the growth attributes and yield components as indicated by the positive correlations of yields with the plant growth parameters and yield components. In conclusion, the joint application of WSW compost and INPF appears promising for improving maize performance under the harsh environmental conditions.

Keywords: effective microorganism inoculation; maize grain yield; nutrient content; nutrient uptake, winery solid waste compost

7.1 Introduction

Maize (*Zea mays* L.) accounts for 40% of the cereal production in Sub-Saharan Africa (SSA), where more than 80% is used as food (Ekpa et al. 2019). Even though maize is the most widely cultivated crop in SSA, large yield gaps still exist (ten Berge et al. 2019). This is mostly due to the prevalence of declining soil fertility in SSA, and partially because of the continued cultivation of crops with little or no addition of nutrient inputs to the inherently infertile soils (Zingore 2011). Nitrogen and P are very essential for good vegetative growth and grain development in maize production (Onasanya et al. 2009). Low soil N and P are among the major constraints for crop production in the whole of sub-Saharan Africa (Edmonds et al. 2009; Gemenet et al. 2016; Masso et al. 2017). The low N fertilizer use in crop production and significant N losses exacerbate N depletion from the agricultural fields in SSA (Masso et al. 2017). The use of mineral fertilizers is the most effective and convenient way to correct the soil N and P deficiency, but their use is limited by their high cost at farmers' level (Nziguheba 2007; Gemenet et al. 2016). Mineral fertilizers sustainably increase crop productivity by 50-100% (Chianu et al. 2012).

The pertinence of minimizing crop fertilization costs has prompted the adoption of innovative and cost-effective soil enhancing mechanisms such as organic soil amendments (Baloyi et al. 2014), which enhance soil fertility by improving soil physico-chemical properties (Anwar et al. 2017). There is still a dearth of research regarding the extent at which organic fertilizers could increase the efficiency of applied mineral fertilizers in sustaining soil and crop productivity (Adamu & Leye 2012; Baloyi et al. 2014). For instance, Baghdadi et al. (2018) reported that treatment with chicken manure combined with NPK fertilizer resulted in dry matter yield of forage that was the same as that resulting from 100% NPK fertilizer. Furthermore, the combination of NPK fertilizer and chicken manure resulted in increased plant height, crop growth rates and leaf area index compared with chicken manure applications alone. Makinde and Ayoola (2010) also showed that maize yields from sole organic fertilizer application are significantly lower than yields from either sole inorganic fertilizer or a combined application of organic and inorganic fertilizers. Nitrogen, P and K uptakes by tomato plants were observed to be significantly higher in both organically and inorganically fertilized plants than their un-fertilized counterparts (Babajide & Salami 2012). Geng et al. (2019) concluded based on their research findings that the appropriate organic substitution is crucial to yield, excessive organic fertilizer substitution leads to insufficient N and accumulation of P and K, potentially endangering the environment. Due to the paucity of research on the use of composted WSW in crop production and in view of the foregoing, this study was conducted to validate the hypothesis that the combined application of WSW compost and inorganic NP fertilizers will improve maize yield and tissue nutrient content and uptake, more than the sole application of either the WSW compost or inorganic fertilizers.

7.2 Materials and methods

7.2.1 Experimental design and procedures

Treatments, experimental design, and procedures have been previously stated in chapter 6. In a nutshell, the treatments consisted of the inorganic N and P fertilizers (INPF) and the tunnel house established optimum rate of each of the two winery solid waste (WSW) compost types combined at different ratios (0:0, 75:25, 50:50, 25:75 and 0:100, w/w) to supply proportionate N and P amount. Recommended inorganic fertilizer rates of 200 kg N ha^{-1} and 90 kg P ha^{-1} were mixed and included as a standard control. The production process and procedure of the inoculated (INC1) and uninoculated (UNC1) WSW compost types used in this experiment are presented in chapter 3, while the estimation of their optimum application rates is presented in chapter 5. The selected physico-chemical properties of initial soil sample are described in sub-section 5.3.3 of chapter 5.

7.2.2 Data collection

7.2.2.1 Grain and total biomass yield

At harvest, cobs were removed from plants from the central four rows of each plot and the grains were shelled. The grain moisture content was determined using a Near Infrared Reflectance Grain Analyzer. After adjusting the grain moisture content to 12%, grain yield (GY) was converted into kg ha^{-1} using the formula below:

GY (kg ha^{-1}) = {GY (kg)/Area harvested (4 m x 2.1 m)} x 10 000 m^2 ha^{-1}}…...(Equation 7.1)

For the determination of total biomass yield (BY), four randomly selected plants with cobs from the central rows were cut from the soil surface using a sharp knife, washed with deionized water, oven-dried (70°C) and then weighed. The BY thus obtained from each plot was converted into kg ha^{-1} using the equation below:

BY (kg ha^{-1}) = {Dry weight of 1 plant (kg) x (plant population ha^{-1})}……..... (Equation 7.2)

Estimation of the harvest index (HI) for each treatment was undertaken using the following formula cited by Iqbal et al. (2015):

HI = (grain yield/biomass yield) × 100……………………………….................(Equation 7.3)

The relative agronomic effectiveness (RAE) was computed using the equation adapted from Law-Ogbomo et al. (2012):

RAE (%) = $(GY_T - GY_C)/(GY_C)$……...…………...……………………….…(Equation 7.4)
whereby: GY_T = maize dry matter yield from compost treated pots, GY_C = maize dry matter yield from control pots.

7.2.2.2 Plant tissue nutrient analysis

Sub-samples of the biomass and grain were washed with distilled water, oven-dried at 70°C, and ground to pass through a 0.5 mm sieve. Total N and P contents were determined by digesting 0.5 g of sample for 3 hours on aluminium digestion block at 360^{o}C after the addition of 10 mL sulphuric acid and a selenium catalyst. Afterwards, contents of total N (Krom 1980) and P (No. 7.125, AOAC 1984) in the digest were determined colorimetrically using a SKALAR continuous flow analyser. For the determining of total contents of K and Zn, 5 g of sample was digested with 5 mL of nitric acid and 3 mL of perchloric acid on an aluminum digestion block. Thereafter, the concentrations of K and Zn in the digest were measured by an atomic absorption spectrometry (No. 7.096, AOAC 1984). The nutrient uptake was estimated as percent grain or biomass nutrient content multiplied by grain yield or biomass yield (Zafar et al. 2011). The percent crude protein content was calculated by multiplying the percent N content by 6.25 (Shad et al. 2009).

7.2.3 Data analysis

Measured data on maize total BY, grain yield, nutrient contents and nutrient uptake were subjected to analysis of variance and separation of differences between treatment means involved Fisher’s protected least significant difference (LSD) test at 5% level of significance using a SAS software version 9.4. Simple Pearson’s correlation analysis was run for maize growth attributes (measured at physiological maturity), soil properties, biomass yield, grain yield and yield components, tissue crude protein and tissue nutrient uptake at crop harvest using the IBM SPSS Statistics software (Version 23). Quadratic model was fitted to the grain yield data using the Microsoft Excel program to determine the optimum compost-INPF rate and grain yield. The quadratic model is defined by equation 7.5 below:

$Y = a + bX + cX^2$……………………………………..………………………… (Equation 7.5)

whereby: Y = grain yield (kg ha^{-1}); X = compost-inorganic fertilizers rate (%); a (intercept); b (linear coefficient); and c (quadratic coefficient) (Moswatsi et al. 2013).

7.3 Results

7.3.1 Treatments and their interaction effects on total biomass yield, grain yield, harvest index and relative agronomic efficiency

The effect of compost type and application rate on total biomass, grain yield, HI and RAE at crop harvest is depicted in Table 7.1. The compost type significantly affected grain yield and HI in the 2018/19 season. The grain yield and HI in 2018/19 recorded from INC1 and UNC1 were statistically at par with those obtained from the INPF treatment. With reference to the untreated control, compost and INPF application significantly increased the grain yield and HI in 2018/19. The compost type and application rate had no significant effects on RAE.

The application rate significantly affected total biomass in 2018, grain yield in 2018/19 and HI in both seasons. The total biomass obtained from treatments with 50:50, 75:25 and 100:0 compost-INPF combinations were 19693, 18835 and 20618 kg ha^{-1} respectively, and were significantly higher than 16161 kg ha^{-1} for the untreated control in 2018. However, the total biomass obtained from the various compost-INPF combinations was statistically comparable to that recorded from the sole INPF treatment in 2018. Grain yields obtained from the 25:75 and 50:50 compost-INPF combinations were 6649 and 6246 kg ha^{-1} respectively and were significantly higher than 4557 kg ha^{-1} for the untreated control in 2018/19. The 25:75 and 50:50 compost-INPF combinations gave quantitatively higher grain yields than the 75:25 and 100:0 compost-INPF combinations in both seasons. The HI value recorded from the 25:75 compost-INPF combination was significantly higher (58%) than those recorded from the 50:50, 75:25 and 100:0 compost-INPF combinations (49%, 45% and 41%, respectively) in 2018. In 2018/19, the various compost-INPF combinations except 100:0 compost-INPF combination resulted in significantly higher HI values than the untreated control. The HI values recorded from the compost-INPF combinations were statistically at par with that recorded from sole INPF treatment in 2018/19. The interaction effect of compost type and application rate on total biomass, grain yield, HI and RAE was not significant.

Table 7.1: Effect of compost type and application rate on total biomass, grain yield, harvest index and relative agronomic efficiency (RAE)

	Total biomass (kg ha^{-1})		Grain yield (kg ha^{-1})		Harvest index (%)		RAE (%)	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type								
INC1	19329	15382	9381	5979a	49	39a	16	33
UNC1	19154	15871	9154	6106a	48	39a	12	36
INPF	19400	16843	10503	6654a	54	40a	35	45
Control	16161	14311	8499	4557b	52	32b	-	-
LSD$_{(0.05)}$	2923	2630	2408	885	11	3.31	21	24
p-value	0.170	0.285	0.566	<0.001	0.6139	<0.001	0.067	0.582
CV (%)	11	20	19	18	17	11	115	75
Application rate (WSWC:INPF)								
0:0	16161c	14311	8499	4557b	52ab	32c	-	-
25:75	17820bc	16125	10365	6649a	58a	42a	30	51
50:50	19693ab	16157	9552	6246a	49bc	39ab	18	39
75:25	18835ab	14248	8594	5641ab	45bc	40ab	2	26
100:0	20618a	15975	8560	5633ab	41c	36bc	7	23
INPF	19400ab	16843	10503	6654a	54ab	40ab	35	45
LSD$_{(0.05)}$	2584	3895	2047	1221	9.16	4.85	29	32
p-value	0.023	0.673	0.160	0.012	0.01	0.003	0.113	0.352
CV (%)	12	21	19	18	15	11	130	74
Compost type x application rate interaction								
F-test probability	ns	ns	ns	ns	ns	ns	ns	ns

Means with the same letter(s) within the same column and treatment factor are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; WSWC = winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation

7.3.2 Treatments and their interaction effects on biomass nutrient content, grain nutrient content and crude protein content

The effect of compost type and application rate on biomass nutrient content and crude protein content is presented in Table 7.2. The compost type had significant effects on biomass N, P, and crude protein contents in 2018/19, and on biomass K content in both cropping seasons. The treatments did not differ in biomass N, P, and crude protein contents in 2018 and in biomass Zn content in both seasons. The biomass N contents recorded from INC1 and UNC1 were 0.78% and 0.89%, respectively and were significantly higher than 0.54% for the untreated control but significantly lower than 1.18% for the INPF in 2018/19. A similar finding was observed for the biomass crude protein content. Both INC1 and UNC1 showed significantly lower biomass P values (0.08%) than the sole INPF treatment (0.14%) in 2018/19. Significantly higher values of biomass K content were observed in treatments with INC1 (1.45%) and UNC1 (1.64%) with reference to the untreated control treatment (1.12%) in 2018. In 2018/19, only UNC1 and sole INPF resulted in significantly higher biomass K contents (1.13 and 1.38%, respectively) than the untreated control (0.82%) in 2018/19. The biomass K content (1.02%) recorded from the INC1 was significantly lower than that recorded from the sole INPF and statistically comparable to that recorded from the UNC1 in 2018/19. The application rate significantly influenced contents of biomass N, K, and crude protein in 2018/19. Compared to the sole INPF treatment, the 50:50, 75:2, 100:0 compost-INPF combinations across the compost types gave insignificantly lower contents of biomass N and crude protein, while the 25:75 compost-INPF combination resulted in significantly lower biomass N and crude protein contents in 2018/19. The compost type and application rate interaction exerted no significant effect on biomass nutrient content, grain nutrient content and crude protein contentat crop harvest.

Table 7.3 indicates the effect of compost type and application rate on grain nutrient content and crude protein content at crop harvest. The compost type significantly affected only grain Zn content in 2018, and grain N and crude protein contents in 2018/19. The INPF treatment resulted in significantly higher contents of grain N (1.53%) and crude protein (9.51%) than the untreated control (1.25% N, 7.80% crude protein) in 2018/19. Significant differences in grain P and K contents among the compost types were not observed in both seasons. Grain nutrients and crude protein contents were not significantly influenced by the application rate and the interaction of the compost type and application rate.

Table 7.2: Effect of compost type and application rate on biomass nutrient content and crude protein content

	N (%)		**P (%)**		**K (%)**		**Zn (mg kg^{-1})**		**Crude protein (%)**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type										
INC1	1.23	0.78b	0.17	0.08b	1.45a	1.02bc	4.75	12.81	7.75	4.89b
UNC1	1.00	0.89b	0.15	0.08b	1.64a	1.13ab	4.88	10.94	6.29	5.54b
INPF	1.15	1.18a	0.17	0.14a	1.36ab	1.38a	2.00	11.75	7.05	7.38a
Control	1.30	0.54c	0.16	0.08b	1.12b	0.82c	4.50	12.00	8.30	3.38c
LSD$_{(0.05)}$	0.3993	0.2311	0.0673	0.0512	0.3033	0.25	6.89	4.9972	2.4731	1.4456
p-value	0.227	<0.001	0.676	0.007	0.001	<0.001	0.630	0.785	0.160	<0.001
CV (%)	25	20	30	39	16	17	125	31	25	20
Application rate (WSWC:INPF)										
0:0	1.30	0.54b	0.16	0.08	1.12	0.82b	4.50	12.00	8.30	3.38b
25:75	1.20	0.70b	0.15	0.08	1.50	1.00ab	2.75	8.38	7.50	4.39b
50:50	1.00	0.89ab	0.15	0.09	1.52	1.08ab	2.00	12.75	6.25	5.54ab
75:25	1.33	0.89ab	0.20	0.08	1.62	1.15ab	4.75	12.63	8.45	5.53ab
100:0	0.93	0.86ab	0.14	0.08	1.54	1.09ab	9.75	13.75	5.88	5.39ab
INPF	1.15	1.18a	0.17	0.14	1.36	1.38a	2.00	11.75	7.05	7.38a
LSD$_{(0.05)}$	0.67	0.43	0.11	0.08	0.53	0.43	11.86	8.94	4.10	2.66
p-value	0.362	0.004	0.539	0.160	0.090	0.016	0.334	0.522	0.296	0.004
CV (%)	26	22	32	40	16	17	123	33	25	22
Compost type x application rate interaction										
F-test prob.	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means with the same letter(s) within the same column and treatment factor are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; WSWC = winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation

Table 7.3: Effect of compost type and application rate on grain nutrient content and crude protein content

	N (%)		**P (%)**		**K (%)**		**Zn (mg kg^{-1})**		**Crude protein (%)**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type										
INC1	1.10	1.41ab	0.22	0.29	0.40	0.36	11.88ab	19.44	6.84	8.81ab
UNC1	0.95	1.44ab	0.17	0.30	0.31	0.36	15.89a	19.00	6.04	8.99ab
INPF	1.15	1.53a	0.27	0.29	0.37	0.34	9.50b	18.75	7.40	9.51a
Control	1.20	1.25b	0.18	0.30	0.31	0.36	11.50ab	20.50	7.75	7.80b
LSD$_{(0.05)}$	0.3403	0.2627	0.1183	0.0288	0.13	0.043	4.8386	4.2722	2.1402	1.5779
p-value	0.236	0.049	0.121	0.923	0.156	0.658	0.010	0.693	0.167	0.044
CV (%)	23	14	42	7	28	9	29	16	22	13
Application rate (WSWC:INPF)										
0:0	1.20	1.25	0.18	0.30	0.31	0.36	11.50	20.50	7.75	7.80
25:75	0.93	1.43	0.18	0.30	0.31	0.35	11.25	18.38	5.93	8.98
50:50	1.00	1.45	0.21	0.31	0.36	0.38	12.75	19.13	6.35	9.03
75:25	1.13	1.42	0.22	0.29	0.39	0.35	18.00	19.75	7.00	8.85
100:0	1.05	1.40	0.17	0.28	0.35	0.35	13.50	19.63	6.48	8.75
INPF	1.15	1.53	0.27	0.29	0.37	0.34	9.50	18.75	7.40	9.55
LSD$_{(0.05)}$	0.58	0.44	0.23	0.05	0.25	0.08	9.24	6.51	3.67	2.77
p-value	0.685	0.520	0.750	0.388	0.887	0.655	0.126	0.919	0.622	0.522
CV (%)	24	14	50	7	32	10	32	15	24	15
Compost type x application rate interaction										
F-test prob.	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means with the same letter(s) within the same column and treatment factor are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; WSWC = winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation; WSWC = winery solid waste compost

7.3.3 Treatments and their interaction effects on biomass and grain nutrient uptake

The effect of compost type and application rate on biomass nutrient uptake is presented in Table 7.4. The compost type significantly affected biomass N and P uptake in 2018/19, and the biomass K uptake in both cropping seasons. Biomass N uptake from the sole INPF treatment (194 kg ha^{-1}) was significantly higher than that recorded from the INC1 (125 kg ha^{-1}) but statistically comparable to that which was obtained from the UNC1 (145 kg ha^{-1}) in 2018/19. The biomass P uptake recorded from the sole INPF (19 kg ha^{-1}) was significantly higher than that recorded from INC1 (13 kg ha^{-1}), UNC1 (13 kg ha^{-1}) and untreated control (12 kg ha^{-1}) in 2018/19. Treatments with INC1, UNC1 and INPF across the application rates gave biomass K uptake values of 150, 178 and 153 kg ha^{-1} respectively, and were significantly higher than 105 kg ha^{-1} for the untreated control in 2018. However, the compost treatments were statistically at par with the untreated control and sole INPF in their effects on biomass K uptake in 2018/19. The interaction effect of compost type and application rate on biomass nutrient uptake was not significant.

Table 7.4: Effect of compost type and application rate on biomass nutrient uptake (kg ha^{-1})

	N		**P**		**K**		**Zn**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type								
INC1	126	125b	18	13b	150a	166ab	0.05	0.21
UNC1	109	145ab	16	13b	178a	186ab	0.06	0.19
INPF	130	194a	20	19a	153a	219a	0.03	0.19
Control	118	83b	14	12b	105b	126b	0.04	0.18
LSD$_{(0.05)}$	41	68	7	4	43	71	0.08	0.1
p-value	0.520	0.001	0.191	<0.001	0.001	0.011	0.704	0.858
CV (%)	25	36	30	20	21	30	135	39
Application rate (WSWC:INPF)								
0:0	118	83	14	12.0b	105	126	0.04	0.18
25:75	123	109	15	11.8b	149	151	0.03	0.13
50:50	105	148	16	14.3ab	159	183	0.02	0.21
75:25	141	134	22	12.3ab	180	176	0.06	0.19
100:0	101	149	15	13.0ab	168	195	0.11	0.25
INPF	130	194	20	19.0a	153	219	0.03	0.19
LSD$_{(0.05)}$	75	106	13	7	80	114	0.14	0.17
p-value	0.567	0.063	0.364	0.029	0.115	0.193	0.399	0.395
CV (%)	27.95	34.77	33.16	22.17	23.48	29.06	134.30	40.54
Compost type x application rate interaction								
F-test prob.	ns	ns	ns	ns	ns	ns	ns	ns

Means with the same letter(s) within the same column and treatment factor are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; WSWC = winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation

The effect of compost type and application rate on grain nutrient uptake is presented in Table 7.5. The compost type significantly affected grain N and Zn uptake in 2018/19 and 2018, respectively. There were no significant differences in grain N uptake in 2018/19 among the compost types. The UNC1 treatment resulted in significantly higher grain Zn uptake (0.16 kg ha^{-1}) than the INPF treatment (0.09 kg ha^{-1}) in 2018. The application rate and its interaction with the compost type exerted no significant effect on grain uptake.

Table 7.5: Effect of compost type and application rate on grain nutrient uptake (kg ha^{-1})

	N		P		K		Zn	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type								
INC1	108	90	22	19	39	23	0.11ab	0.13
UNC1	90	90	17	19	29	23	0.16a	0.12
INPF	108	91	25	19	34	22	0.09b	0.11
Control	119	63	17	15	31	18	0.12ab	0.10
LSD$_{(0.05)}$	28	29	10	6	11	8	0.06	0.03
p-value	0.069	0.034	0.116	0.274	0.102	0.301	0.015	0.075
CV (%)	19	25	36	27	25	26	34	18
Application rate (WSWC:INPF)								
0:0	119	63	18	15	31	18	0.12	0.10
25:75	97	94	18	20	33	23	0.12	0.12
50:50	96	93	21	20	35	24	0.12	0.13
75:25	110	85	22	17	38	21	0.18	0.12
100:0	93	87	16	17	30	22	0.12	0.12
INPF	108	91	25	19	34	22	0.09	0.11
LSD$_{(0.05)}$	57	45	20	10	24	12	0.11	0.05
p-value	0.669	0.302	0.775	0.530	0.899	0.660	0.227	0.523
CV (%)	24.26	23.50	44.46	24.71	32.32	24.43	39.49	19.40
Compost type x application rate interaction								
F-test prob.	ns	ns	ns	ns	ns	ns	Ns	ns

Means with the same letter(s) within the same column and treatment factor are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; WSWC = winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = least significant difference; CV = coefficient of variation

7.3.4 Correlations among the maize growth parameters, soil properties, total biomass yield, grain yield, tissue crude protein content and tissue nutrient uptake

The results of correlation analysis of maize growth parameters and yield components with the total biomass yield and grain yield are indicated in Table 7.6. Grain yield gave positive and significant (p = 0.05) correlation with cob length and grain number cob^{-1}, but it showed positive and highly significant (p = 0.01) correlation with plant height, stem girth, LAI, cob weight, grain weight cob^{-1}, TSW and BY. The total BY showed positive and highly significant correlation with plant height, stem girth, LAI, cob length, cob weight, grain weight cob^{-1}, grain number cob^{-1} and TSW. Harvest index showed positive and highly significant correlation with plant height, LAI, grain weight cob^{-1}, TSW and grain yield but it gave positive and significant correlation with stem girth and cob weight.

Table 7.6: Results of correlation analysis of the maize growth parameters and yield components with the total biomass yield and grain yield

Parameters	**PLHT**	**SG**	**LAI**	**CL**	**CW**	**GWC**	**GNC**	**TSW**	**TBY**	**GY**	**HI**
TBY	0.83**	0.85**	0.73**	0.66**	0.94**	0.90**	0.68**	0.86**	1		
GY	0.95**	0.80**	0.87**	0.54*	0.81**	0.88**	0.53*	0.88**	0.79**	1	
HI	0.78**	0.53*	0.73**	0.33	0.50*	0.62**	0.30	0.64**	0.41	0.88**	1

PLHT = plant height; SG = stem girth; LAI = leaf area index; CL = cob length; CW = cob weight; GWC = grain weight per cob; GNC = grain number per cob; TSW = thousand seed weight; TBY = total biomass yield; GY = grain yield; HI = harvest index; *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

Table 7.7 depicts the results of correlation analysis of the yield components, total BY, grain yield and HI with the grain nutrient uptake and grain crude protein content. Grain N uptake correlated positively and significantly with cob length, cob weight, grain weight cob^{-1}, TSW, total BY, grain yield and HI. Grain K uptake showed positive and significant correlation with cob length, but it gave highly significant and positive correlation with cob weight, grain weight cob^{-1}, TSW, total BY, grain yield and HI. Grain crude protein content had a negative and highly significant correlation with cob weight, grain weight cob^{-1}, TSW, total BY, grain yield and HI.

Table 7.7: Results of correlation analysis between biomass yield, grain yield, grain nutrient uptake and grain crude protein content

Parameters	**CL**	**CW**	**GWC**	**GNC**	**TSW**	**TBY**	**GY**	**HI**
Grain N uptake	0.51*	0.48*	0.48*	0.40	0.40*	0.51*	0.61**	0.53*
Grain P uptake	0.01	0-.12	-0.12	0.02	-0.13	-0.06	0.02	0.08
Grain K uptake	0.54*	0.74**	0.76**	0.36	0.78**	0.69**	0.79**	0.63**
Grain Zn uptake	0.24	0.21	0.22	0.07	0.24	0.31	0.17	0.02
Grain crude protein content	-0.33	-0.72**	-0.80**	-0.35	-0.84**	-0.61**	-0.73**	-0.60**

CL = cob length; CW = cob weight; GWC = grain weight per cob; GNC = grain number per cob; TSW = thousand seed weight; TBY = total biomass yield; GY = grain yield; HI = harvest index; *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

Table 7.8 presents the results of correlation analysis of maize growth parameters with tissue crude protein content and nutrient uptake. The biomass N uptake was significantly and negatively correlated with plant height, stem girth and LAI whereas the biomass P uptake showed positive and highly significant correlation with these growth parameters. The biomass crude protein content had positive and significant correlation with stem girth, but it showed highly significant and positive correlation with plant height and LAI. Grain N uptake presented a highly significant and positive correlation with plant height, but it showed a significant and positive correlation with LAI. Grain K uptake showed positive and highly significant correlation with plant height, stem girth and LAI. Grain crude protein content gave negative and highly significant correlation with plant height, stem girth and LAI.

Table 7.8: Results of correlation analysis of maize growth parameters with tissue crude protein content and nutrient uptake

Parameters	**Plant height**	**Stem girth**	**Leaf area index**
Biomass N uptake	-0.48^{*}	-0.45^{*}	-0.45^{*}
Biomass P uptake	0.61^{**}	0.63^{**}	0.57^{**}
Biomass K uptake	-0.06	0.03	-0.19
Biomass Zn uptake	-0.35	-0.26	-0.33
Biomass crude protein content	0.56^{**}	0.53^{*}	0.60^{**}
Grain N uptake	0.58^{**}	0.41	0.44^{*}
Grain P uptake	-0.06	-0.11	-0.09
Grain K uptake	0.75^{**}	0.67^{**}	0.68^{**}
Grain Zn uptake	0.22	0.29	0.20
Grain crude protein content	-0.76^{**}	-0.77^{**}	-0.83^{**}

*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

The results of correlation analysis of soil properties with plant growth parameters, biomass yield, grain yield, tissue nutrient uptake and crude protein content are indicated in Table 7.9. The correlation of soil bulk density, porosity, pH and the contents of NO_3, Na, Zn and organic C with the plant growth and yield parameters as well as tissue nutrient uptake and crude protein content was insignificant. The soil NH_4 content showed positive and significant correlation with cob weight, biomass crude protein content and grain K uptake. Furthermore, its correlations with plant height, stem girth, LAI, grain weight cob^{-1}, TSW, GY and HI was positive and highly significant. The grain crude protein content correlated negatively and significantly with the soil NH_4 content. The soil P content gave positive and significant correlation with plant height, stem girth, cob weight, grain weight cob^{-1}, TSW and grain yield, but it showed positive and highly significant correlation with biomass P uptake and total BY. The stem girth showed positive and highly significant correlation with the soil K content, while cob weight, grain weight cob^{-1}, TSW, total BY and grain Zn uptake correlated significantly and positively with the soil K content.

Table 7.9: Results of correlation analysis of soil properties with plant growth parameters, biomass yield, grain yield, tissue nutrient uptake and tissue crude protein content

Parameters	**BD**	**Porosity**	**pH**	**NO_3**	**NH_4**	**P**	**K**	**Na**	**Zn**	**OC**
PLHT	-0.17	0.19	-0.23	0.20	0.59^{**}	0.48^{*}	0.37	-0.13	-0.16	0.11
SG	-0.28	0.29	-0.25	0.26	0.59^{**}	0.54^{*}	0.67^{**}	-0.01	-0.35	0.24
LAI	-0.29	0.30	-0.24	0.23	0.67^{**}	0.38	0.41	-0.16	-0.40	0.10
CL	0.12	-0.12	0.12	0.16	0.29	0.40	0.39	0.28	0.27	0.42
CW	-0.28	0.28	-0.13	0.09	0.52^{*}	0.53^{*}	0.47^{*}	-0.09	-0.05	0.26
GWC	-0.28	0.28	-0.19	0.15	0.60^{**}	0.53^{*}	0.49^{*}	-0.11	-0.20	0.20
GNC	-0.04	0.04	0.24	0.16	0.17	0.39	0.31	0.09	0.25	0.32
TSW	-0.30	0.30	-0.23	0.14	0.65^{**}	0.50^{*}	0.48^{*}	-0.13	-0.27	0.18
TBY	-0.26	0.27	-0.17	0.05	0.35	0.59^{**}	0.48^{*}	-0.09	0.09	0.19
GY	-0.23	0.26	-0.27	0.14	0.59^{**}	0.53^{*}	0.21	-0.19	-0.10	0.07
HI	-0.12	0.15	-0.28	0.17	0.59^{**}	0.35	-0.05	-0.23	-0.18	-0.05
Biomass CPc	-0.14	0.13	-0.17	0.08	0.53^{*}	0.42	0.13	-0.04	-0.21	0.09
Biomass N uptake	-0.08	0.07	0.11	-0.29	-0.29	-0.36	-0.31	-0.08	-0.22	-0.20
Biomass P uptake	-0.15	0.15	-0.22	-0.01	0.35	0.59^{**}	0.31	-0.09	-0.05	0.08
Biomass K uptake	0.07	-0.07	-0.001	0.11	-0.38	0.31	0.35	0.23	0.37	0.08
Biomass Zn uptake	0.26	-0.26	0.19	-0.19	-0.23	-0.22	-0.09	0.17	-0.06	-0.04
Grain CPc	0.31	-0.32	0.22	-0.28	-0.63^{**}	-0.35	-0.44	0.16	0.42	-0.02
Grain N uptake	0.05	-0.03	-0.09	-0.17	0.27	0.32	0.04	-0.07	0.13	0.14
Grain P uptake	0.09	-0.12	0.03	0.29	0.17	0.37	-0.15	0.02	0.27	0.24
Grain K uptake	-0.10	0.11	-0.08	-0.15	0.56^{*}	0.35	0.21	0.02	-0.13	0.24
Grain Zn uptake	0.02	-0.02	-0.12	-0.06	0.003	0.30	0.53^{*}	-0.06	0.03	-0.18

BD = soil bulk density; OC = soil organic carbon; PLHT = plant height; SG = stem girth; LAI = leaf area index; CL = cob length; CW = cob weight; GWC = grain weight per cob; GNC = grain number per cob; TSW = thousand seed weight; TBY = total biomass yield; GY = grain yield; HI = harvest index; CPc = crude protein content; *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

7.3.5 Optimum compost-INPF combination

The optimum compost-INPF rate and grain yield are presented in Table 7.10. The optimum rate of INC1-INPF (36:64) was associated with the higher optimum grain yield of 9887 kg ha^{-1} as compared to the optimum rate of UNC1-INPF (50:50) with grain yield of 9560 kg ha^{-1} in 2018. In 2018/19, the application rate of 52:48 was optimal for UNC1-INPF with higher optimum grain yield of 6728 kg ha^{-1}, whereas the INC1-INPF combination was optimal at 61:39 with grain yield of 6056 kg ha^{-1}. Across the cropping seasons, the optimum rate of UNC1-INPF (51:49) was associated with higher grain yield than the optimum combination of INC1-INPF (45:55). The R^2-values the quadratic equations were lower for INC-INPF combination (range: 0.18-0.29) and remarkably high for the UNC1-INPF combination (range: 0.91-0.98).

Table 7.10: Regression equations, predicted optimum grain yield and compost-INPF application rates

Treatments	Season	Regression equation	R^2	X (%)	Y (kg ha^{-1})
INC1+INPF	2018	$Y = 9275 + 33.99X - 0.472X^2$	0.29	36:64	9887
	2018/19	$Y = 5084 + 32.10X - 0.265X^2$	0.19	61:39	6056
	2018+2018/19	$Y = 7180 + 33.06X - 0.369X^2$	0.18	45:55	7920
UNC1+INPF	2018	$Y = 8485+42.95X - 0.429X^2$	0.94	50:50	9560
	2018/19	$Y = 5084 + 32.10X - 0.265X^2$	0.91	52:48	6728
	2018+2018/19	$Y = 6587 + 60.30X - 0.584X^2$	0.98	51:49	8143

X = optimum application rate; Y = optimum grain yield; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; INPF = inorganic nitrogen and phosphorus fertilizers

7.4 Discussion

Increased biomass production depends on the agricultural practices and genetic modifications that would increase plant growth and produce augmented dry matter (Lima et al. 2017). The increase in total BY observed from treatments with 50:50, 75:25 and 100:0 compost-INPF combinations compared to the untreated control across the compost types may be attributed to improved crop growth due to enhanced nutrients availability and other soil properties in 2018. However, treatments with compost-INPF combinations presented a total biomass that was statistically comparable to that obtained from the sole INPF treatment in 2018. The increase in GY and HI given by WSW compost types and INPF in comparison to the untreated control across the application rate during the drier 2018/19 season may be due to the increased availability of nutrients for crop uptake. Muhammad and Jan (2016) attributed the increase in HI following compost application to greater yields, yield components and grain N use efficiency increased nutrient availability for uptake. The enhanced GY with 25:75 and 50:50 combinations of compost and INPF across the compost types in 2018/19 may be due to increased N and P availability in the soil for crop uptake. Shah et al. (2007) also reported higher grain yield from a treatment that received compost and N from urea in 25:75 and 50:50 ratios.

The prediction of optimal rate using the quadratic model indicated that the INC1 needs to be applied in higher quantities under harsh environmental conditions to obtain the optimum grain yield. The predicted optimum application rates using the grain yield data across the cropping seasons were approximately 50:50. The combined application of organic manures and inorganic P fertilizer at 50:50 ratio performed better as compared 100:0 and 75:25 ratios and produced higher yield and yield components (Ali et al. 2019). Ojiem et al. (2003) reported that a 50:50 combination of organic and inorganic P fertilizers appears to be the optimum for maize.

Shah et al. (2007) recommended both 50:50 and 75:25 ratios (urea and compost) for profitable maize yield.

It is vital to note that the significant correlation between maize grain yield and the contents of soil NH_4 and P indicates that these soil health properties contributed to the final grain yield. Consequently, the contents of soil NH_4 and P following the application of compost-INPF played a significant role in the selection of the combination of compost and INPF for higher grain yield. Grain K and N uptake may also be used as indicators for selecting the suitable compost and INPF for higher GY based on their highly significant and positive relationships with the grain yield. The significant and positive (r = 0.53-0.95) correlations of GY and total BY with the measured plant growth parameters and yield components is a further indication that any WSW compost and INPF combination that influences the measured growth attributes and yield components will likely affect the GY and total BY. These positive and significant relationships between the maize growth parameters, yield and yield components parameters observed in this study reiterates the findings of other researchers. For instance, Kara et al. (1999) reported that the green forage yield in maize was positively correlated with stem diameter and cob weight. Similarly, Gallais et al. (1976) showed that plant height and stem diameter are associated to dry matter yield, while Carpici and Celik (2010) stated that the dry forage yield was positively and significantly correlated with plant height and leaf area index. The finding that the total BY was positively correlated with grain yield is consistent with the findings reported by Iptaş and Yavuz (2008) and Tajul et al. (2013). Rahman et al. (2017) demonstrated that yield plant^{-1} was positively and significantly associated with plant height, cob length, TSW, grain number cob^{-1}. Additionally, Tajul et al. (2013) demonstrated that GY had significant positive correlation with LAI, whereas Inamullah et al. (2011) reported that HI showed positive and highly significant correlation with TSW and grain yield.

7.5 Conclusions and recommendations

The results deduced from this study evinced that the combined application of winery solid waste compost and INPF holds immense possiblities for the improvement of maize productivity. The fertilization of soil with sole INPF, 25:75 and 50:50 combinations of compost and INPF across the compost types was beneficial to improve maize grain yield under the harsh environmental conditions of the 2018/19 seasons. It is reasonable then to recommend the 50:50 compost-INPF combination for grain yield production since the predicted optimum rates using the grain yield data across the cropping seasons were approximately 50:50. Maize grain yield correlated positively and significantly with the soil NH_4 and P contents, indicating that these soil health properties contributed to the final grain yield. Therefore, the selection of the combination of compost and INPF for higher grain yields demands the consideration of the contents of soil NH_4 and P following the application of that selected combination. Grain K and N uptake may also be used as indicators for selecting the suitable compost and INPF for higher GY based on their significant and positive relationships with the grain yield. The selection of the compost-INPF combinations for the production of higher yields must also take into cognisance the combinations that enhance the growth attributes and yield components as indicated by the positive correlations of yields with the plant growth parameters and yield components.

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CHAPTER 8

Soil health indicators as affected by combined application of inorganic fertilizers and winery solid waste compost produced with and without effective microorganisms inoculation

Abstract

Soil health indicators were evaluated following the combined application of inorganic nitrogen (N) and phosphorus (P) fertilizers (INPF) and winery solid waste (WSW) compost during the 2018 and 2018/19 summer cropping seasons under field conditions. The INPF and previously obtained optimum rates of the two WSW composts were combined at different ratios (0:0, 75:25, 50:50, 25:75 and 0:100 w/w) to supply proportionate N and P amount for the field trial. Recommended inorganic fertilizer rates of 200 kg N ha^{-1} and 90 kg P ha^{-1} were mixed and included as a standard control. All treatments were combined and arranged in factorial arrangement fitted in a randomized complete block design with three replicates. Results revealed that the sole application of compost or combined application with the INPF increased soil pH and soil organic C, P, K, Na and Zn contents. Sole INC1 application resulted in the highest soil pH values of 7.58 and 7.90 in 2018 and 2018/19, respectively. The highest contents of soil organic C were found in the UNC1 treatment (1.15%) in 2018 and in the INC1 treatment (1.17%) in 2018/19. The soil NO_3 content ranged from 3.03 mg kg^{-1} with UNC1-INPF at 50:50 to 40.50 mg $kg^{-1}$with UNC1-INPF at 100:0 in 2018 and from 4.07 mg kg^{-1} with the control to 21.38 mg kg^{-1} with UNC1-INPF at 100:0 in 2018/19. The soil NH_4 content was highest in the UNC1 treatment (4.30 mg kg^{-1}) in 2018 and in the treatment with 50:50 mix ratio of INC1. The 25:75 mix ratio of UNC1 and INPF gave the highest Bray-1 P content of 188 mg kg^{-1} in 2018. The highest exchangeable K contents of 1526 mg kg^{-1} was obtained in 2018 trial from the UNC1 treatment. It also gave the highest Na content of 148 mg kg^{-1} in 2018/19. The 50:50 mix ratio of UNC1 and INPF resulted in the highest soil extractable Zn contents of 23.80 mg kg^{-1} in 2018/19. In conclusion, the combined use of WSW compost and INPF may prove an indispensable alternative way for the improvement of soil health indicators. The WSW compost may be used on acidic soils for addressing soil acidity problems, maximize plant nutrient availability and for increasing microbial activity.

Keywords: effective microorganism inoculation, soil health indicators, winery solid waste compost

8.1 Introduction

Soil quality or health is defined as the capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Bonilla et al. 2012). According to Iqbal et al. (2014), recent emphasis on sustainable agriculture has generated interest regarding the optimization of all aspects of the soil's physical, chemical and biological functioning. Soil health indicators are a composite set of measurable soil properties, which relate to functional soil processes and can be used to evaluate the health status of soil, as affected by soil use, management and climate change drivers (Allen et al. 2011; Cardoso et al. 2013). Soil properties with a rapid response to natural or anthropogenic actions are considered as good indicators of soil health. The physical indicators of soil health include soil texture, aggregation, moisture, porosity, and bulk density, while chemical indicators comprise total C and N, mineral nutrients, organic matter, cation exchange capacity, to mention a few (Cardoso et al. 2013). An optimal level of soil organic matter content is essential to all soil properties and processes (Lal 2011). The soil organic matter and total N are the major determinants and indicators of soil quality and fertility and are closely related to soil productivity in an agricultural ecosystem (Adeboye et al. 2011). The biological indicators include measurements of microorganisms and macroorganisms, their activities (for example, enzyme activity) or functions (Martinez-Salgado et al. 2010). The soil microbial biomass is a small but key component of the active soil organic matter pool and serves as a source and sink of soil nutrients (Adeboye et al. 2011).

Soil degradation implies a decline in soil quality with an attendant reduction in ecosystem functions and services (Lal 2015). Du Preez et al. (2011) opine that the degradation of South African's soil resource base poses a serious threat to sustainable agricultural production. According to Chianu et al. (2012), the devastating consequence of severe soil degradation is such that even legumes perform poorly and are unable to produce sufficient biomass. Some of the contributing factors to soil degradation include the increasing intensity of land use without adequate and balanced use of chemical fertilizers and with little or no use of organic manure (Ali et al. 2009). The soil organic matter is a key factor to crop productivity and sustainable soil fertility (Ali et al. 2009). It is necessary to develop alternative nutrient management practices to maintain soil health to increase productivity and crop yields (El Sheikha 2016). According to Chen (2006), the advantages of the different fertilizers (chemical fertilizer, organic fertilizer or bio-fertilizer) need to be integrated to maximize the use of each type of fertilizer and achieve balanced nutrient management for crop growth and environmental quality. Given the interconnectedness of soil health challenges, sustainable agriculture and food security, the pertinence of maintaining qualitative soil health cannot be overemphasised. Against this background, this study was conducted to evaluate the effects of the combined application of winery solid waste compost and inorganic N and P fertilizers onsoil health indicators.

8.2 Materials and methods

8.2.1 Experimental design and procedures

The full details of the design and procedures of the trials have been previously presented in chapter 6. Briefly, inoculated (INC1) and uninoculated (UNC1) compost types were initially evaluated through a 7 weeks tunnel house maize pot trial at 0, 5, 10, 20 and 40 kg ha^{-1} application rates to predict their optimum rate based on maize dry matter yield using a quadratic model (refer to Chapter 5). Thereafter, the INPF and obtained optimum rates for the two composts were combined at different ratios (0:0, 75:25, 50:50, 25:75 and 0:100, w/w) to supply proportionate N and P amount for the field trial. The recommended inorganic fertilizer rates of 200 kg N ha^{-1} and 90 kg P ha^{-1} were mixed and included as a standard control. All treatments were combined and arranged in factorial arrangement fitted in a randomized complete block design with three replicates. Selected physico-chemical properties of the soil determined before planting following standard laboratory procedures are described in sub-section 5.3.3 of chapter 5.

8.2.2 Data collection

The assessment of bulk density and porosity took place at maize harvest. The bulk density was determined by collecting a known volume of soil using a metal ring pressed into the soil (0 - 15 cm depth), and determining the weight after drying (McKenzie et al. 2004; Lal & Shukla 2004). The porosity of the soil was estimated using the following equation and assuming that the soil particle density is 2.65 g cm^{-3} (Brady 1984):

Porosity = $\{1 - (\rho_b/\rho_s) \times 100\}$………………………………………………….. (Equation 6.1)

whereby: ρ_b and ρ_s represent soil bulk density and particle density, respectively.

Soil samples (0-15 cm depth) were collected from each plot, bulked according to their treatments at crop harvest. Subsequently, the soil chemical health indicators that included pH

(KCl), electrical conductivity, organic C (Walkley-Black method), available P (Bray-1), extractable K (NASAWC, 1990) and mineral N (Okalebo et al. 2002) were analyzed.

8.2.3 Data analysis

Soil physical properties were subjected to analysis of variance and separation of differences between treatment means using Fisher's protected least significant difference (LSD) test at 5% level of significance using a SAS software version 9.4. The collected data on soil chemical properties were subjected to classical statistical methods to obtain the minimum, maximum, mean, median, skewness (Phefadu & Kutu 2016).

8.3 Results

8.3.1 Treatments and their interaction effects on soil bulk density and porosity at tasselling stage and crop harvest

Table 8.1 indicates the effect of compost type and application rate on soil bulk density and porosity at tasselling stage and crop harvest. The compost type significantly affected soil bulk density and porosity at tasselling stage in both cropping seasons. It also significantly influenced these parameters at crop harvest only in 2018/19. The soil bulk densities measured at tasselling stage from the INC1 and UNC1 were significantly lower than that from the untreated control in 2018. In 2018/19, significant decreases in bulk density were recorded from INC1 and UNC1 treatments with reference to both the untreated control and INPF at tasselling stage. Both INC1 and UNC1 treatments resulted in significantly lower bulk densities than the untreated control and INPF at crop harvest in 2018/19. Soil porosity was increased significantly following compost application with reference to the untreated control at tasselling stage in both cropping seasons. Soil porosity values recorded from the INC1 and UNC1 treatments were quantitatively higher than that recorded from the INPF treatment and the untreated control at crop harvest in 2018. The UNC1 application resulted in higher and significant increase in soil porosity followed by the INC1 application at crop harvest in 2018/19. The soil bulk density was significantly influenced by the application rate in both seasons, while porosity was not affected by the application rate only at crop harvest in 2018.

Table 8.1: Effect of compost type and application rate on soil bulk density and porosity at tasselling stage and crop harvest

	Tasselling stage				**Crop harvest**			
	Bulk density (g cm^{-3})		**Porosity (%)**		**Bulk density (g cm^{-3})**		**Porosity (%)**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
Compost type								
INC1	1.17b	1.14c	56a	57a	1.16a	1.22b	56a	54b
UNC1	1.14b	1.15c	57a	57a	1.13a	1.13c	58a	57a
INPF	1.23ab	1.21b	54ab	54b	1.24a	1.43a	54a	46c
Control	1.30a	1.27a	51b	52c	1.23a	1.36a	54a	49c
LSD$_{(0.05)}$	0.11	0.0525	4.02	1.98	0.10	0.0735	4	2.775
p-value	0.030	<0.001	0.028	<0.001	0.094	<0.001	0.139	<0.001
CV (%)	6.94	5.35	5.32	4.37	6.65	6.95	5.25	6.54
Application rate (WSWC:INPF)								
0:0	1.30a	1.27a	51.0d	52.1d	1.23a	1.36ab	54.0a	48.8de
25:75	1.19bc	1.21ab	55.3bc	54.3cd	1.16ab	1.21cd	56.2a	54.5bc
50:50	1.21bc	1.20b	54.7bc	54.8c	1.17ab	1.29bc	56.0a	51.2cd
75:25	1.13cd	1.12c	57.3ab	57.8b	1.14b	1.12de	56.8a	57.6ab
100:0	1.09d	1.05d	58.8a	60.3a	1.11b	1.09e	58.2a	58.8a
INPF	1.23ab	1.21b	54.0c	54.4c	1.24a	1.43a	53.7a	46.2e
LSD$_{(0.05)}$	0.0829	0.0591	2.966	2.23	0.0843	0.0981	3.2474	3.7027
p-value	<0.001	<0.001	<0.001	<0.001	0.032	<0.001	0.069	<0.001
CV (%)	5.89	4.25	4.54	3.39	6.08	6.64	4.92	5.92

Means with the same letter(s) within the same column and treatment are not significantly different at 5% probability level; INPF = nitrogen and phosphorus fertilizers; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; LSD = least significant difference; CV = coefficient of variation; WSWC = winery solid waste compost

The various compost-INPF combinations resulted in significantly lower soil bulk densities than the untreated control at tasselling stage in 2018. In 2018/19, lower soil bulk densities were recorded only from 50:50, 75:25 and 100:0 compost-INPF combinations with reference to the untreated control at tasselling stage. Only 75:25 and 100:0 gave lower soil bulk densities in comparison with both the untreated control and INPF at crop harvest in 2018. The compost-INPF combinations resulted in significantly lower soil bulk densities and higher soil porosity than the INPF, but only soil bulk density and porosity recorded from the 50:50 compost-INPF combination were statistically comparable to that recorded from the untreated control at crop harvest in 2018/19. Only 100:0 of compost-INPF combination gave significantly higher soil porosity than both the untreated control and INPF at crop harvest in 2018/19. Compared to the untreated control, the various compost-INPF combinations induced significant increases insoil porosity at tassellingstage in 2018. In 2018/19, the various application rates except 25:75 compost-INPF combinations resulted in significant increase in soil porosity with reference to the untreated control at tasselling stage. The 75:25 and 100:0 compost-INPF combinations resulted in significantly higher soil porosity than the INPF at tasselling stage in both seasons.

The interaction effect of compost type and application rate on soil bulk density and porosity measured at tasselling stage and crop harvest was significant only in 2018/19 (Table 8.2). At tasselling stage, soil bulk density ranged from 1.06 g cm^{-3} with UNC1-INPF (100:0) to 1.30 g cm^{-3} with the untreated control in 2018 and from 1.02 g cm^{-3} INC1-INPF (100:0) to 1.27 g cm^{-3} with the untreated control in 2018/19. Treatments with INC1-INPF (75:25; 100:0) and UNC1-INPF (75:25; 100:0) significantly decreased soil bulk density with reference to the untreated control at tasselling stage in 2018/19. Both INC1-INPF (100:0) and UNC1-INPF (100:0) gave significantly lower soil bulk densities than the INPF in 2018/19 at tasselling stage. At crop harvest, the soil bulk density varied between 1.09 g cm^{-3} with UNC1-INPF (75:25) and 1.24 g cm^{-3} with the INPF in 2018 and between 1.05 g cm^{-3} UNC1-INPF (100:0) and 1.43 g cm^{-3} with INPF in 2018/19. The compost-INPF combinations except the INC1-INPF (50:50) combination decreased soil bulk density significantly with reference to the INPF at crop harvest in 2018/19. Only treatments with INC1-INPF (25:75; 50:50) had insignificantly lower soil bulk densities than the untreated control at crop harvest in 2018/19. The soil porosity ranged from 51% with the untreated control to 60% with UNC1-INPF (100:0) in 2018 and from 52.1% with the untreated control to 61.5% with INC1-INPF (100:0)

Table 8.2: Interaction effect of compost type and application rate on soil bulk density and porosity at tasselling stage and crop harvest

	Tasselling stage				**Crop harvest**			
	Bulk density (g cm^{-3})		**Porosity (%)**		**Bulk density (g cm^{-3})**		**Porosity (%)**	
Treatments	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**	**2018**	**2018/19**
INC1+INPF (25:75)	1.19	1.23a	55	53.6e	1.18	1.30bc	55	51cd
INC1+INPF (50:50)	1.23	1.18abcd	54	55.6bcde	1.18	1.35abc	55	49.1cde
INC1+INPF (75:25)	1.14	1.12bcd	57	57.6bcd	1.19	1.11e	55	58.1a
INC1+INPF (100:0)	1.12	1.02e	58	61.5a	1.10	1.13de	59	57.2ab
UNC1+INPF (25:75)	1.18	1.19abc	56	54.9cde	1.14	1.12e	57	57.9a
UNC1+INPF (50:50)	1.18	1.22ab	55	54.0de	1.15	1.24cd	57	53.4bc
UNC1+INPF (75:25)	1.12	1.11cde	58	58.0abc	1.09	1.14de	59	57.1ab
UNC1+INPF (100:0)	1.06	1.08de	60	59.1ab	1.12	1.05e	58	60.4a
INPF	1.23	1.21abc	54	54.4cde	1.24	1.43a	54	46.2e
Control	1.30	1.27a	51	52.1e	1.23	1.36ab	54	48.8de
LSD$_{(0.05)}$	0.14	0.0964	5	3.638	0.13	0.12	5	4.5283
p-value	0.081	0.001	0.082	0.001	0.333	<0.001	0.394	<0.001
CV (%)	6.94	4.23	5.32	3.78	6.65	5.73	5.25	4.90

Means with the same letter(s) within the same column are not significantly different at 5% probability level; where letters are not presented indicate no significant differences; INC1 denotes inoculated winery solid waste compost; UNC1 denotes uninoculated winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; LSD = Least significant difference; CV = coefficient of variation in 2018/19 at tasselling stage. The INC1-INPF (75:25; 100:0) and UNC1-INPF (75:25; 100:0) combinations significantly increased the soil porosity with reference to the untreated control at tasselling stage in 2018/19. The INC1-INPF (100:0) and UNC1-INPF (100:0) gave significantly higher values of soil porosity than the INPF at tasselling stage in 2018/19. The soil porosity varied between 54% with the untreated control/INPF and 59% with INC1-INPF (100:0)/UNC1-INPF (75:25) in 2018 and between 46.2% with the untreated control and 60% with UNC1-INPF (100:0) in 2018/19 at crop harvest. There was no significant difference in soil porosity among the compost-combinations in 2018. The compost-INPF combinations except INC1-INPF (50:50) combination significantly increase the soil porosity at crop harvest in 2018/19 with reference to the INPF. The soil porosity recorded from the treatments with INC1-INPF (25:75; 50:50) was statistically comparable to that recorded from the untreated control at crop harvest in 2018/19.

8.3.2 Soil chemical properties measured at crop harvest

Table 8.3 presents soil chemical properties measured at crop harvest during the 2018 and 2018/19 cropping seasons. The soil pH ranged from 6.29 with the sole INPF to 7.58 with the INC-INPF (100:0) in 2018, and from 6.35 with the sole INPF to 7.90 with INC1-INPF (100:0) in 2018/19. The compost-INPF application increased soil pH with reference to both the untreated control and sole INPF treatment in 2018. Only treatments with the INC1-INPF (25:75; 50:50) combinations did not increase the soil pH compared to the untreated control in 2018/19. The soil organic C ranged from 0.58% with the untreated control to 1.15% with the UNC1-INPF (100:0) in 2018 and from 0.48% with INPF to 1.17% with the INC1-INPF (100:0) in 2018/19. Compared to control and sole INPF treatment, the UNC1-INPF (50:50) gave lower soil organic C in 2018, but higher soil organic C in 2018/19, whereas the remaining treatments resulted in higher soil organic C in both cropping seasons. The 100:0 compost-INPF gave higher values of soil organic C than the remaining treatment combinations. The compost-INPF combinations increased the soil P, K, Na and Zn contents as compared to the untreated control in both cropping seasons. Treatments with INC1-INPF (25:75) and UNC1-INPF (50:50) gave lower soil P content when compared to sole INPF in 2018, whereas all treatment combinations except UNC1-INPF (50:50) resulted in lower soil P content than the sole INPF treatment in 2018/19. The highest NO_3 content of 40.50 mg kg^{-1} was recorded from the UNC1-INPF (100:0) in 2018. In 2018/19, the compost-INPF combinations gave higher amounts of NO_3 than the untreated control and the sole INPF.

Table 8.3: Soil chemical properties measured at crop harvest during the 2018 and 2018/19 cropping seasons

	2018 cropping season								2018/19 cropping season							
			NO_3	NH_4	P	K	Na	Zn			NO_3	NH_4	P	K	Na	Zn
Treatments	**pH$_{(KCl)}$**	**OC (%)**	**(mg kg^{-1})**						**pH$_{(KCl)}$**	**OC (%)**	**(mg kg^{-1})**					
INC1+INPF (25:75)	7.07	1.04	14.60	4.25	129	295	85	10.13	7.14	0.58	9.35	1.70	118	248	43	15.40
INC1+INPF (50:50)	7.09	0.60	4.63	2.20	166	806	58	9.40	7.19	0.71	19.00	2.55	104	550	80	11.00
INC1+INPF (75:25)	7.26	1.03	14.08	4.05	177	841	75	5.99	7.53	0.72	5.33	1.45	80	480	90	8.72
INC1+INPF (100:0)	7.58	1.13	10.22	2.65	142	1257	85	8.42	7.90	1.17	11.96	1.55	62	590	103	12.60
UNC1+INPF (25:75)	7.12	0.45	29.14	2.95	188	837	45	7.58	7.18	0.74	7.44	1.35	131	400	70	11.68
UNC1+INPF (50:50)	7.22	0.37	3.03	1.60	109	759	55	11.03	7.38	0.76	10.71	1.70	184	343	63	23.80
UNC1+INPF (75:25)	7.22	0.55	4.34	2.15	177	1476	63	7.90	7.53	0.92	13.57	1.70	82	500	78	10.16
UNC1+INPF (100:0)	7.49	1.15	40.50	4.30	151	1526	88	5.93	7.78	0.91	21.38	1.70	81	1080	148	7.60
INPF	6.29	1.07	21.74	3.20	142	221	83	10.45	6.35	0.48	6.93	1.15	152	200	45	14.60
Control	6.98	0.58	4.51	3.00	38	205	50	5.07	7.32	0.50	4.07	1.95	30	193	40	4.44
Minimum	6.29	0.37	3.03	1.60	38	205	45	5.07	6.35	0.48	4.07	1.15	30	193	40	4.44
Maximum	7.58	1.15	40.50	4.30	188	1526	88	11.03	7.90	1.17	21.38	2.55	184	1080	148	23.80
Mean	7.13	0.80	14.68	3.04	142	822	69	8.19	7.33	0.75	10.97	1.68	102	458	76	12.00
Median	7.17	0.82	12.15	2.98	147	821	69	8.16	7.35	0.73	10.03	1.70	93	440	74	11.34
Standard deviation	0.35	0.31	12.44	0.93	43.84	487	16.31	2.07	0.43	0.21	5.69	0.38	45.26	261	33	5.27
SEM	0.11	0.10	3.93	0.29	13.86	154	5.16	0.66	0.14	0.07	1.80	0.12	14.31	83	10.37	1.67
Skewness	-1.50	-0.11	1.14	0.10	-1.58	0.13	-0.15	-0.15	-1.17	0.66	0.78	1.22	0.33	1.54	1.11	1.08
CV (%)	4.90	39.08	84.75	31.73	31	59	24	25.31	5.84	28.07	51.86	22.54	44	57	43	43.89

OC = soil organic carbon; INC1 = inoculated winery solid waste compost; UNC1 = uninoculated winery solid waste compost; INPF = nitrogen and phosphorus fertilizers; SEM = standard error of mean; CV = coefficient of variation

Only treatments with UNC1-INPF (100:0) and INC1-INPF (25:75; 75:25) gave higher NH_4 contents than the untreated control and INPF in 2018. In 2018/19, only INC1-INPF (50:50) resulted in higher NH_4 content than the untreated control, but all treatment combinations gave higher NH_4 contents than the sole INPF treatment. The soil chemical parameters gave the mean and median values that were close or equivalent to each other. Among the soil chemical properties, only NO_3, NH_4 and K were positively skewed in 2018. Negative and very high coefficients of skewness were given by soil pH in both cropping season and P content in 2018. The soil pH, organic C, NH_4, P, K, Na and Zn were normally distributed with coefficients of skewness below 0.5 in 2018, whereas only soil pH and P followed the normal distribution in 2018/19.

8.4 Discussion

The various combinations of compost and INPF induced significant increases in soil porosity in 2018/19 compared to the untreated control. The increased soil porosity following compost application indicates the soil's permeability not only for water, but also for air and roots (Cardoso et al. 2013). This affirms that the addition of organic materials represents a viable solution to the reduction of soil compaction by decreasing the soil bulk density (Hamza & Anderson 2005). Research conducted by Mbagwu (1992) showed that the decrease in bulk density recorded from the soil treated with rice-shaving and poultry manure were directly related to increased organic matter which played a significant role in reducing the compaction of soil. The soil pH evinced a trend of increasing with compost application rate. This indicated that an increase in WSW compost rate leads to a greater supply of exchangeable cations such as Ca, K, Na and Mg in the soil due to the alkaline nature of these WSW compost type indicated by their higher pH (Table 3.4, Chapter 3). Therefore, the use of WSW compost on acidic soil may be beneficial to increase the soil pH to the optimum level for maximum plant nutrient availability. This finding agrees with the earlier results reported in chapter 4. Although the increases in soil organic C following sole application of WSW compost or combined application of WSW compost and INPF were observed with reference to the untreated control, the soil organic C in the root zone was found to be below the threshold level of 1.5 to 2.0% (Lal 2016).

The compost-INPF combinations increased the soil P, K, Na and Zn contents as compared to the untreated control in both cropping seasons. The increases in the contents of P, K, Na and Zn in the soil indicated that the WSW compost may serve as P, K and Zn source. However, the increases in soil K and Na contents from the WSW compost-INPF (100:0) may result in K and Na toxicity problems eventually. The soil K content from treatments with either sole compost or combination of compost and INPF were found to be in the high to excessive range (Horneck et al. 2011). Consequently, frequent application of WSW compost on soil is highly not recommended to avoid unnecessary K build-up in the soil. Treatments with INC1-INPF (25:75) and UNC1-INPF (50:50) gave lower soil P content as compared to sole INPF in 2018, whereas all treatment combinations except UNC1-INPF (50:50) resulted in lower soil P content than the sole INPF treatment in 2018/19. The soil P contents from treatments with sole or combined application of compost and INPF were found to be in the high to excessive range (London 2013; Horneck et al. 2011).

8.5 Conclusions and recommendations

The results from this study have demonstrated that the combined application of winery solid waste compost and INPF appear promising for the improvement and maintenance of soil health. The compost and INPF combinations increased the contents of soil organic C, P, K, Na and Zn as compared to the untreated control in both cropping seasons. However, a frequent application of winery solid waste compost to croplands is not recommended to avoid unnecessary potassium build-up that may cause plant and soil toxicities. The winery solid waste compost may be used on acidic soils to increase the soil pH to an optimum level for maximum plant nutrient availability and better microbial activity.

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CHAPTER 9

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The evaluation of the physico-chemical properties of winery solid waste (WSW) compost showed that effective microorganisms (EM) inoculation influenced compost Bray-2 P content, while the interaction of EM inoculation and pile size similarly had significant effect on ammonium-N content. The produced composts demonstrated high electrical conductivity values due to high concentrations of soluble salts that could be possibly deleterious to crops and the soil. The low Cr concentrations and apparent absence of other heavy metals in the WSW compost eliminated the potential risks of their use on croplands. The use of 1.0 m pile size promoted extended thermophilic phase during compost production that could ensure better sanitization of the compost. The phyto-toxicity effects recorded in maize and tomato may be minimized by using lower application rates. The greater than 100% root length and germination index values revealed the phyto-nutrient and phyto-stimulant nature of the WSW compost extracts.

Increased P and K mineralization across the incubation period, and the cumulative net mineralized P and K recorded from the in-field incubated sandy loam Ferric Luvisol treated with different rates of compost revealed the promising potentials of using this compost as P and K source. The observed high net P and K mineralization is associated with the high availability of P and K contents in the WSW compost. Compost application at 40 t ha^{-1} increased soil pH throughout the incubation period, thereby raising serious soil health concerns for the use of this compost on high pH soils. The cautious use of WSW compost as soil amendment is crucial for mitigating possible risks of unnecessary soil pH increases, nutrient imbalance, toxicity and the antagonistic effects of P and K on other plants nutrients.

The response of maize growth and yield after WSW compost application on sandy loam soil under tunnel house conditions was positive in terms of improving maize performance. In general, stem girth, plant height, number of functional leaves per plant, dry matter yield and relative agronomic effectiveness increased with the increasing compost rate. The microbial inoculation and variation of compost with pile size did not influence maize performance and soil chemical properties. In most cases, the higher optimum rates predicted by the quadratic model were associated with dry matter yield that were slightly higher compared to the optimum dry matter yield predicted by the linear-plus-plateau model. The WSW compost has an immense potential for the improvement of maize productivity, but its application at rates above 40 t ha^{-1} induced massive increase in exchangeable soil-Na content and soil pH, which had undesirable effects on maize seedlings. Due to the very strongly alkaline nature of the WSW compostand its high Na content, lowering WSW compost application rates may minimize increases in soil pH and soil-Na content.

The results from the field evaluation of sole and combined application of WSW compost and inorganic N and P fertilizers (INPF) during the 2018 and 2018/19 summer cropping seasons showed that the WSW compost-INPF combination appears promising for improving maize productivity and soil health indicators. The interaction of compost type and application rate influenced plant height and leaf area index during 2018 season, and number of leaves and stem girth at tasselling during 2018/19 season. The application of inoculated compost without INPF increased cob weight, grain number cob^{-1}, total biomass yield, grain weight cob^{-1} and 1000-seed weight than the untreated control during the 2018 season. The INPF, 25:75 inoculated/un-inoculated compost-INPF and 50:50 un-inoculated compost-INPF proved beneficial in improving grain yield under the harsh environmental conditions. The prediction of the optimum rates using grain yield data across the cropping seasons showed that the predicted rates were closer to 50:50 ratio, making it the best compost-INPF combination. The ability of the WSW compost to raise soil pH showed that the use of this compost on acidic soil will be beneficial to increase the soil pH to the optimum level for maximum plant nutrient availability and better soil health. Similarly, compost application with or without INPF increases the contents of soil organic C, P, K, Na and Zn. Soil NH_4 and P may be used as suitable indicators for selecting the best compost and INPF combination that will boost grain yield as shown by the positive correlation between grain yield and the contents of these soil properties.

The following recommendations are drawn based on the findings from this study:

- The use of EM inoculants may not be necessary in composting the winery solid waste.
- The use of composting pile size of 1.5 m will help in eliminating huge amount of waste from the wineries and vineyards than the 1.0 m pile size, but the use of the 1.0 m composting pile size is recommended to ensure sanitized compost product.
- Since phyto-toxicity was recorded in maize and tomato, suitable lower application rates need to be established to eliminate such occurrences.

- The serious soil health concerns highlighted by the increase in the soil pH following application of 40 t ha^{-1} compost throughout the incubation period encourages the recommendation of the use of WSW compost on acidic soil in order to raise soil pH suitable for optimum nutrient availability and microbial activity.
- The linear-plus-plateau model (as compared to the quadratic model) is recommended for predicting optimum rate of WSW compost for optimum maize dry matter production. Several follow-up field experiments are highly recommended to evaluate the predicted rates.
- The use of 50:50 WSW compost-INPF rate is recommended for optimum maize grain yield production.
- The use of WSW compost alone or in combination with the INPF is recommended for improving the soil health indicators such as organic C, P, K, Na and Zn. However, studies to evaluate the long-term effects of sole or combined application of WSW compost and INPF on maize performance and soil health indicators are recommended.
- The multi-environment trials to evaluate the different combinations of WSW compost and inorganic fertilizers are recommended in order to consider the effect of soil types and different climatic conditions on the performance of maize following the application of WSW compost solely or in combination with INPF.
- Finally, further studies to evaluate the economic feasibility of using WSW compost solely or in combination with INPF are recommended