CRANFIELD UNIVERSITY

BENEDICT ONYEBUCHI UNAGWU

APPLICATION OF ORGANIC AMENDMENTS TO RESTORE SOIL HEALTH AND PRODUCTIVITY OF A DEGRADED SOIL

SCHOOL OF WATER ENERGY AND ENVIRONMENT

PhD THESIS

PhD
Academic Year: 2016 - 2017

Supervisor: Dr. R. W. Simmons and Professor R. J. Rickson
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

Organic amendments (OAs) have the capacity to enhance physical, chemical, biological soil quality indicators (SQIs) and to improve soil productivity. This study investigated the effects of different OAs (Mushroom Compost, MC; PAS-100 compost, PAS; Anaerobic Digestate Solid Waste, AD_SW; and Poultry Manure, PM), applied at 10 t ha^{-1} and 30 t ha^{-1} with or without inorganic fertilizer (applied at 50% of the RB209 recommended rates for maize) on key SQIs, soil health and plant performance on a degraded sandy loam soil. The treatments were laid out in a greenhouse using a completely randomized design and replicated four times. The soil and OAs were thoroughly mixed and incubated for two weeks. Thereafter, composite 3-point soil samples were taken from each treatment replicate for post-incubation (POI) soil analysis. Maize (*Zea mays*, Severus variety), was used to assess the impact of the OAs on plant performance. Plant height, number of plant leaves and stem diameter were measured weekly. Post-harvest (POH) composite 3-point soil samples were again taken for soil analysis. The data generated from POI and POH laboratory analyses and plant measurements were subjected to analysis of variance (ANOVA) followed by *post-hoc* Fisher LSD analysis at 5% probability level. At POI, the OAs had 22-44.5% higher water holding capacity [WHC], increased porosity and reduced bulk density [BD] as compared with the un-amended control treatment (CNF).

The results indicate that 1% increase in soil organic matter (SOM) increased the Available Water Content (AWC) by 5.31 g g^{-1} while reducing the BD by 1 g cm^{-1} and increasing the soil Water Content at Field Capacity (WC_{FC}) by 36.5 g g^{-1}. The Olsen-P, Available-K, Available-Mg, Total-N, and microbial biomass C [MB_C] associated with the OA treatments were significantly higher as compared with CNF treatment. At POH, across application rates, OA treatments with or without inorganic fertilizer addition had >15% higher ($p < 0.05$) WHC [WC_{FC}], 40% higher porosity and 55% lower BD as compared with CNF treatment. For both POI and POH, higher rates (30 t ha^{-1}) of OAs with or without inorganic fertilizer addition had higher ($p < 0.05$) effects on the water release characteristics [WC_{FC}, EAW, AWC] than lower (10 t ha^{-1}) rates of OAs.

At POH, across application rates, the OA treatments increased the Olsen-P, SOM, Total-C, and TOC by over 37, 23, 75 and 81%, respectively, relative to CNF. Across application rates with or without inorganic fertilizer addition, the OA treatments did not significantly affect the CEC as compared with CNF. The OAs increased the P, K and Mg indices relative to the CNF which increased with increase in OA application rates. Further, the OA treatments increased the MB_C by 72-95% ($p < 0.05$) and reduced microbial stress by over 30% relative to CNF. Without inorganic fertilizer addition, the OA treatments increased the above ground and below ground plant biomass (AG_{DB} and BG_{DB}) by 24-65% and 38-88% respectively, compared with the CNF treatment except for the PAS treatments. The OAs had 100% increases in cob yield as compared with CNF, except for PAS1NF/2NF and AD_SW1NF treatments. Inorganic fertilizer addition had marked effects on plant performance, particularly when combined with the PAS OA. The study concludes that application of OAs has the potential to improve soil health and productivity of a degraded sandy loam soil. Long term effects of these OAs merit further detailed exploration.

Keywords: Degradation, Organic amendments, Improvement, Maize production, Soil health, Nutrient uptake

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LIST OF ABBREVIATIONS

AD_SW	Anaerobic digestate solid waste
AG_{DB}	Above ground dry biomass
AWC	Available water content
BD	Bulk density
BG_{DB}	Below ground dry biomass
BSI	British Standard Institution
BS	British Standard
CEC	Cation exchange capacity
C_{mic}	Microbial biomass carbon
C_{org}	Organic carbon
DW	Dry weight
EAW	Easily available water
FAO	Food and Agriculture Organisation
FAAS	Flame atomic absorption spectroscopy
FCM	Fuzzy Cognitive Mapping
FYM	Farmyard yard manure
g	Grams
ISO	International Standard Organization
kg	Kilogram
KPa	Kilo-Pascal
MB_C	Microbial biomass carbon
MB_N	Microbial biomass nitrogen
MB_P	Microbial biomass phosphorous
MC	Mushroom compost
MSW	Municipal solid waste
NH_4-N	Ammonium-N
NUE	Nutrient/Nitrogen use efficiency
OA(s)	Organic amendment(s)
PAS	Publicly Available Specification for composted material
PM	Poultry manure
POI	Post-Incubation
POH	Post-harvest
PSD	Particle size distribution
PUE	Phosphorous use efficiency
qCO_2	Metabolic quotient
SMC	Soil moisture content
SOC	Soil organic carbon
SOM	Soil organic matter
SQIs	Soil quality indicators
SS	Sewage sludge
SSA	Sub-Saharan Africa
TOC	Total Organic Carbon
TON	Total oxides of nitrogen
WAP	Week after planting
WC_{FC}	Water content at field capacity
WC_{PWP}	Water content at permanent wilting point

WHC	Water holding capacity
WRC	Water retention characteristic

1 INTRODUCTION

Soil degradation remains a major threat to achieving global food security, due to its detrimental impacts on soil health and the simultaneous decline in agricultural productivity (Agegnehu *et al.*, 2015). According to Agegnehu *et al.* (2015), nutrient mining, inappropriate land use and management, and insufficient application of external inputs, such as mineral (inorganic) fertilizers and organic amendments (OAs), greatly contributed to the global decline in soil health. With the current estimated world population of 9.7 billion by 2050 (United Nations, 2015) and the potential devastating effects of climate change, there will be more demands on available land for agriculture, road networks, housing, and other land-use-related needs to satisfy the demands of the growing population. This, nevertheless, will subject the existing agricultural lands (especially the less productive and marginal lands) to further pressure to produce more food, timber and fibre to cope with the surging population, thereby resulting in further degradation.

Currently, soil degradation is prevalent in the tropics, where most small-scale farmers are often trapped in a cycle of nutrient mining agriculture (Bedada *et al.*, 2014) without replenishing the soil with adequate nutrients to compensate for the nutrients taken up by crops. This is because farmers cannot afford to regularly apply costly inorganic fertilizers and OAs, such as manures and composts, are at times not easily accessible. Often, the high cost of inorganic fertilizers is due to poor transportation infrastructure, insufficient, and inefficient distribution networks (Bedada *et al.*, 2014). Thus, the effects of soil degradation will continue unless drastic and fundamental approaches are taken towards combating soil degradation, especially in Sub-Saharan Africa (SSA) and other countries. In tropical and subtropical climatic regions, even with the practice of continuous farming without fallow (a farming practice that exhaust the soil nutrients and deplete the soil organic matter content [SOM]), the use of OAs to improve the SOM content of the farmland is generally low (Chang *et al.*, 2007), due to farmers' overdependence on inorganic fertilizers. In addition, the use of cover crops, mulching, and green manures is not commonly practiced by the farmers. Due to the important roles soils play in maintaining the complex terrestrial ecosystem and climate systems (Jie *et al.*, 2002), Mosaddeghi *et al.* (2009) suggested that a carefully planned soil management strategy is key to ensuring sustainable agricultural production, by improving the soil health. Soil management practices include efficient use of OAs to restore degraded soils (Khaliq and Abbasi, 2015). Further, soil management practices that improve SOM status have been shown to sustain higher crop productivity (Bandyopadhyay *et al.*, 2010) and have significant impacts on soil physical, chemical, biological and biochemical properties (Lupwayi *et al.*, 2005).

The use of OAs in combination with inorganic fertilizers is shown to be fundamental to safeguarding soil health, increasing crop productivity and ensuring input use efficiency (Bandyopadhyay *et al.*, 2010). Studies have shown that OA application has positive effects in improving nutrient availability (Bandyopadhyay *et al.*, 2010; Surekha *et al.*, 2010; Jannoura *et al.,* 2013). Unlike inorganic fertilizers, the positive effects OAs on soil properties may take time to manifest. This is because the nutrients contained in OAs are initially immobilised by the soil microbes, with subsequent release through microbial enzymatic activities (Biau *et al.*, 2012). Application of farmyard manure a widely used OA was reported to affect soil properties and plant performance significantly and was recommended as an effective strategy for improving degraded (saline) soils (Zhang *et al.*, 2014). Mandal *et al.* (2007) regarded good soil management as an adequate means of enhancing nutrient availability to plants and increasing crop yields.

Decline in soil health due to SOM depletion is considered a major threat to agricultural productivity (Agegnehu *et al.*, 2015). The productive function of any soil is greatly influenced by the state of its health (soil health) (Bandyopadhyay *et al.*, 2010). Therefore, greater agricultural crop production will depend on how well the soil health is maintained, since the physical, chemical and biological properties of a soil are in large part a function of organic matter content (Abawi and Windmer, 2000).

Maize is the most important and dominant food crop in many African countries including Nigeria (Fischer *et al.*, 2014). It is a cheaper and a more affordable cereal to the majority of the population than rice and wheat (FARA, 2009). Because of this, maize occupies a prominent position in the agricultural development agenda in Africa (FARA, 2009). Currently, it is estimated that by 2050, the demand for maize in developing countries will double, and by 2025 maize will have become the crop with the greatest production globally and in developing countries (CIMMYT and IITA, 2011).

Although maize production in Africa is increasing at a faster rate (2.8% per annum) than global production (2.5% per annum), the global maize yields are increasingly higher (1.6% per annum) than that in Africa (1.3% per annum) (CIMMYT and IITA, 2011). Studies have shown that most of the increase in maize production in Africa is due to increase in the cultivated land area rather than increase in yields as a result of improvement in soil health (Hillocks, 2014). This implies that in Africa (Nigeria in particular), pasture and forested lands are cleared (deforested) for farming purposes to increase crop yield production. This practise is not sustainable in the 21st century. Thus improving the health of degraded soil through OA application can provide a better measure in curtailing this practice.

Maize yield output in Africa is at 1.7 t ha^{-1} which is only 35% of the global average yield output (4.9 t ha^{-1}) (FARA, 2009). Thus, the current yield of maize in Africa cannot meet the food demand of the projected growing population (Fischer *et al.*, 2014). Among other factors (such as inadequate use of inorganic fertilizers, OAs, improved seed, pesticides and poor water and nutrient management by the smallholder farmers in Africa), the low maize yield in Nigeria and Africa in general is associated with the low and declining soil productivity and high levels of soil degradation (Bationo *et al.*, 2011; Craswell and Vlek, 2013; Fischer *et al.*, 2014). Soils in Nigeria (Africa in general) have characteristically very low SOM content (an indication of poor soil health) attributed to decades of land-use practices that encouraged nutrient mining by crops, leaching, and inadequate erosion control (Morris *et al.*, 2007). Therefore, the high level of soil degradation in Africa is responsible for the low crop yields which affect crops' yield gaps. For instance, maize yield gaps in Africa in most cases are between 200-400% of the farm yield (Fischer *et al.*, 2014). Yield gap refers to the difference between 'yield potentials of a crop' and the actual average farm yields of that crop. Yield potential refers to the yield that can be obtained when the non-genetic factors such as water availability, solar radiation, nutrients, temperature and pests and diseases are not limiting (Hillocks, 2014). It is suggested that sufficient biomass and forage production without adequate improvement in soil health is impossible (Valbuena *et al.*, 2012).

Unlike in South America and Asia, where soil responds to inorganic fertilizer application at comparably lower application rates, the reverse is the true for soils in Nigeria and other African countries due to inherent low soil nutrient levels (Fischer *et al.*, 2014). This suggests that higher rates of inorganic fertilizer application are required to achieve high maize yield in Africa. This is a massive challenge, considering the high cost of procuring inorganic fertilizers. Because soil nutrient depletion is extreme in most areas in Africa, particularly among small land holding farmers, Sanchez and Swaminathan (2005) advocated that restoring soil health in such areas is key to increasing agricultural productivity. This is because the application of appropriate combinations of inorganic fertilizer and OAs, using leguminous green manures and agroforestry fertilizer trees, composts, returning crop residues to the soil, and using improved methods of soil conservation, can restore soil health and double or triple yields of the cereal and staple crops.

Soil degradation effects can be reversible (Lal, 2001), when prompt and adequate measures are put in place to contend the menace of soil degradation, at the early developmental stage. Unfortunately, because adequate soil management techniques are not often enforced, soil degradation and its devastating effects will persist much longer, predominantly in the SSA (Lal, 2001) and Nigeria in particular where farming has been relegated to the resource poor and often less educated farmers. It is therefore pertinent to improve the health of degraded soils in Nigeria through adequate use of OAs since Morris *et al.* (2007) suggested that OAs are integral components of soil management strategies required to increase crop yields. Thus, improving the health of degraded soils will go a long way in increasing crop yields, reducing the yield gaps, improving the standard of living (farmers' income) of resource poor farmers, and increasing other ecosystem goods and services, such as nutrient cycling, air and water purification, aesthetics and food, fibre and fuel provisioning.

2 LITERATURE REVIEW

With the current increase in the global population, soil management schemes, approaches and/or practises that are aimed at improving the health and function of degraded soils are key to achieving improvement in crop yields, meeting the current food demands, ensuring future global food security, and providing greater ecosystem goods and services.

This Chapter will in detail discuss soil degradation, its impact on soil health, crop yield and also the effects of organic amendment (OA) applications in improving physical, chemical and biological soil quality indicators (SQIs).

2.1 Soil Degradation: An Overview

Soil plays a key role in crop production, protecting water quality, and also acts as a major store of carbon; it purifies the atmosphere via exchange of gases especially CO_2 and N_2 (Gil-Sotres *et al.*, 2005). This emphasizes the importance of soil both for crop production and in maintaining environmental quality (Gil-Sotresa *et al*., 2005). Currently, the world is facing serious threats to soil functions owing to soil degradation and that is threatening global food production (food security) (Lilburne *et al.*, 2002; Montanarella, 2013). Soil degradation occurs due to human and/or environmental influence that results in the deterioration of physical, chemical and biological soil properties with a resultant decline in soil health and reduction in the capacity of soil to perform its specific functions (Lal, 2001) (Figure 1).

Soil degradation is defined as a measurable loss or reduction in the current or potential capability of soils to produce plant materials of desired quantity and quality (Jie *et al.*, 2002). FAO (2014) defined soil degradation as “the change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries”. For Muchena *et al.* (2005), soil degradation is the loss of both the biological and economic productivity of the land.

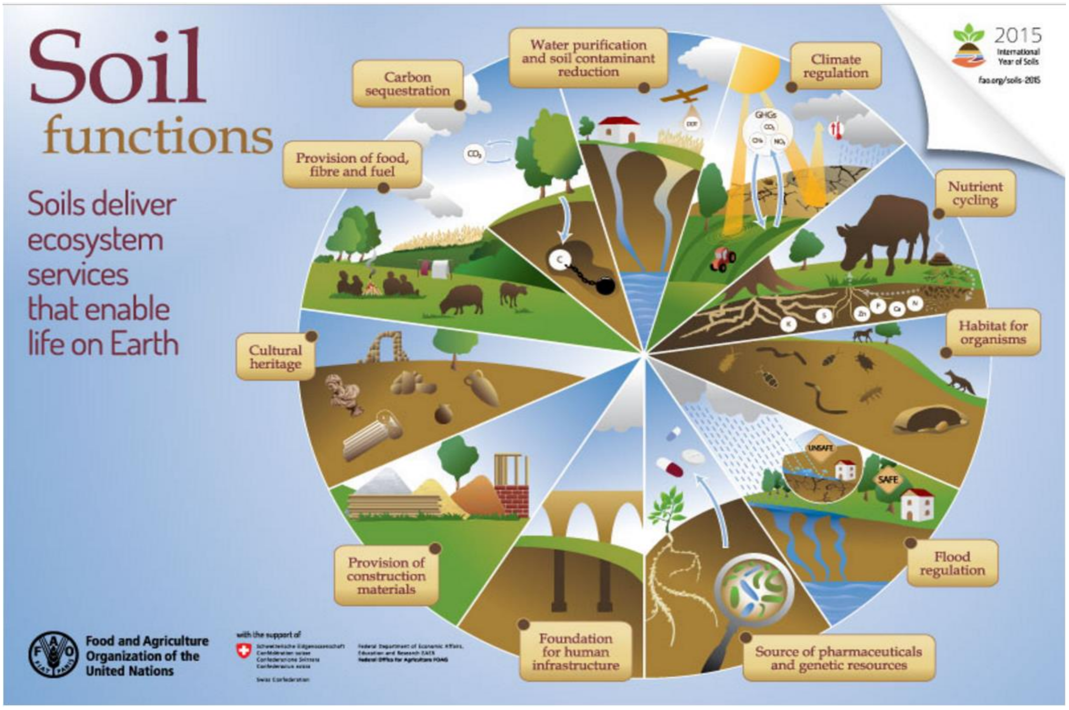


Figure 1 Pictorial presentation of soil functions

Source: http://www.fao.org/resources/infographics/infographics-details/en/c/284478/

Soil degradation causes a long-term decline in a soil's productivity and has devastating impacts on the environment (Lal, 2001). It is reported that about 33% of the world's soils are moderately to highly degraded of which 40% of these soils are located in Africa and the remaining amount are in countries that are afflicted by poverty and food insecurity (FAO, 2015a). Soil degradation and the wanton destruction of agricultural soils are increasing at an alarming rate (Lal, 2001). Tropical soils are the most affected, especially in developing countries in the tropics and subtropics due to the nature of the soils and harsh climates (Steiner, 1996; Lal, 2001). Thus, this presents a challenge to increase food production in those regions while conserving the soil, preserving ecosystems, maintaining biodiversity, and protecting ground- and surface water. According to FAO (2015a), there is a strong relationship between soil health and food security and this calls for strategic and immediate actions to combat soil degradation, in order to increase food production and alleviate food insecurity in the affected areas.

2.1.1 Types and causes of soil degradation

Soil degradation is often anthropogenic and exacerbated by socio-economic and political factors (Lal, 2001). Soil degradation can exist or occur in different forms. The European Union Soil Thematic Strategy identified eight major threats of soil degradation processes. These are: decline in SOM, soil erosion, loss of biodiversity, soil contamination, salinization, compaction, soil sealing and landslides (Montanarella, 2013). Also, soil degradation can largely be grouped into physical, chemical and biological degradative processes (Lal, 2001).

Physical soil degradation occurs due to the deterioration of physical soil properties, including a change in soil structure resulting in an increase in soil bulk density, decrease in soil hydraulic conductivity, poor aggregate stability, decrease in soil porosity and infiltration due to soil compaction, and increase in erosion caused by wind or water erosion (Lal and Stewart, 1990; Lal, 2001). Chemical soil degradation is the decline in SOM, nutrient depletion [particularly N, P and K which are the major plant nutrients (Yang *et al.*, 2014)], shifts towards extreme soil pH, increase in salt concentration, and contamination by toxic substances such as heavy metals (Lal and Stewart, 1990; Nwachukwu and Pulford, 2009; Sato *et al.*, 2010; Singh and Agrawal, 2010; Montanarella, 2013). Biological soil degradation occurs as a result of a decline in the amount of stored carbon biomass, and reduction in the activity and diversity of the organisms living in the soil (Navarrete *et al.,* 2012; Blum, 2013).

In the Mediterranean, decrease in SOM content was regarded as one of the most important causes of soil degradation (Diacono and Montemurro, 2010; García *et al.*, 2012) which hinders adequate vegetative cover and further predisposes the soil to higher degree of degradation via erosion processes such as runoff, surface- and ground-water pollution and CO_2 emissions (Bronick and Lal, 2005). Decline in SOM content has been associated with decline in physical soil properties (Chan *et al.*, 2003), which can have consequential effects on crop performance.

Some other factors, such as deforestation, extensive cultivation on marginal land, cultivation practices (such as mono-cropping; tillage system, surface irrigation, steep slope farming, inadequate use of cover crops especially in areas prone to soil erosion), inadequate use of manure and other OAs, inappropriate (misuse or excess) use of inorganic fertilizers, over-grazing particularly on fragile (marginal) agricultural lands, adverse weather and mining, can also accelerate the process of soil degradation.

2.1.2 Consequences of soil degradation

As a critical component of the biosphere, soil is not only essential for food production but also for the maintenance of environmental quality (Ferreras *et al.*, 2006) and provisioning of ecosystem goods and services. Soil degradation is increasingly recognized as an important environmental issue in many parts of the world (Lilburne *et al.*, 2002) due to its serious threats to soil functions (Fallah *et al.*, 2013). Following the decreases in SOM content [one of the most important causes of degradation (Garcia *et al.,* 1992)], there are rising concerns about environmental problems associated with soil degradation. This is because the intensity of agricultural production and changes in land use due to rapid increases in human population have put more pressure on land and soil resources, and contributed to the various forms of soil degradation (Lilburne *et al.*, 2002) and this is posing a serious challenge to global food security (Jie *et al.*, 2002; Bronick and Lal, 2005).

Soil degradation lowers the capacity of soil to function (Figure 1) and that has significant negetive impacts on the soil's ability to deliver ecosystem goods and services (Figure 1) including food production, buffering, nutrient recycling, filtering, cultural heritage and infrastructure (Navarrete *et al.,* 2012; Blum, 2013). Furthermore, soil degradation was reported to have a severe negative effect in SSA, especially where small scale and resource-poor farmers continuously carry out extractive farming practices (Sanchez, 2015). This extractive form of farming is prevalent in some developing countries, because the farmers cannot afford off-farm input (OAs or inorganic fertilizers) which is essential for sustainable farming.

It was reported that soil degradation contributed to the non-attainment of Vision 2015 of the World Food, Summit which aimed at achieving sustainable food security for all, through eradication of hunger and reduction in the number of undernourished people by 2015 (FAO, 2015). A major reason for many unsustainable agricultural systems is the loss of organic matter [soil degradation] (Antle and Diagana, 2003). Decline in soil structure, a form of physical soil degradation that is associated with poor land use and soil/crop management practices influences soil nutrient recycling, root penetration, soil water retention and crop yield (Chan *et al.,* 2003). Soil structure is a spatial arrangement of the solid soil particles and their associated pore space. It is a key factor in the functioning of soil, its ability to support plant and animal life, and moderate environmental quality with particular emphasis on soil carbon (C) sequestration and has profound effects on soil water holding capacity, nutrient retention and supply, drainage, and nutrient leaching (Abbasi and Khizar, 2012; McClellan *et al.*, 2014). Soil degradation affects soil aggregate stability. Aggregate stability has been reported as an indicator of soil structure (Six *et al.*, 2000) which results from the arrangement of particles, flocculation and cementation (Duiker *et al.*, 2003).

In summary, the effects of soil degradation either due to erosion, desertification, contamination, salinization, compaction, loss of biodiversity or decline in soil organic matter (Doran, 2002); not only affects a soil's productive capacity but it can in extreme cases lead to loss of agricultural land, increase environmental pollution and sedimentation in streams and rivers; and disrupt carbon (C), nitrogen (N) and sulphur (S) cycles. These effects impact the soil ecosystem and disrupt ecosystem benefits.

It is widely acclaimed that sustainable agricultural development is a critical approach to combating poverty, global environmental issues and soil degradation effects. Yet, the goal of achieving sustainable agriculture still remains elusive due to the severe impacts of soil degradation (Antle and Diagana, 2003). Therefore, managing soil sustainably through improved soil health via OA application is essential in improving degraded soils (Kulcu *et al.*, 2008).

2.1.3 Strategies to reverse soil degradation

The application of OAs has been suggested as an appropriate soil management strategy to prevent soil degradation and improve soil health by providing better soil conditions for below- and above-ground plants and soil microbial community [microbial biomass] (Bastida *et al.*, 2008; Abbasi and Khizar, 2012). Regular application of OAs, such as biosolids and manure composts to agricultural soils, influences soil physical, chemical and biological properties (Park *et al.*, 2011). Bastida *et al.* (2008) regarded compost as a better organic material for restoring degraded soils than sludge, due to the presence of pathogens in sludge and the stable nature of carbon in compost. OA application is a restoration technique that can alter the soil constraints or physical conditions that retard plant establishment and growth and also improve below and above ground biological community diversity (Biederman and Whisenant, 2009).

2.2 Organic Amendments (OAs)

OAs are organic materials that are applied to the soil as soil conditioners or enrichments to improve soil conditions (physical, chemical and/or biological soil properties). In general, unlike inorganic fertilizers, OAs (e.g. plant residues, animal manures, industrial/domestic wastes and composts) release their nutrients slowly and over a longer time period at a rate that depends on soil microbial activity. This is because OAs vary in their chemical composition and complexity: structural/physical (lignin, bulk density, water holding capacity), chemical (nutrient content, organic matter content) and biological (microbial diversity, microbial population and enzyme activities). Thus, these differences affect OA decomposition rates, the amount of N immobilised (N taken up by the soil microbes) and the amount of N mineralised (released by the soil microbes) (Norton, 2000). Further, these differences can influence the efficacy of OAs in improving or enhancing soil properties (Gould, 2015). This therefore implies that the quality of the OAs applied can be as important as the function it performs. For instance, the N content and the C:N ratio of an OA may not only affect the OA decomposition rate but it may also influence the N mineralization - immobilization turnover. To further illustrate, composts made from manure is not the same as composts made from plant material, such as plant leaves, bark, branches or stems. This is because the nutrient content, microorganism diversity and population, and organic matter content associated with these composts vary depending on the feedstocks used, the processing method applied and the maturity of the compost at the time of application (Gould, 2015).

Tejada *et al.* (2006) demonstrated that the application of 10 t ha^{-1} beet vinasse compost [BV] and cotton gin crushed compost [CGCC], respectively, can improve soil physical properties. At the end of the experiment, the authors observed that the BV and CGCC amended soils decreased soil bulk density (by 7% and 6%) as compared with the un-amended treatment. The addition of OAs not only increases SOM content but also has the capacity to improve soil nutrients (Evanylo *et al.*, 2008). Application of pig slurry increased SOM content which improved the soil physical, chemical and biological properties with a resultant increase in soil resilience (i.e. the dynamic ability of the soil to withstand or resist soil degradative processes such as erosion) and productivity due to its rich source of both macronutrients and micronutrients (Biau *et al.*, 2012). Evanylo *et al.* (2008) found significant increases in the amounts of C and N sequestered with the applications of compost, which increased with increasing rates of the composts applied.

A detailed review of other studies looking at the benefits of OAs in tackling soil degradation is summarised in Table 1.

Table 1 A review of different studies on the use of organic amendments in mitigating related soil degradation problems

Location	Manure	Compost	Mushroom Compost	Solid waste	Crop(s)	Fertilizer	Research purpose	Research outcome	Soil type and class	Author(s)
Northern Germany (54° 30" 41°.47"N latitude; 12° 50" 5°.59"E).	30 t ha^{-1} Cattle manure	-	-	30 t ha^{-1} Bio-waste	Maize	-	To investigate the impact of a ten-year continuous application of organic and inorganic P fertilizers on P nutrition of maize	OA application positively affected soil properties, increased maize growth and soil P pools.	Loamy sand; Stagnic Cambisol soil	Krey *et al.* (2013)
Swiss Research Station Agroscope (06°13" N; 46°24 " E), western Switzerland.	12 t ha^{-1} Cattle manure	-	-	-	Maize, Rape-seed, Spring, Oats, and Winter Wheat	-	To quantify the effect of organic fertilization on soil properties ties and crop yield.	Organic fertilizers enhanced soil fertility and maize production.	Silty-clay Calcaric Cambisol	Maltas *et al.* (2013)
Zimbabwe (17° 35" S latitude, 31° 14" E longitude)	17 t ha^{-1} Cattle manure	-	-	-	Soybean, Mucuna, Maize	90 kg N ha^{-1}, 18 kg P ha^{-1}, 17 kg K ha^{-1}	To evaluate the performance of different soil fertility improvement practices on a degraded granitic sandy soil	Mineral N supplied via OA was inadequate to sustain high maize yields.	Sandy soil	Chikowo *et al.* (2004)
New Delhi, India (28° 37" –28° 39" N latitude and 77° 9" – 77° 11" E longitude).	15 t ha^{-1} Cattle manure	-	-	-	Maize (*Zea mays*), Wheat (*Triticum aestivum*) Cowpea (*Vigna ungui-culata*)	NPK used were urea, phosphate, muriate of potash; and $ZnSO_4$ applied at different rates	To investigate the changes in soil organic matter and biological properties due to long-term application of manure and fertilizers in maize–wheat–cowpea cropping system	Balanced application of inorganic fertilizer and manure enhanced SOM content and soil microbial activities,	Loamy sand Cambisol	Kanchikeri-math and Singh (2001)
Two Malian soils: Baguineda, 12° 23" S, 7.45 " W and Gao, 16° 18" N, 0° GM; Mali.	-	25, 50 and 100 t ha^{-1}	-	-	Ryegrass (*Lolium perenne* L.)	NPK at different rates were used	To compare the effects of compost and inorganic fertilization on the growth and chemical composition of ryegrass in two Malian agricultural soils.	Combined application of compost and mineral NPK increased SOC, available P, Fe, Mn, Zn, Cu, K and pH	Sandy clay loam and Loamy sand	Soumare *et al.* (2003)

Location	Manure	Compost	Mushroom Compost	Solid waste	Crop(s)	Fertilizer	Research purpose	Research outcome	Soil type and class	Author(s)
Tunisia and Tunis City	-	-	-	Municipal solid waste compost (MSWC) at 40, 80 and 120 t ha^{-1}	Alfalfa (*Medicago sativa)*	-	To evaluate the contrasting effects of MSWC on alfalfa growth in clay and in sandy soils: N, P, K, content	40 t ha^{-1}, MSWC increased alfalfa growth	Clay and sandy soils	Mbarki *et al.* (2008)
Two locations in Greece: Aliartos in Biotia and Kiourka in Attiki	-	Compost (62% town wastes, 21% sewage sludge and 17% sawdust by volume) applied at 39, 78 and 156 t ha^{-1}	-	-	Garden cress (*Lepidium sativum* L.)	-	To investigate the potential soil improvement with waste application on almost all physical properties	Compost application improved soil physical properties (BD, WHC, aggregation and aggregate stability, total porosity, soil resistance)	Loamy soil (Typic Xerochrept) and clay soil	Aggelides and Londra (2000)
Tunisia; Mornag 36° 50" N 10° 9" E	Farmyard manure at a rate of 40 t ha^{-1}	-	-	Municipal solid waste compost (MSWC) at rates of 40 and 80 t ha^{-1}	Wheat (*Triticum turgidum* subsp. Durum, var. Karim)	0.3 Mg ha^{-1} NH_4NO_3, and 0.1 Mg ha^{-1} P_2O_5	To assess the impact of five years' applications of different organic and mineral fertilizers on wheat grain yields and soil chemical and microbial characteristics	MSWC applied at 40 Mg ha^{-1} increased ($p < 0.05$) crop productivity without affecting the reduce soil contamination with heavy metals and fecal coliforms	Clayey-loamy, Vertic Xero Fluvent,	Cherif *et al.* (2009)
Field site I (Foulum, 56° 30" N, 9° 34" E) and site II (Risø, 55° 44" N, 12° 05" E); Denmark	Household compost 17 t ha^{-1} dry matter	-	-	Anerobic digested sewage sludge (4.2 t ha^{-1} dry matter	-		To quantify effect of organic fertilization and reduced-tillage practices on soil properties ties, crop yield and crop response to N fertilization	OA application influenced different soil properties measured	Sandy loam	Debosz *et al.* (2002)
Zaragoza City; Spain.	-	-	-	40,80, 160 and 320 t ha^{-1} sewage sludge (SS)	Barley	-	To re-establish vegetation cover on degraded gypsiferous soils	SS rates significantly reduced pH, increased salinity in SOM, N, and soil moisture	Silty loam Gypsisols soil	Navas, *et al.* (1998)

Location	Manure	Compost	Mushroom Compost	Solid waste	Crop(s)	Fertilizer	Research purpose	Research outcome	Soil type and class	Author(s)
Santa Olalla (Toledo) in Central Spain.	Cow manure 20 t ha^{-1} (CM)	-	-	Municipal solid waste (MSW) compost at 30 kg K ha^{-1} Muriate, 30 kg P ha^{-1} ammonium nitrate at 20 and 80 t ha^{-1}	Barley	-	To assess long-term (nine years) effects of organic mature application on soil enzyme activities and microbial biomass on a barley farm	MSW and CM had affected the soil enzymes activities: Phosphatase activity decreased with MSW (62%) and CM (73%), Urease activity decreased by 21% and 28%, and β-glucosidase increased in all the OA treatments	Typic haploxeralf with a sandy texture	García-Gil *et al.* (2000)
Domboshawa, Zimbabwe (31° 09' E, 17° 36 'S	12.5 and 37.5 t ha^{-1} cattle manure	-	-	-	Maize	30 kg P ha^{-1} SSP 30 kg K ha^{-1} Muriate, 30 kg P ha^{-1} ammonium nitrate	To assess the effect cattle manure on soil aggregate stability and water retention	Manure treatments increased soil aggregate stability (measured as the mean weight diameter) and water retention	Loamy sand Typic Kandius-talf (USDA) or Haplic Lixisol (FAO)	Nyaman-gara *et al.* (2001)
Nova Scotia; Canada	-	-	-	12, 24, 15, 18, 48 and 72 t ha^{-1} MSWC	Squash (*Cucurbi-ta maxi-ma* cv. Butter-cup)		To evaluate changes in soil fertility associated with MSW applications	High rates of MSWC and/ or NPK fertilizer enhanced nutrient availability for winter squash crop	Sandy loam	Warman *et al.* (2009)
Gortmore, Silvermines	-	-	50, 100, 200 and 400 t ha^{-1} spent mushroom compost (SMC)	-	Ryegrass (*Lolium perenne* L.)		To promote sustainable vegetation cover on metalliferous tailings with the application of spent mushroom compost (SMC)	Application of SMC had significant effect on the physical and chemical soil properties	-	Jordan *et al.* (2008)
Chongqing, southwest of China (29° 22' N, 105°54')	-	25 t ha^{-1} fresh weight Green compost *Vicia sepium* L.	25 t ha^{-1} fresh weight spent mushroom compost	-	Rice	-	To improve soil quality and rice productivity	OA application increased soil water-stable aggregates, organic carbon, total N, available K, CEC, and decreased bulk density, pH, and phyto-available	Silty Loam soil	Li *et al.* (2012)

Location	Manure	Compost	Mushroom Compost	Solid waste	Crop(s)	Fertilizer	Research purpose	Research outcome	Soil type and class	Author(s)
								heavy metals.		
Vertic Argiudoll located in Zavalla, Argentina (32° 43" S; 60° 55"	10 t ha^{-1} and 20 t ha^{-1} Vermi-composted horse; rabbit manure; chicken manure	-	-	10 t ha^{-1} and 20 t ha^{-1} Vermi-composted household solid waste	Broccoli (*Brassica oleracea* L.) and lettuce (*Lactuca sativa* L.)	-	To assess the response of different organic amendments on selected soil physical, chemical and biological properties, after two applications	The authors found a significant linear relationships between water stable soil aggregates and ethanol stable soil aggregates with SOC	Silty Loam soil	Ferreras *et al.* (2006)
Nsukka, Nigeria	8 tha^{-1} poultry manure (PM)	-	-	-	Maize	15:15:15 NPK	To increase maize yield and improve soil physical and chemical properties of a degraded Ultisol	PM increased maize yield and enhance the soil physical and chemical properties	Sandy loam	Unagwu *et al*. (2013)
Organic farm at Hau Tau, Hong Kong	0, 10, 25, 50 and 75 t ha^{-1} manure compost	**-**	**-**	**-**	*Brassica chinensis* and maize		To increase soil fertility and crop production	Manure applied of 25-50 t ha^{-1} had the highest crop yield	Loamy soil	Wong *et al.* (1999)

Table 1 indicates that the application of OAs is a potential option for improving degraded soils, due to its benefits on soil properties. Improving the health of degraded soils for specific crop production through OA addition by tailoring the soil to the needs of the crop/s in question may offer in future, a more promising approach to tackling soil degradation and ensuring higher yields from less productive (degraded) agricultural soils.

2.3 Soil Health

The concept of soil health dates back to ancient civilizations (Doran, 2002). Soil health is a very complex term which has received different interpretations from policy makers, farmers, scientists, land owners/managers and environmentalists. From an agricultural and horticultural standpoint, soil health is more focused on crop performance (crop growth, yield and biomass production). However, defining soil health is not without challenges. Several attempts have been made to clearly distinguish the concept of soil quality from that of soil health, but the boundaries of the two concepts are still indistinct. Nevertheless, according to Doran (2002), the term soil quality refers to the capacity of a soil to carry out a specific function, while soil health refers to its overall condition. Soil health has been defined by Doran *et al.* (1996) as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health"

Soil health does not depend solely on either the soil physical, chemical or biological properties but on the closely linked interaction between these soil properties due to the complex interrelatedness that exist between these properties (Figure 2). A recent infusion into the soil health concept is the inclusion of aspects of crop (yield) production (Bhaduri *et al.*, 2015). Improvements in physical, chemical and biological soil properties should translate to a positive yield potential or improvement in plant performance which is the tangible aspect and the ultimate driver for soil improvement. The essential components necessary to maintain soil health is a unique distribution or mix between chemical, physical and biological (including microbial) soil properties (Nielsen and Winding, 2002). Thus, an integrated approach that involves a combination of selected soil quality indicators (SQIs) offers a better approach in assessing improvement in soil health than the use of few individual SQIs (Figure 2).

A healthy soil is one that has the capacity to retain soil nutrients as well as withstand contaminants and other solutes through sorption to the clay particles and soil organic matter (Nielsen and Winding, 2002). More so, a healthy soil must also be capable of sustaining adequate food and fibre production and maintain soil productivity over a long term period, regulate water, support biodiversity and ensure plant and animal well-being (disease free) (Figure 2). Therefore, a healthy soil must be one that has the ability to provide a full range of ecosystem goods and services and carryout other soil functions (Figure 3). Such a healthy soil can be achieved through adequate use of OAs that encourage soil biological activities (which are vital for effective nutrient recycling), and improve the SOM content**.**

As demonstrated in Figure 2, the schematic diagram indicates that improvement in soil health (which is associated with many ecosystem goods and services) is a function of improvement in the physical (e.g. bulk density, water holding capacity, porosity, aggregate stability), chemical (e.g. SOM; soil nutrients) and biological (e.g. microbial biomass and microbial respiration) SQIs. This highlights the important role OA application can play in improving soil health. Therefore, it is important to note that soil health depends on the overall functioning conditions of the physical, chemical and biological soil properties (Figure 2).

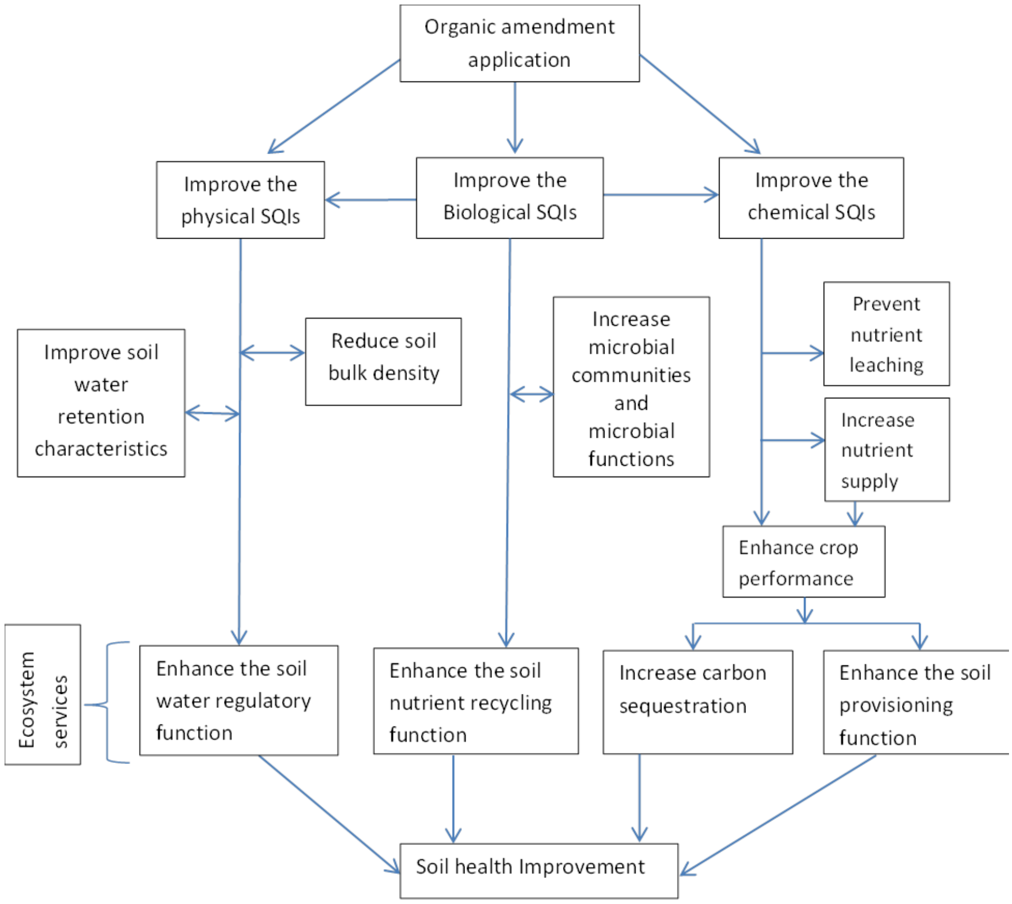


Figure 2 Relationship between organic amendment application and soil health

Soil health involves a complex interaction among the various indicators of soil quality working together in closed synergy, while supporting soil functions and other soil processes (Figure 3).

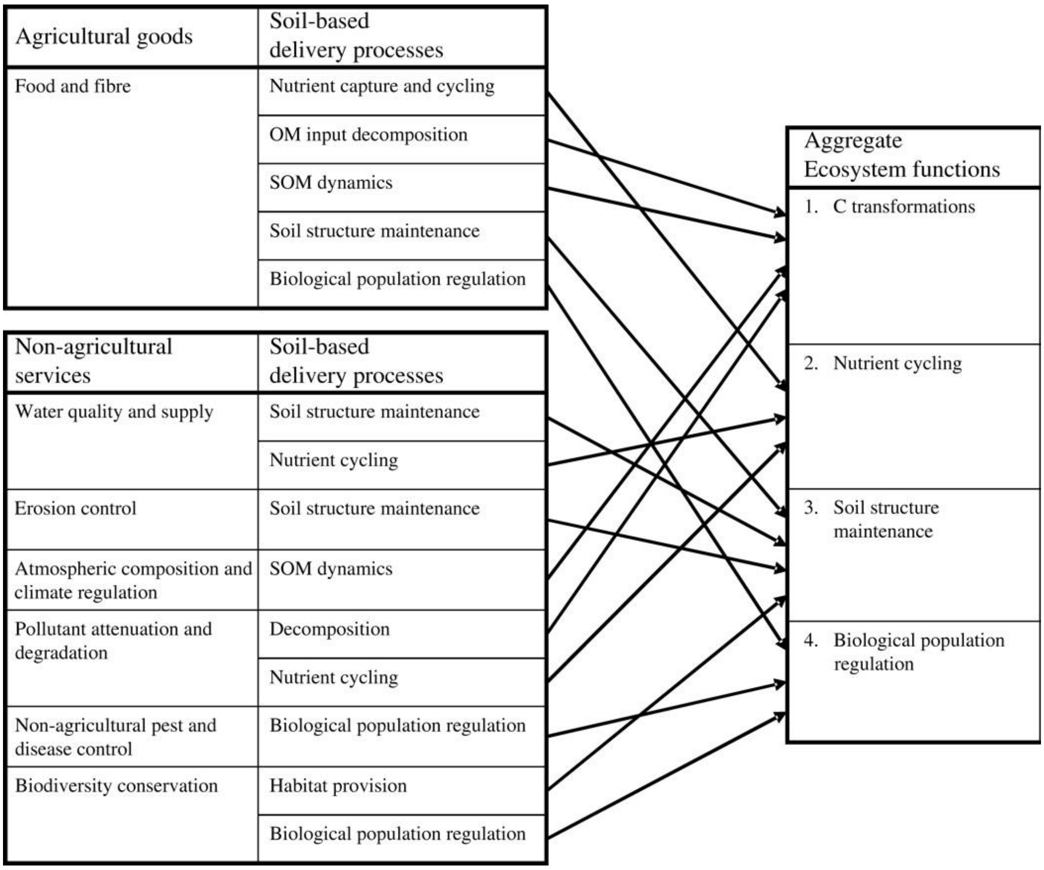


Figure 2 Pictorial representation of soil health

Adapted from Kibblewhite *et al.* (2008).

2.4 Maize Production

As mentioned in Chapter one, maize (*Zea mays* L.) is the third most widely grown grain cereal after wheat and rice and is the main staple food for many people in SSA countries (Muyayabantu *et al.*, 2012) and in other countries of the world (Moore *et al.*, 2014). Maize grows best in deep, well drained, fertile soils that are slightly acid to neutral pH *circa* 5.5 to 7.0 (Moore *et al.*, 2014). As an important global cereal crop, maize has a significant economic value in livestock and poultry production (Harris *et al.*, 2007; Mohsin *et al.*, 2012). It also has other multiple uses namely in the manufacturing of pharmaceuticals and industrial products (such as production of starch, ethanol and plastics and antibiotic production) (O'Keeffe, 2009; Moore *et al.*, 2014). It can also be processed into other industrial products for human consumption (Ortiz-Monasterio *et al.*, 2007) such as corn flour and cornmeal.

Maize requires an adequate supply of nutrients, particularly N, phosphorus (P) and potassium (K) and micronutrients namely copper (Cu) and zinc (Zn) for good growth and high yields (O'Keeffe, 2009). Phosphorus is vital for early root and seedling development. For normal growth, young maize plants need a high percentage of P in their tissues (O'Keeffe, 2009). Nitrogen is the main nutrient limiting yield in all maize producing regions (Moore *et al.*, 2014). Maize being a nutrient exhausting crop, requires an adequate amount of nutrients (NPK) at different growth stages (Bhatti *et al.*, 1988; Nafziger, 2010; Moore *et al.*, 2014). During flowering (tasselling), P in older plants is translocated into the fruiting areas of the plant, where it is needed for the formation of seeds. Phosphorus deficiencies late in the growing season affect both seed development and normal crop maturity. Thus, nutrient supply must be adequate throughout the full growth period to meet the daily nutrient uptake demands (Nafziger, 2010), especially from 4 weeks after planting as this is when nutrient uptake of maize increases rapidly (Moore *et al.*, 2014).

Maize is sensitive to Zn deficiency in soil (Alloway, 2008). Thus, application of Zn fertilizers is a viable option to fulfil the crop demand for Zn and also to increase Zn content in grains (Kanwal *et al.*, 2010). In addition, Zn fertilizer application not only enhances maize crop production, but also addresses Zn deficiency problems in humans (Kanwal *et al.*, 2010). Furthermore, maize is less tolerant to moisture stress than other cereal crops, such as grain sorghum and wheat. It is particularly vulnerable to moisture stress just prior to flowering (tasselling) and through to three weeks after flowering (silking) is finished (Nafziger, 2010; Moore *et al.*, 2014). Moisture stress in the first four (4) weeks of growth can reduce leaf expansion and crop height, but is less detrimental to yield than later moisture stresses. Stress at tassel initiation results in smaller cobs, whilst stress at tasselling (flowering) and silking (pollination) can result in unset kernels (Moore *et al.*, 2014).

Maize is also one of the most strategic cereal crops in Africa and other developing countries, because it is a source of food to more than 300 million vulnerable rural poor (FARA, 2009). Because of this and in line with the millennium development goals, the African Heads of State and Governments adopted a policy that will facilitate the attainment of the continental self-sufficiency in maize production in order to reduce hunger and poverty (FARA, 2009). Out of 194 million hectares (ha) of cultivated lands in SSA, maize is grown in about 33 million ha (DTMA, 2013). By world standards, maize yields in Africa are low, accounting for only 7% of global production with an average production of 1.7 t ha^{-1} as compared with the global average of about 5 t ha^{-1} (DTMA, 2013). This yield is far below the crop's genetic potential yield (DTMA, 2013). The low yield of maize in Africa, and Nigeria in particular, is attributed to soil degradation caused by improper and inadequate soil management, diseases, limited use of inorganic and organic fertilizers, and inherently low nutrient status (DTMA, 2013).

It is estimated that by 2025 maize will become the crop with the greatest production globally, while the demand for maize in developing countries will double by 2050 (CIMMYT and IITA, 2011). Therefore, to achieve this goal, there is an urgent need to tackle soil degradation, which remains the key factor hindering Nigeria (and Africa in general) from attaining food self-sufficiency.

2.5 Soil Quality Indicators (SQIs)

Soil quality indicators (SQIs) are measurable soil attributes that affect the capacity of soil to perform its full range of ecosystem goods and services. SQIs are sensitive to changes in land use, soil management and conservation practices (Bhaduri *et al.*, 2015). Soil quality assessment was envisioned as a tool to help balance challenges associated with: (1) increasing world demand for food, feed, and fibre, (2) increasing public demand for environmental protection, and (3) decreasing supplies of non-renewable energy and mineral resources (Larson and Pierce 1991; Doran *et al.,* 1996). The Soil Science Society of America (1997) defined soil quality as "the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health". There are many indicators that reflect the capacity of the soil to function, however, only a few of these indicators can predict whether or not the soil will maintain its capacity to function following disturbance (Herrick, 2000). The capacity of a soil to continue to support the same range of uses (i.e. providing ecosystem services) in the future as much as it supports today depends on the soil's resistance and its resilience to degradation (resilience is the potential ability of soil to recover following degradation) (Herrick, 2000). The concept of SQIs involves the assessment of physical, chemical and biological soil properties that are related to the ability of soil to function efficiently as a component of a healthy ecosystem (Schoenholtz *et al.*, 2000; Karlen *et al.*, 2003). This implies that pertinent SQIs must be sensitive to changes in soil management practices (Marinari *et al.*, 2006) and should reflect major ecological processes in soil and have the ability to deliver ecosystem benefits [goods and services] (Doran and Zeiss, 2000).

Many authors have adopted different SQIs by measuring various soil characteristics and relating them to different management practices, productivity, or environmental quality (Staben *et al.*, 1997). The choice of SQIs depends among other factors on the soil management objectives. The SQIs selected should be sensitive to management-induced changes, easily measured, relevant over time, inexpensive to measure, and adaptable for specific ecosystems (Schoenholtz *et al.*, 2000). For example, the following have been identified as indicators of soil physical quality: field capacity, available water capacity, air capacity, macroporosity, bulk density, rooting depth, texture, aggregate stability, penetrative resistance, and hydraulic conductivity. This is because they quantify either directly or indirectly from the soil's ability to store and provide crop-essential water, air and nutrients (Dexter and Czyz, 2007; Reynolds *et al.*, 2007; Dexter and Richard, 2009).

Soil pH; cation exchange capacity and anion adsorption capacity in topsoil; and base saturation (Merrington, 2006), SOM, available-P, Available-K, soil micronutrients (Fe, Mn, Zn and Cu) (Khaliq and Abbasi, 2015), available N, Total N, Total P, Total K (Li *et al.*, 2013) as the chemical SQIs have been reported. Further, soil microbial biomass (C, N, P), metabolic quotient (qCO_2), microbial biomass quotient (i.e. the ratio of microbial biomass carbon to soil (total) organic carbon [C_{mic}:C_{org}]), microbial respiration; microbial biodiversity, and enzyme activity assays have also been identified as biological SQIs (Arshad and Martin, 2002; van Bruggen and Semenov, 2000; Gil-Sotres *et al.*, 2005; van Diepeningen *et al.*, 2006; Garbisu *et al.*, 2011; Epelde *et al.*, 2012).

Several studies have tried to identify a 'minimum data set' of SQIs that will capture the relevant SQIs, without having to measure all possible soil indicators (Staben *et al.*, 1997). Thus, the concept of a 'minimum data set' was initially used in soil quality evaluation by Doran *et al.* (1996). This included physical (texture, rooting depth, infiltration rate, bulk density, water retention capacity), chemical (pH, total C, electrical conductivity, nutrient levels) and biological (C and N microbial biomass, potentially mineralizable N, soil respiration) properties. A selection of soil indicators that enable the quantification of the quality or health of a soil is important because in the optimum functioning of soil, a range of physical, chemical, biological and or biochemical properties are involved (Gil-Sotres *et al.*, 2005).

Evaluating improvement to soil health will have little or no value if the SQIs are not selected rigorously. Thus, the selected indicators must have reference points to be able to measure trends and patterns, and to relate soil quality to other components of the soil system, such as the interactions between physical, geochemical and biological soil processes (Nortcliff, 2002; Gil-Sotres *et al.*, 2005). To avoid the need to consider all the soil properties as potential SQIs, Elliott (1994) suggested that any selected SQIs must satisfy a series of requisites such that the selected indictors must be: (a) sensitive to the presence of the greatest possible number of degrading agents, (b) consistent with the change the soil undergoes and (c) able to reflect the difference in the levels of degradation. Some physical and chemical soil parameters have been considered to be of little use as they change only when the soil undergoes a really drastic change (Filip, 2002) compared to the biological and biochemical soil parameters which are more sensitive to the slight modifications the soil undergoes (Yakovchenko *et al.*, 1996), such as soil erosion, loss of soil organic matter, water logging, compaction and salinity. Gil-Sotresa *et al.* (2005)

considered microbial biomass C as the most reliable SQI (41% of authors) followed by dehydrogenase activity (28%) and N mineralization capacity (16%). Gil-Sotres *et al.* (2005) reported that a majority of authors use a small group of edaphic properties (biological and biochemical properties) to assess soil quality and concentrate on finding those soil properties which best reflect the change in soil quality. Nevertheless, the authors suggested that there are no suitable or agreed upon evaluation procedures by which key soil properties are adequately measured nor a general consensus regarding soils that should be considered of optimum quality (Gil-Sotres *et al.*, 2005).

One of the key essences of improving the health of a degraded soil is to increase food production and biodiversity i.e. a food web with many chains of different plants (USDA, 2012). This is because the critical functions of a healthy soil include sustaining agricultural productivity, promoting biological activity and biodiversity; regulating, filtering, and storage of water; C sequestrating, provisioning of habitat, and cycling nutrients (Figure 1). Further, there are increasing signs that agricultural soils are being neglected resulting in the loss of SOM and biodiversity to the extent that such neglected soils may not recover from degradation without adequate soil management measures (Merrington, 2006). This thus suggests that there is an urgent need to preserve, protect and prevent our agricultural soils from further degradation.

Improving the health of degraded soils is critical to improving the soil ecosystem and achieving a sustainable environment. This is because healthy soils not only provide food and fibre, they also protect the environment by their carbon capture and storage capability, by enhancing nutrient cycling, water filtering, water regulation and supporting and providing habitats for wildlife (Merrington, 2006). Therefore, soil health and its productive capacity must be enhanced or improved beyond soil preservation *status quo* so as to meet the increasingly global food demand. This can be achieved by providing measures or approaches that prevent SOM loss or depletion, nutrient depletion and other forms of soil degradation and promoting SOM-building and replenishing nutrients mined from soil by harvested crops through the use of OAs.

2.6 Potential Effects of Organic Amendments on Soil Physical Quality Indicators

Maintenance of optimum soil physical conditions through appropriate soil management techniques or systems is an important step towards overcoming physical soil degradation (Diacono and Montemurro, 2010). OAs are associated with improvements in the soil physical properties (Aggelides and Londra, 2000). With appropriate soil management, OAs can influence many soil physical properties (such as the available water content [AWC], water holding capacity [WHC], porosity and bulk density [BD]). Continual application of OAs to cropland increase the physical SQIs by improving soil aggregate stability and decreasing soil BD (Diacono and Montemurro, 2010). Aggelides and Londra (2000) observed that compost application (mixture of 17% sawdust, 21% sewage sludge and 62% town wastes by volume) had a significant effect on the measured physical soil properties [BD, total porosity, and water retention characteristics]. According to the authors, improvement in the soil properties was proportional to the rate of compost applied.

Addition of OAs improves soil aggregation, WHC, hydraulic conductivity, alleviates soil compaction, and resistance to water and wind erosion (Franzluebbers, 2002; Bulluck *et al.*, 2002). This in turn positively affects seed germination and the growth and development of plant roots and shoots (van Noordwijk *et al.*, 1993; Bulluck *et al.*, 2002). Application of OAs can improve soil structure by increasing fungal populations in the soil with fungal hyphae 'enmeshing' soil aggregates (Rhodes and Hrubant, 1972; Miller *et al.*, 2002). Further, the end product of microbial action on SOM is the release of cementing agents [polysaccharides] (Lynch and Bragg, 1985) that bind soil particles. Darwish *et al.* (1995) in a long term study following manure application observed that manure-induced physical changes in the soil did not last over a long time, due to the rapid microbial degradation of the manure.

2.6.1 Bulk density

Bulk density (BD) [g cm^{-3}] is the ratio of oven-dry mass of soil to the corresponding bulk (undisturbed) soil volume (Reynolds and Topp, 2008). Soil

BD has been used as an indirect indicator of aeration, soil strength, and ability of a soil to store and transmit water (Reynolds *et al.*, 2007). In medium to fine textured soils, a proposed optimal BD range for maximal field crop production is 0.9 g-1.2 g cm^{-3}. Values greater than 1.25-1.30 g cm^{-3} can potentially cause yield loss due to inadequate soil aeration (Drewry *et al.*, 2001). In contrast, values below 0.9 g cm^{-3} can potentially cause yield loss due to inadequate plant anchoring, reduced plant available water capacity, reduced unsaturated flow of water and dissolved nutrients to plant roots (Mueller *et al.*, 2008; Reynolds and Topp, 2008). Further, high BD influences plant root distribution, downward roots progression in the soil profile and restricts the plant roots to the upper parts of the profile which can change the morphology of the plant root system (Mosaddeghi *et al.*, 2009). Application of OA has been shown to decrease BD due to a dilution of the denser soil mineral fraction and increased soil aeration due to an increase in soil porosity (Tejada, *et al.*, 2008). Celik *et al.* (2004) obtained a significantly lower BD (1.17 g cm^{-3}) following the addition of compost addition and manure (1.24 g cm^{-3}) application as compared to chemical fertilizer alone (1.47 g cm^{-3}) and control (1.46 g cm^{-3}) [un-amended] treatments at a depth of 0–15 cm.

In a similar study, the application of 100% NPK + FYM treatment was reported to significantly lowered the BD of clayey soil as compared with the control (Un-amended) treatment by 0.06 g cm^{-3} (Hati *et al.*, 2007). However, the authors found no significance difference in BD with the application of inorganic fertilizer (100% NPK, 50% NPK, and 100% N) as compared with the control treatment. The significant decrease in BD with OA application was attributed to the highly significant and negative linear relationship of BD (r = -0.59) with the soil organic carbon (SOC) (Hati *et al.*, 2007). Further, the soil BD of cotton gin crushed compost and poultry manure amended soils was reported to have decreased by 23% and 22%, respectively as compared with the control (un-amended) treatment (Tejada *et al.*, 2006). Miller *et al.* (2002) reported significant effects on BD at 0-5 cm and 10-15 cm depths following cattle manure application on clay loam soil. The authors obtained significantly lower BD values for the OA treated soil as compared with the control treatment. They attributed the decrease in the

BD to the increase in organic C due to increase in the rates of manure applied. This was evidently supported by the significantly negative correlations (r = –0.99) observed between soil BD and soil organic C. Further, results of a study on the effects of farmyard manure (FYM) and mulch on soil physical properties in a reclaimed coastal tidal flat saline soil indicated that application of FYM and straw mulch decreased the soil BD (Zhang *et al.*, 2014).

Bandyopadhyay *et al.* (2010) reported that the BD under integrated NPK (at 30:26:25 kg ha^{-1}) + FYM (at 4 t ha^{-1}) treatment was 5.6% and 9.3% lower than the NPK and un-amended control treatment, respectively. Further, they observed that the BD of 0–15 cm soil layer was significantly and negatively correlated with the SOC. The decrease in the BD was linked to the higher SOC content of soil, better aggregation and increased root growth due to treatments (inorganic fertilizer and manure) application effects. In addition, Mosaddeghi *et al.* (2009), reported short-term beneficial effects in soil BD with the application of 30 t ha^{-1} and 60 t ha^{-1} dry weight cattle manure. The authors observed that increase in treatment application rates significantly lowered the soil BD. Zhou *et al.* (2016) also found significant reduction in the soil BD with the application of 22.5 t ha^{-1} OA (organic manure). The authors attributed the reduction in the BD to the bio-pores (small channels created in the soil by the plant roots) formed by decayed plant roots and stubble. Guo *et al.* (2016) also reported significant reductions in the BD with NPK application and that was linked to increase in plant root biomass.

2.6.2 Porosity

Soil porosity refers to the amount of pore, or open space between soil particles. It also refers to as the volume of soil voids (spaces) that can be filled by water and/or air. Porosity is calculated as:

$$\text{Porosity} = \left({(1 - \text{bulk density})}/{\text{soil particle density}} \right) * 100 \qquad \textbf{(1)}$$

Soil porosity varies depending on the soil particle size (soil texture). Smaller sized soil particles (clayey soils) have higher porosity than sandy soils with larger particles which have less pore spaces. Soil compaction is an indication of high BD affects on soil porosity. Thus, this suggests that an increase in the soil BD can be accompanied with a decrease in the soil (pore spaces) porosity. Studies have shown that application of OAs improve soil porosity. For instance, Evanylo *et al.* (2008) observed that application of higher rates of OAs (144 t ha^{-1} compost [dry weight]) had quicker positive effects on the soil porosity than at lower rates (31 t ha^{-1}) due to increase in SOM content. Soil porosity was significantly higher with OA (compost and cattle dung) application compared with inorganic fertilizer and control treatments due to the positive effects of the OAs on the soil micro-porosity (Celik *et al.*, 2004).

Studies have further shown that application of compost significantly increased total porosity and also changed the distribution of pore sizes by increasing the proportion of soil macro-pores of loamy and clay textured soils (Aggelides and Londra, 2000; Marinari *et al.*, 2000). Further, Marinari *et al.* (2000) found that increase in total porosity was dependent on the amount (rates) of organic materials applied. To have a long lasting effect on the soil physical properties following OA application, Celik *et al.* (2004) suggested that OA rich in lignin (high-lignin content) should be used. Lignin-rich OAs have greater improvement effects on soil physical properties than OAs with less lignin content since these OAs are easily decomposed by the soil microbes. Thus, less lignin OAs have intense but transient effects on physical properties unlike recalcitrant (high-lignin) OAs which have a lower but longer term effect (Abiven *et al.*, 2009). Miller *et al.* (2002) recorded a 2-17% significant increase in total porosity with the application of 30, 60 and 90 t ha^{-1} of cattle manure as compared with the control (0 t ha^{-1}) plot. The authors attributed the increases in the soil porosity associated with the OA treatments to the significant reduction in BD.

Zhou *et al.* (2016) investigated the effects of inorganic and organic fertilization on the soil micro and macro structures of rice paddies using the following treatments: no fertilization (control [CK]) inorganic fertilizer ([NPK]: 90 kg N ha^{-1}, 20 kg P ha^{-1} , and 62 kg K ha^{-1}) and organic manure (22.5 t ha^{-1}) + inorganic fertilizer [NPKOM]. They found that compared with the CK treatment, the

NPKOM treatment recorded a significantly higher porosity. The authors attributed the increased soil porosity to the biopores formed from decayed plant roots and stubble; also to larger pore sizes and greater intra- and inter-aggregate pores due to the effects of the OA applied. Li *et al*. (2011) found that the application of poultry litter and livestock manure amendments increased soil macro-pore and meso-pore volumes and decreased soil micro-pore volumes as compared with inorganic fertilizer and control treatments. Thus, changes in the soil porosity due to OAs application affect the water regulating capacity of soil (See Section 2.6.3).

2.6.3 Soil Water Characteristics

The soil water retention characteristic (WRC) is an important physical soil property which regulates the amount of rainfall or irrigation water that is retained in the soil for plant use. Plants require adequate soil moisture for growth and development. Plant growth and development depend on the availability of soil (moisture) water supplied either through irrigation or directly by rainfall. Thus, improving soil water storage through the application of OAs is crucial to overcome water deficiency or stress which can adversely affect crop yield performance (Moore *et al.*, 2014). Maize is intolerant to water stress and cannot tolerate a water logged soil (NSW DPI, 2014; Nafziger, 2010).

The WRC is used in determining available water in the soil for plant use. The soil pores play crucial roles in the movement and storage of water in the soil. While the micro-pores help in soil water retention; the macro-pores help in draining the soil water (Figure 4Figure 3). Gould (2015) reported that for every one percent of organic matter content, the soil can hold up to ca 75,000 litres of plant-available water per acre (0.4 ha) of soil to 0.3 m depth. This implies that increasing the SOM content through application of OAs can increase the volume of plant-available water retained in the soil. Therefore, in the long term, the SOM level can directly influence the availability of water for plant uptake (Gould, 2015).

Boateng *et al.* (2006) reported a significant increase in soil moisture content following poultry manure application. As demonstrated in Figure 4, soil water retention is governed by the distributions, size and continuity of soil pores, number of soil pores; and the specific surface area of the soils (Haynes and Naidu, 1998). Ideally, well-structured soils have proportionate (adequate distribution) and good networks of macro-pores and micro-pores interlinking and traversing the soil system (Figure 4Figure 3). This allows entry and drainage of excessive water and also retains and provides water for plant use. However, poorly structured and/or degraded soils have either too few or too many large pores which will affect the soil water movement, storage, and plant water availability and this can have significant impacts on plant performance (Figure 4).

According to Hati *et al.* (2007), application of 100% NPK + FYM retained significantly higher water content than the control and inorganic fertilizer (100% N and 50% NPK) treatments due to an increased number of small pores at low tensions (0.033 MPa). Following OA application, Celik *et al.* (2004) observed that compost and manure treatments had a significant effect on available water capacity (AWC) as compared with NPK fertilizer treatment at different soil depths. At 15–30 cm depth, the compost treatment had the highest AWC of 0.173 g g^{-1} as compared with (0.09 g g^{-1}) for the control treatment. The authors linked the effects of OA on AWC to increases in the soil micro-porosity and macro-porosity due to compost and manure application. AWC is a range of plant available water a soil can store (Figure 4). The upper limit (point) of the range is referred to as ‘field capacity’. This is the condition in which saturated soil ceases to drain freely from gravity after wetting. The lower limit of AWC is the permanent wilting point. At this point, water is not available to plants and the plant permanent wilts. This is because the available water is tightly held by the soil against gravity.

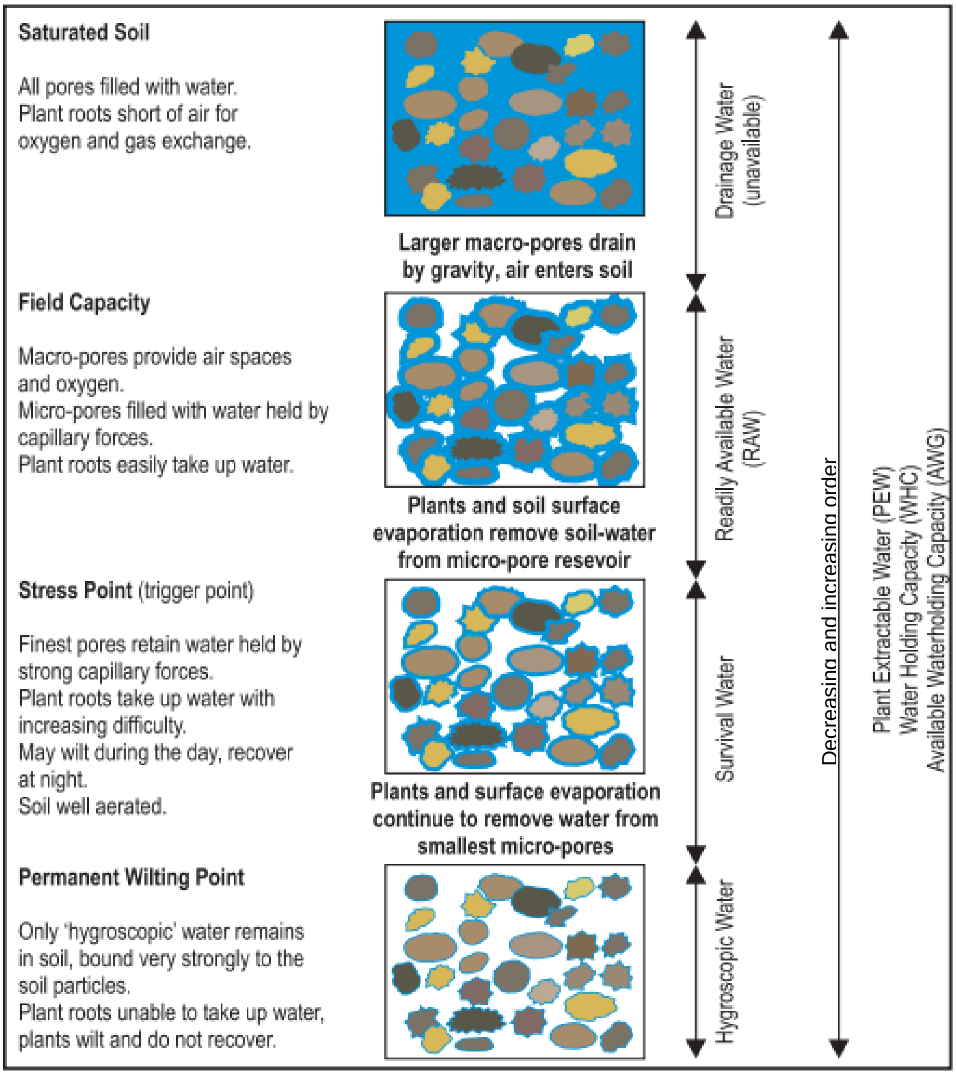


Figure 3 Soil-water properties: water storage and movement.

Adapted from: ET:WM1 (2006).

Agegnehu *et al.* (2015) reported that maize shoot and root biomass was significantly correlated with soil water content. The AWC (g g^{-1}), indicates the soil's ability to store and provide water that is available to plant roots (White, 2006). A soil with an AWC ≥ 0.20 g g^{-1} is often considered “ideal” for maximal root growth and function (Cockroft and Olsson, 1997), while 0.15 ≤ AWC < 0.20 g g^{-1} is “good”, 0.10 ≤ AWC < 0.15 g g^{-1} is “limited”, and AWC < 0.10 g g^{-1} is considered “poor” or “droughty” (Warrick, 2002; White, 2006). The result of a study on the effects of farmyard manure (FYM) and mulch on soil physical properties in a reclaimed coastal tidal flat saline soil showed that the application of FYM and straw mulch decreased the soil BD with a corresponding increase in the soil WHC. This result was supported by a highly significant strong negative correlation (r^2 = 0.79) between the BD and WHC (Zhang *et al.*, 2014).

SOM content affects the soil pore spaces by aggregating soil particle together, increasing soil aggregate stability and positively affecting soil water properties due to the binding effects of microbes, such as the microbial cells and fungal hyphae (Abiven *et al.*, 2009). Thus, application of OAs increases the soils' ability to retain water. Reynolds *et al.* (2009) assessed the impacts of compost applied at 75 t ha^{-1} and 300 t ha^{-1} (dry weight basis) on the physical quality and productivity of a Brookston clay loam soil. They found that the control treatment was substantially below the optimal range, due to poor aeration capacity characterized by high relative field capacity, high BD; low AWC, low macro-porosity, high risk for structural degradation (due to low organic carbon, low structural stability index), and poor structural quality [low S_{gi}] (Table 2). However, unlike the 75 t ha^{-1} compost treatment, application of compost at 300 t ha^{-1} improved the indicator parameters to their optimal ranges (Table 2).

Table 2 Indicator values for Brookston clay loam soil following compost application

Treatment	RFC (-)	AWC (g g^{-1})	AC (g g^{-1})	P_{MAC} (g g^{-1})	BD (g cm^{-3})	OC (%)	SI (%)	S_{gi} (-)
Control	0.77	0.13	0.11	0.06	1.37	2.3	5.5	0.020
75 t ha^{-1} Compost	0.73	0.13	0.14	0.08	1.26	3.0	7.1	0.023
300 t ha^{-1} Compost	0.68	0.22	0.19	0.11	1.08	3.6	8.5	0.045
''Optimal'' range	0.6-0.7	≥0.15	≥0.14	≥0.07	0.9-1.2	3-5	>7	≥0.035

Adapted from Reynolds *et al.,*(2009).

RFC = Relative field capacity; AWC = Available water capacity; AC = Air capacity; PMAC= Macroporosity; BD = bulk density; OC = Organic carbon content; SI = Structural Stability Index, Sgi = inflection point slope of gravimetric soil water release curve.

In this present study, following the schematic diagrams (Figure 2); and based on the earlier stated hypothesis; it is expected that OA application will have significant positive effects on the above physical SQIs relative to the control treatment**.**

2.7 Potential Effects of Organic Amendments on Chemical Soil Quality Indicators

Organic matter plays a vital role in restoring and providing soil nutrients and also in preventing nutrient loses. Nutrient release from soil OAs involves complex biogeochemical processes; thus the influence of OAs on soil properties depends on the amount, type, and components of the added OAs (Tejada, *et al.*, 2008). As a major source of soil nutrients, OAs improve soil productivity (Basamba *et al.*, 2006), which is the ability of soil to provide the essential nutrients required by the crop plants in available forms and in the right amount for plant growth and development (Thierfelder and Wall, 2008; Maltas *et al.*, 2013).

Decomposition of OAs is complex and it is controlled by many factors, such as the amount and availability of C and N, the biochemical nature of the plant residue, and contact between soil and compost (Tejada *et al.*, 2008). During organic matter decomposition (plant residue), there is a strong relationship between the C and N cycles in the soil. This is due to the simultaneous uptake of C and N by the soil microbes (Mary *et al.*, 1996). The rate of C assimilation depends on the decomposition rates of the decomposing organic material by the soil micro-fauna. The C:N ratio of the decomposers influences N assimilation which may come either from the residue itself, or mineral N already present in the soil and/or the recycling of soil biomass (Mary *et al.*, 1996). Animal manures, such as pig slurry, cattle dung, and poultry manure, provide rich sources of both macronutrients, and micronutrients especially for agroecosystems with low fertility levels (Biau *et al.*, 2012). Poultry manure has long been recognized as the most desirable natural fertilizer because of its high N content (Delgado *et al.*, 2012).

2.7.1 Electrical Conductivity (EC)

Electrical conductivity (EC) is a measure of soil salinity (Azeez and Van Averbeke, 2012). It can also serve as a measure of soluble nutrients for both cations and anions. Soil EC reflects the sum of salts and ions in the soil solution (Carmo *et al.*, 2016). EC is also attributed as an index of soil fertility since soil

EC is highly correlated to crop yield (Carmo *et al.*, 2016). Addition of manures to soil increases the soil EC level. This is because manures added to the soil mineralize and release nutrients to the soil, thereby increasing the soil salt content (Azeez and Van Averbeke, 2012). The pH of a soil can influence its soil EC, since pH is the key factor that regulates the solubility and availability of nutrients in soil (Carmo *et al.*, 2016).

It is also reported that high salt content can negatively affect soil structure and this negates the ameliorative effects of manure application (Azeez and Van Averbeke, 2012). Excessive salt (high soil EC level) can adversely influence the physical, chemical, and biological properties of soils, mainly in arid and semi-arid world regions (Diacono and Montemurro, 2015). At the end of an incubation study, Roy and Kashem (2014) reported that application of cow dung and chicken manure had higher EC than the un-amended (control) soil. In another study, it was found that the soil EC significantly increased following the application of poultry, cattle and goat manures and the manure-induced soil salinization was very high in poultry manure and goat manure treatments compared with cattle manure treatment (Azeez and Van Averbeke, 2012). At post-harvest, Hewidy *et al.* (2015) observed a slight increase in the soil EC across the compost amended treatments as compared to the un-amended control. They attributed the increased EC to nutrient enrichment due to compost fertilization. It is reported that the soil EC level are affected by the type, composition and amount of OAs added to the soil (Carmo *et al.*, 2016).

2.7.2 Soil pH

The soil pH is a measure of the hydrogen ion concentration in soil. Soil pH can be influenced by both the acid forming cations (Al^{3+}, H^{+}, Fe^{2+} or Fe^{3+}) and the base forming cations (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}). This thus suggests that pH plays a significant role in the soil with respect to nutrient availability for plant uptake (Jones and Jeff Jacobsen, 2001). Soil is a microenvironment with application of OAs causing alterations in the soil pH. Such change in the soil pH due to OA application can influence the availability of nutrients, either positively or negatively (Ahmad *et al.*, 2009).

The application of quicklime [CaO] (2550 kg ha^{-1}), NPK (300 kg N ha^{-1}, 53 kg P ha^{-1}, 100 kg K ha^{-1}) and swine manure [SM] (300 kg N ha^{-1}) was reported to have different effects on remediating soil acidification. It was reported that the soil pH increased significantly ($p < 0.05$) following the application of NPK + CaO treatments, but the increase in soil pH was less ($p < 0.05$) than that achieved by long-term NPK + SM application (Xun *et al.*, 2016). According to Xun *et al.* (2016), manure is a complex composition of proteins, organic acids, cellulose, hemicelluloses, and inorganic salts. Most of the components, such as amino acids, carboxylic acids and glycogen, can be easily decomposed during glycolysis (enzymatic breakdown of carbohydrates and sugars, especially glucose) to release base cations and hence increase the soil pH.

Hati *et al.* (2007) found no significant changes in the soil pH following the application of manure and NPK fertilizer. They attributed the stability of the soil pH to the high buffering capacity of the clayey soil and the presence of weak carbonates or bicarbonates salts, which on dissolution release free cations, thus counteracting the effects associated with the manure applied. Soil buffering capacity is the ability of the soil to resist change in pH due to protonation/deprotonation of acidic groups on organic matter, oxides, and hydroxides (Nelson and Su, 2010).

Mineralization of organic-P is influenced by the soil pH because the solubility of the compounds binding to P is directly related to the soil pH (Busman *et al.*, 2009). In alkaline soils (soil with pH greater than 7) Ca is the dominant cation that will react with phosphate to form insoluble phosphate compounds (such as dibasic calcium phosphate dehydrate [CaH_5O_6P], octocalcium phosphate [$Ca_8H_2(PO_4)_6.5H_2O$], and hydroxyapatite [$Ca_5(PO_4)_3(OH)$]) that decrease the solubility and availability of phosphate in the soil (Figure 5, Section 2.7.3).

Similarly, in acidic soils mostly where the soil pH is less than 5.5, Al and Fe are the dominant ions that react with phosphate to form an insoluble Al phosphate [$AlPO_4$] and Fe phosphate [$FePO_4$], compounds which reduce P availability for plant uptake (Busman *et al.*, 2009). Therefore, Busman *et al.* (2009) suggested that maintaining soil pH between 6 and 7 will result in the most efficient use of phosphate.

2.7.3 Soil P and P dynamics

Phosphorus is a macronutrient and an essential plant nutrient needed for plant development and adequate yield promoting plant root growth and hastening crop maturity (Mkhabela and Warman, 2005; Jin *et al.*, 2016). However, P is in relatively short supply in most natural ecosystems and unlike other macronutrients: N, K, S, Ca, and Mg; P is by far the least mobile nutrient which is available to plants in most soil conditions due to soil-system-induced P deficiency (Basamba *et al.*, 2006). Due to the reactive nature of P, it is often characterised by low availability due to slow diffusion and high fixation in soils and this makes P not readily available (and sometimes unavailable) for plant uptake (Shen *et al.*, 2011).

The reactive nature of P accounts for P deficiency that occurs in soils. For instance, P deficiency in tropical soils is mostly due to strong adsorption of $H_2PO_4^-$ to Al and Fe oxides and hydroxides (sesquioxides) (Figure 5) which adsorb inorganic P and hold it in a form that is unavailable to plants while the presence of carbonates is responsible for P adsorption in alkaline soil (Fontes and Weed, 1996). Plants only take up P in an available form ($H_2PO_4^-$ or HPO_4^{2-}), thus the other forms of P in the P pool can be made available for plant uptake through the actions or activities of soil microbes (mineralization) (Figure 5). The amount of P present in soil solution depends on the extent to which it is adsorbed or desorbed by iron oxides or the carbonates, and that can be influenced by interactions with organic matter (Fink *et al.*, 2016). Thus, P availability can depend on the activities of soil microbiology in breaking down organic matter and releasing P into available forms. As mentioned in Section 2.7.2, at lower pH (acidic condition) more Fe and Al are available in soil solution and they have high affinity for P; thus Fe and Al react with P to form insoluble phosphate compounds (Fink *et al.*, 2016), thus adsorbing P from the soil solution making P less available for plant uptake. However, at high pH (alkaline condition), P reacts with excess Ca forming insoluble compounds in the soil (Figure 5).

Application of OAs can potentially influence soil P dynamics (Mkhabela and Warman, 2005) due to the activities of soil microbes (mineralization) which play a major role in soil P availability for plant uptake (Figure 5). In a 98-day microcosm incubation study on the influence of manure biochar on soil properties, Jin *et al.* (2016) reported a significantly higher Olsen-P with manure biochar as compared with the un-amended control. Mkhabela and Warman (2005) reported that the application of composts increased P availability indirectly due to the formation of phosphor-humic complexes (fulvic-acid), replacement of P by humate ions and the coating of sesquioxide particles by humus which reduced access to P binding sites. Humic-metal-phosphate complexes were reported to decrease phosphate fixation in soils, increased P availability and resulted in greater phosphate uptake and plant growth (Urrutia *et al.*, 2014).

Addition of urban-waste compost increased soil P solubility. According to the authors, this was due to the formation of phosphor-humic complexes which reduced the P immobilization process, thus decreasing potential P binding sites (Giusquiani *et al.*, 1988). Similarly, it was found that the application of inorganic fertilizers (NPK) and municipal solid waste (MSW) compost decreased P adsorption to soil by up to 30% as compared with the control treatment (Mkhabela and Warman, 2005). The authors also found that MSW compost supplied similar amounts of P as with the inorganic P fertilizer applied. Thus, they recommended MSW as a good source of P for potatoes and sweet corn production.

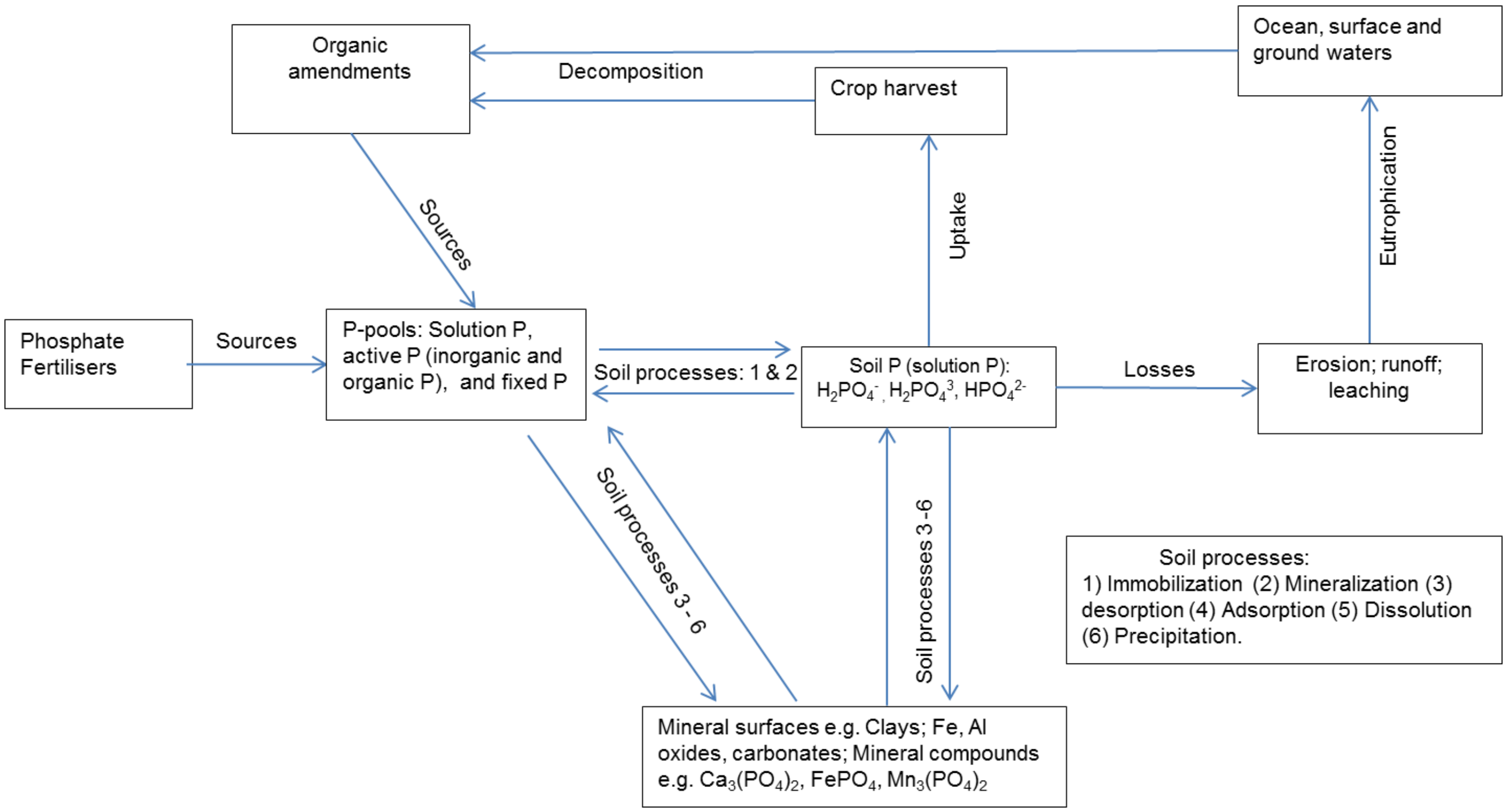


Figure 5 Mechanistic diagram of the Phosphorus cycle.

Yang *et al.* (2014) found a significant increase in Olsen P with the application of OAs, with or without supplementary inorganic fertilizer. Nevertheless, application of OAs can result in accumulation of large quantities of P in soil, which can pose a potential environmental threat. A high tendency of P accumulation in soil occurs when OAs, especially manures, are conventionally applied as a N rather than a P-source (Yang *et al.*, 2014). The authors reported an annual increase in Olsen P of about 7 mg kg^{-1} yr^{-1} following continuous application of dairy manure in addition to NPK fertilizer, which resulted in an accumulation of more than 200 mg kg^{-1} Olsen P over a 20 year-period. Such high Olsen-P concentrations might cause environmental problems when leached from the soil (Yang *et al.*, 2014).

2.7.4 Soil Nitrogen (N) and N dynamics

Nitrogen is another important plant nutrient and one of the primary macronutrients required by plants for adequate growth and development. OAs are a source of N for plants and soil microbes. The soil provides or supplies available N either in organic or inorganic forms. Studies have shown that the application OAs, such as poultry manure, farmyard manure, composts and municipal wastes, increase soil available N (Norton, 2000; Magdoff and Weil, 2004; Dijkstra *et al.*, 2013). The N contained in OAs are made available via the actions of soil micro-organisms predominantly through oxidation (mineralization) of organic matter (Dijkstra *et al.*, 2013).

Soil micro-organisms are crucial in plant nutrition through the continued cycling of nutrients, mostly N, P, and S [soil nutrient regulatory function] (Figures 5 and 6, Sections 2.7.3 and 2.7.4) contained in OAs (Magdoff and Weil, 2004) and these nutrients drive the above-ground ecosystems (plants). Almost all the N and large proportions of P and S that exist in soils occur as constituents of SOM, which serves (both in short and long terms) as the source of soil nutrients (Aponte *et al.*, 2010). The capacity of soil micro-organisms to act both as a sink and a source of soil nutrients is vital for plant nutrition, because most of the N and P requirements of plants come from organic pools that are cycled by the actions of the soil microbes (Figures 5 and 6) supplied through organic matter decomposition (Aponte *et al.*, 2010; Magdoff and Weil, 2004; De Neve *et al.*, 2004). Decomposer micro-organisms (especially fungi and bacteria) carry out most of the decomposition activity that release plant available nutrients from OAs (Magdoff and Weil, 2004). During the mineralization process, fractions of the C, N and P in the decomposing residues are immobilized in the microbial biomass as part of their cellular constituents (e.g. phospholipids and proteins) (Aponte *et al.*, 2010). Thus, during OA (organic matter) decomposition, net N mineralization will occur if the OA has excess N relative to the N demands of the micro-organisms. On the contrary, if the reverse is the case, the micro-organisms will immobilise inorganic N from the soil solution (Norton, 2000) and this will adversely affect plant growth and yield performance.

OAs differ greatly in their chemical compositions and that can affect their rate of mineralization (De Neve *et al.*, 2004; Hewidy *et al.*, 2015) and the quantity of nutrients mineralized. Nitrogen released from some OAs has little effect on crop growth in the year of application, due to the slow-release characteristics of the organically-bound N associated with OAs (Gutser *et al.*, 2005). De Neve *et al.* (2004) observed that application of immature composts, unlike the mature composts, did not immobilize mineral N because the immature compost was associated with more labile and more readily available organic C for microbial uptake. Therefore, N availability of organic materials depends largely on factors such as: (1) mineral-N content, (2) total N content and (3) the C:N ratio of the organic materials (Gutser *et al.*, 2005). Thus, an OA high in mineral N has shorter-term N availability as compared with OAs that have low mineral N content. In addition, the C:N ratio of an OA is important with respect to the availability of N. Hence, low-N OA with a C:N ratio > 15 can limited N availability due to N immobilization in soil by the soil microbes (i.e., use of mineral N to build micro-organism protein) (Gutser *et al.*, 2005).

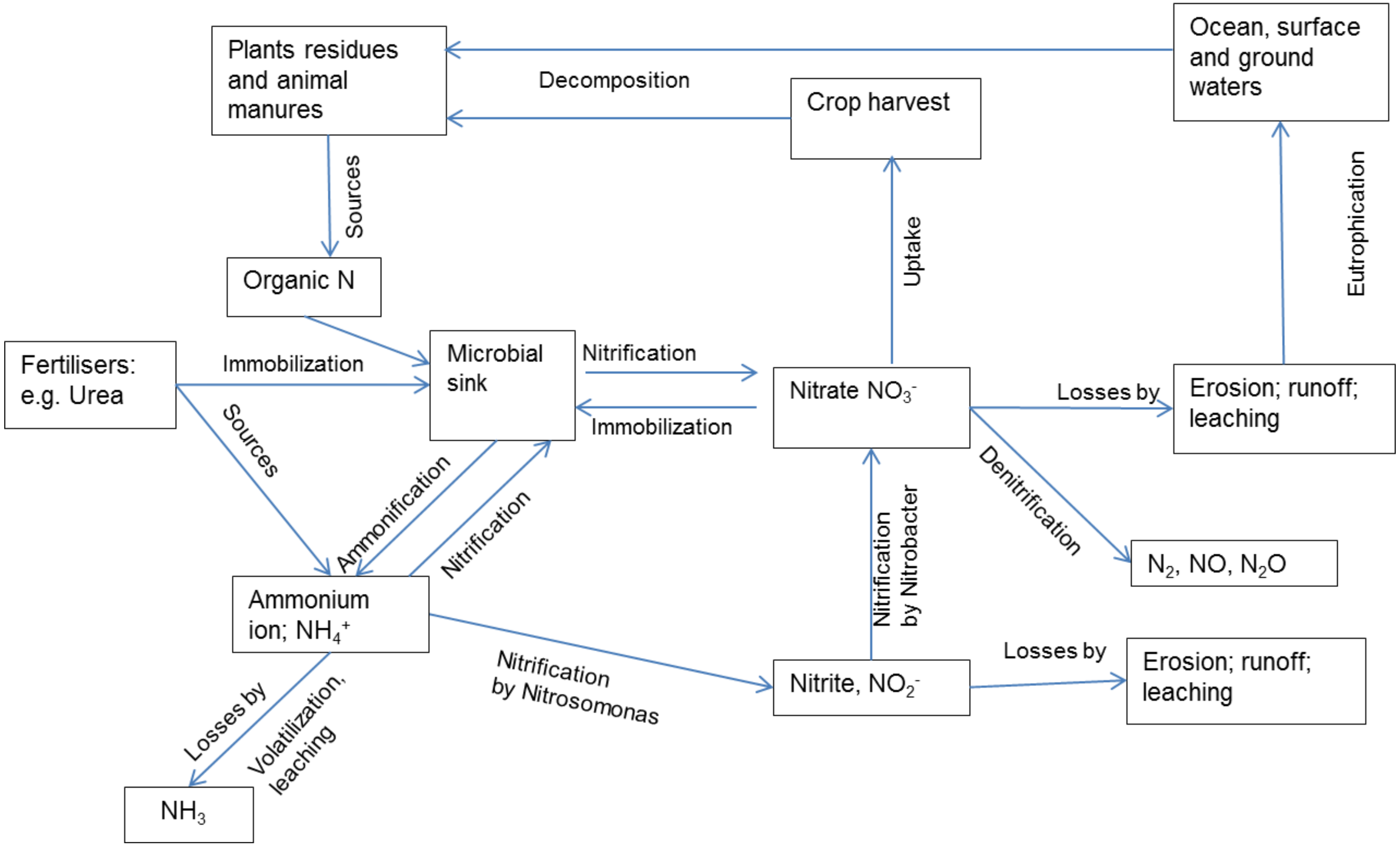


Figure 6 Mechanistic representation of the Nitrogen cycle.

Application of 100 kg N ha^{-1} via composted municipal solid wastes and composted manure resulted in significantly higher N as compared with the un-amended control (Hewidy *et al.*, 2015). According to the authors, the higher N was due to the different quality of the N compounds contained in the treatments and their comparative availability for crop uptake, which influenced the N adsorption by seedlings, NH_3 volatilization, and NO_3^- leaching from the topsoil. Due to low availability of compost-N associated with the municipal solid waste (MSW) Mkhabela and Warman (2005) suggested that supplementary inorganic N should be added to compost to enhance N availability to crops.

2.7.5 Soil Organic Matter (SOM) and Total Organic Carbon (TOC)

Soil organic matter (SOM) refers to plant and animal organic remains contained in the soil at different stages of decomposition, while soil organic carbon (SOC) (or TOC = Total organic carbon) is the organic fraction of the SOM. SOM and SOC content have been identified as useful indicators of both soil chemical and biological quality, which also have strong direct and indirect effects on soil physical quality (Shukla *et. al*, 2006; Kirkby *et al.*, 2013). Consequently, SOM and SOC play an important role in soil health. Increasing the size of the soil organic carbon (SOC) pool through appropriate management practices, such as the regular addition of OAs, will improve the physical, chemical and biological properties of degraded soils (Epelde *et al.*, 2012; Barzegar *et al.*, 2002; Kirkby *et al.*, 2013).

Ouédraogo *et al.* (2001) recommended the use of compost to combat soil degradation and alleviate food shortages and poverty in the Sahel. Pascual *et al.* (1999) reported that incorporation of OAs (fresh and composted municipal solid waste [MSW]) and sewage sludge (SS) significantly increased SOM. According to the authors, improving the quality of a degraded soil [increasing the SOM levels] was more effective with the application of composted MSW and SS than with fresh MSW and SS treatment. This was because the organic fractions (water soluble carbon and organic acids [humic and fluvic acids: which are factions of SOM]) in the fresh MSW and SS amendments were substantially reduced during the incubation period, resulting in a higher microbial activity which in turn reactivated soil biogeochemical cycles (Pascual *et al.*, 1997). Further, Hati *et al.* (2007) reported that inorganic fertilizer and OA (manure) application had a significant influence on SOC. They found that SOC content (1.78 kg m^{-2} [17.8 t ha^{-1}]) in 100% NPK + FYM treatment was significantly higher when compared with 100% NPK treatment (1.39 kg m^{-2} [13.9 t ha^{-1}]) and the un-amended control (1.12 kg m^{-2} [11.2 t ha^{-1}]).

Hewidy *et al.,* (2015) showed that short-term effects of OAs on soil properties, broccoli growth and yield following the application of 100 kg N ha^{-1} (ca 21 t ha^{-1}) of municipal compost increased the SOM content indicating that the enrichment in SOM was transitory. According to the authors, the increased SOM was due to the effects of residues from the added OAs, rhizospheric deposition and plant debris, rather than due to an increase in the humified moieties. Moieties are functional groups that are involved in the conversion of OAs by the action of decomposers, such as bacteria and fungi to humus (Hewidy *et al.*, 2015). Xie *et al.* (2014) found that long-term application of animal manure on a Mollisol increased SOM content due to continuous accumulation of organic matter contained in the manure and through the return of crop residues due to higher crop yields. However, Xie *et al.* (2014) found no significant increase in SOM as compared with the control treatment after 25-years of continuous inorganic fertilization in a clay loam.

Bandyopadhyay *et al.* (2010) studied the effect of the integrated use of farmyard yard manure (FYM) and inorganic fertilizer (NPK) on soil physical properties and productivity of soybean. They found that the integrated use of NPK and FYM applied at 4 t ha^{-1} significantly improved the SOC content by 29.8 and 45.2% as compared to NPK and control treatments, respectively. The higher SOC content in the NPK + FYM treatments was attributed to higher crop biomass, leaf shedding (due to higher growth) and increased root biomass. Further, the authors reported no significant difference in the SOC content between the control and the NPK treatments.

In another study, Masto *et al.* (2006) reported a significant increase in SOC following the application of 100% NPK (120 kg N, 60 K P_2O_5 and 40 kg K_2O) + 15 t ha^{-1} farm-yard manure. The increase in the SOC was also attributed to greater input of root biomass and better crop productivity over the years and also due to exudates from the plant roots that can contribute to the C pool resulting in the observed differences in the SOC. Maltas *et al.* (2013) reported an increase in the SOM by more than 0.7 g kg^{-1} with OAs, while the SOM in inorganic fertilizer treated plots decreased by 0.5 g kg^{-1}. The significant increase in the SOM contents was linked to high organic matter contained in the OAs. Further, long term application of 20 t ha^{-1} dairy manure + NPK, 4.5 t ha^{-1}straw + NPK, NPK, NP treatments resulted in significantly higher SOM as compared with the untreated control due to the addition of carbon via the roots (root exudates) and crop residues (Yang *et al*., 2014). However, Yang *et al.* (2014) found no significant effect on SOM with the application of N, PK, NK fertilizers as compared with the control and suggested root exudates and crop residues effects might explain the non-significant difference in the SOM for the N, PK, NK and control treatments.

2.7.6 Cation exchange capacity (CEC)

The cation exchange capacity (CEC) of a soil refers to the total number of exchangeable cations a soil can hold as determined by the number of exchange sites. Thus, CEC is the capacity of soil to retain or hold cations (positively-charged ions) such as Ca^{2+}, K^+, NH_4^+, Mg^{2+}, Cu^{+2}, Fe^{2+} and Mn^{2+} by attracting these cations to the negative charged surfaces and preventing these cations from being leached from the soil.

The soil CEC can be influenced by the amount and type of clay minerals (which are composed of layers or sheets of silica and alumina) and importantly, the SOM content because it contains negative charged surfaces that can attract and hold positively charged cations (nutrients) through electrostatic forces (i.e. negative soil particles attract the positive cations) (Fact Sheet, 2007). CEC is lower in acid soils than in alkaline soils due to the influence of pH on nutrient availability. Soil with a CEC >15 meq/100 g has a relatively high capacity to hold nutrient cations (Jones and Jacobsen, 2001). Generally, soils with higher clay content have higher CEC values, although the clay type can also substantially affect the CEC (Jones and Jacobsen, 2001). As shown in Table 3, soil texture is another intrinsic property of soil that influences the CEC of a soil. Thus, CEC is not a soil property that is independent of the conditions under which it is measured (Rhoades, 1982).

Table 3 Cation exchange capacities (CEC) for a range of soil textures

Soil Texture	CEC range (mg kg^{-1} soil)
Sand	2 - 4
Sandy loam	2 - 17
Loam	8 - 16
Silt loam	9 - 26
Clay	5 - 58

Adapted from Jones and Jacobsen (2001).

To summarise, the soil colloidal fraction which consists of clay and humified organic matter is the seat of chemical activity (sites for cations or anions exchange) in soils. The CEC of a soil depends on the amount of SOM, the amount and mineralogy of clay and the soil pH, as well as the amount of Fe, Al and Mn oxides. For example, for soils that have low clay content, SOM of the soil is responsible for the CEC (Magdoff and Weil, 2004). Soils with high CEC often have high buffering capacity. This means that such soil (a high CEC soil) can resist change in the soil pH. After 12 years of application of OA at 12 t ha^{-1} every year and 36 t ha^{-1} every three years; Maltas *et al.* (2013) found no significant effect on CEC. However, they found that application of ammonium-fertilizers lowered soil pH and consequently decreased the CEC due to the effects of NH_4^+ nitrification.

2.7.7 C:N ratio

Soil microbes are a major sink and source of soil nutrients, especially N and P. However, immobilization or mineralization of soil N is influenced by the C:N of the OA applied (Janssen, 1996; Bengtson, 2004). The idea that the C:N ratio is important for the immobilization rate is based on the assumption that micro-organisms are C limited below a certain C:N ratio and N limited above this ratio (Tate, 1995; Bengtson, 2004). OAs with a high C:N ratio suggests higher immobilization of soil N (that is N in the soil is used by the soil microbes during OAs decomposition). On the other hand, OAs with a low C:N ratio will be more easily mineralized thus making available the nutrients tied up in the OAs for plant uptake. The C:N of an OA can influence the type and dominance of particular soil microbes. Although a high proportion of both fungi and bacteria are soil dwelling decomposers, these organisms degrade organic residues differently. For instance, decomposition of an OA with a high C:N ratio is mostly fungi dominated, because the high C richness of the OAs satisfies the C needs of the fungi. In contrast, an OA with a low C:N ratio favours bacterial growth and dominance as a low C:N ratio organic amendment is rich in N which meets the high N demands of bacteria.

Micro-organisms that are decomposing a high C:N ratio SOM will be confronted with a surplus of C in relation to N. This is because microbes growing on or decomposing N-poor substrate organic material do not have enough N to build up as much biomass as the C concentration would allow (Spohn, 2014). Hence, in such situations the soil microbes will immobilize N nutrients from the soil to build-up its biomass (for protein production) and subsequently decompose the organic materials. However, the immobilized N is made available for plant uptake after the soil microbes have met their N requirement.

The nitrogen cycle (Figure 6Figure) illustrates the roles of soil microbes in N-cycling. As mentioned earlier, the C:N ratio of an OA can influence the ability of microbes to mineralize the nutrient content. During N immobilization, the soil is temporarily deficient in available N for plant uptake. This can have a negative effect on the plant growth and yield performance, especially for maize since maize is a heavy nutrient feeder. The polyphenol and lignin contents of OAs decrease the decomposition and mineralization rate of OAs and also lowers the rate of N release (Shisanya *et al.*, 2009). Tejada *et al.* (2008) reported that green manures with a C:N ratio of about 20 facilitated optimal organic matter degradation, increased soil microbial activity and resulted in high productivity of maize. It is, however, suggested that during OA decomposition in the soil, N mineralization and immobilization processes are simultaneously taking place in the soil. This is because the intensity and kinetics of N immobilization and subsequent re-mineralization depend on the nature of the decomposing material and types of decomposers involved (Mary *et al* ., 1996).

2.7.8 Available-K and Available-Mg

Potassium (K) is an essential and major nutrient for agricultural crop production and a macro-nutrient required in large amounts by maize (George and Michael, 2002). It plays an important role in regulating the water content of the plant and helps plants survive drought stress conditions, thus application of K improves plant photosynthetic rate, plant growth and yield (Egilla *et al.,* 2001; George and Michael, 2002; Al-Zubaidi *et al.*, 2008). Potassium is essential for the transport of sugar from the leaves to the storage organs where the sugar is converted to starch and also in maintaining the turgor (i.e. rigidity) of plant tissue (Al-Zubaidi *et al.*, 2008; Mallarino *et al.,* 2012).

In spite of the high total K content of most soils, a small portion of K is accessible for plant uptake (Al-Zubaidi *et al.*, 2008). Inadequate K in soil is one of the major factors limiting the productivity of the predominantly humid wetland soils of the tropics (Ajiboye *et al.*, 2015). Ajiboye *et al.* (2015) suggested that the low K fertility status of most soils is either due to nutrient mining by plants (over utilization of K the soils) or due to the low native K content resulting from the nature of the parent material. As such, external K fertilizer application will be required to sustain the productivity of these soils (Ajiboye *et al.*, 2015).

Potassium deficiency is accompanied by a weakening of the stalk, resulting in lodging, drying along the tips and edges of lower leaves and crop loss (Xin *et al.*, 2011; Mallarino *et al.,* 2012). Application of OAs is expected to provide greater supply of Available-K, thereby increasing its availability for maize growth and yield as compared with the un-amended control treatment (Mallarino *et al.,* 2012). Thus, insufficient K amounts in the soil or applied via inorganic fertilizer or OAs significantly decreases maize yield (Xin *et al.*, 2011; Mallarino *et al.,* 2012).

Like K, magnesium (Mg) is an essential plant nutrient and one of the nine essential macro-nutrients that plants utilize in relatively large amounts for their growth and development (Williams and Salt, 2009; Hermans *et al.*, 2010). Mg promotes the activation of enzymes for metabolic functions and plays an important regulatory role in the cell energy balance, interacting with the pyrophosphate structure of nucleotide tri- and di-phosphates (Hermans *et al.*, 2010; Zhao *et al.*, 2012). Mg deficiency in plants occurs globally and affects the productivity and quality of most crops (Gerendás and Führs, 2013). This is because of the complex role Mg plays in chlorophyll and protein biosynthesis; as such Mg deficiency results in a decline in the activities of key photosynthetic enzymes and thus inhibits CO_2 assimilation and N metabolism, thereby affecting crop yield and quality (Zhao *et al.*, 2012; Gerendás and Führs, 2013). Studies have shown that Mg treatment application had significant positive effects in the growth and yield attributes of maize (Chwil, 2009; Noor *et al.*, 2015).

2.7.9 Micro-nutrients

2.7.9.1 Zinc (Zn)

Zinc (Zn) is essential for the normal healthy growth and reproduction of plants, animals and humans (Shabaz *et al.*, 2015). Inadequate supply of plant-available Zn reduces crop yields and also affects the quality of crop produced (Alloway, 2008; Shabaz *et al.*, 2015). Zinc plays a key role as a structural constituent or regulatory co-factor in a wide range of different enzymes and proteins in many biochemical pathways (Asif *et al.*, 2013; Shabaz *et al.*, 2015). These roles include carbohydrate metabolism, both in photosynthesis and in the conversion of sugars to starch, protein metabolism, auxin (growth regulator) metabolism, pollen formation, and the maintenance of the integrity of biological resistance to infection by certain pathogens (Alloway, 2008; Asif *et al.*, 2013). Zn deficiency appears to be the most widespread and frequent micronutrient deficiency problem in crop and pasture plants worldwide, resulting in severe losses in yield and nutritional quality (Rashid and Ryan., 2004; Alloway, 2008). It is estimated that nearly half the soils where cereals are grown do not have sufficient available Zn, growing cereals on these potentially Zn-deficient soils without Zn supplementation further decreases grain Zn concentration (Alloway, 2008; Shabaz *et al.*, 2015). Maize is most susceptible to Zn deficiency and because of that, maize receives the highest proportion of Zn fertilizer applications (Alloway, 2008). Use of OAs can provide micronutrients that are not often supplied with inorganic fertilization (Nawab *et al.*, 2016).

2.7.9.2 Copper (Cu)

Like Zn, Cu is another essential micronutrient which is important for the healthy growth and development of plants, especially maize (NSW DPI, 2009). Inadequate supply of plant-available Cu reduce crop yields and also affect the quality of crop produced (Alloway, 2008). Application of OAs increases Cu availability. This is because OAs influence soil attributes, such as soil pH, CEC and OM, which thus exert influence on the soil Cu reactions, such as adsorption/desorption, precipitation/dissolution, complexation and redox processes, as well as on the availability of Cu (Zeng *et al.*, 2011; Carmo *et al.*, 2016).

2.8 Potential Effects of Organic Amendments on Biological Soil Quality Indicators

The biological components (especially soil micro-organisms) only occupy a tiny fraction (<0.5%) of the total soil volume and make up less than 10% of the total organic matter in soil (Nielsen and Winding, 2002). Despite their small volume in soil, soil micro-organisms are key players in the cycling of N, S, and P (Figures 5 and 6, Sections 2.7.3 - 2.7.4), and the decomposition of organic residues (Nielsen and Winding, 2002). Addition of OAs is a strategy to improve soil health where the SOM content is low (Bastida *et al.*, 2008). The status of a soil can be evaluated by assessing the state of its microbial community (Bastid *et al.*, 2008). Microbes are largely responsible for the decomposition of SOM at the soil ecosystem level due to the huge variety of enzymes associated with micro-organisms (Bastida *et al.*, 2012). SOM also enhances the activities of beneficial soil micro-organisms (Drinkwater *et al.*, 1995). Nielsen and Winding (2002) concluded that soil microbes are excellent indicators of soil health because they respond quickly to changes in the soil ecosystem. Changes in the microbial populations or activity can show measurable changes in the soil physical and chemical properties, which could provide an early sign of soil improvement or an early warning of soil degradation (Tejada *et al.*, 2008). The application of OAs as 'green manures' to soil stimulates microbial growth and activity and is regarded as a good management practice in any agricultural production system (Eriksen, 2005). Green manures are crops or plants that are sown or grown with the intention to be ploughed back to improve soil properties.

Short-term OA (organic manure) application has been reported to increase soil microbial activity, microbial diversity and C turnover and lead to greater enzyme synthesis, activity and accumulation in the soil matrix (Dinesh *et al.*, 2000). OAs (green manure, paddy straw, and poultry manure) have been found to improve soil nutrient availability and affect the soil biological activity by increasing microbial populations, microbial biomass C, N, enzyme activities, and soil fertility (Surekha *et al.*, 2010). According to Delgado *et al.* (2012), poultry manure application improved the soil nutrient status due to the additional supply of nutrients and also significantly increased enzymatic activities (dehydrogenase, phosphatase) and microbial activity (soil basal respiration rate) as compared with the control treatment. However, they further observed that all these parameters decreased due to depletion of the OAs, with a progressive decrease in microbial and enzymatic activities due to mineralization processes in soils. Soil microbial biomass C [MB_C] was significantly increased with green manure application as compared with the un-amended control and increased progressively as the rate of OA applied increased (Tejada *et al.*, 2008).

As explained earlier in Sections 2.6 and 2.7, differences in the physico-chemical composition of OAs can have differential effects on the soil microbiota and influence the microbial use of the C and N contained in the OAs. This in turn can affect the preferential development of a groups of microbes that are better adapted to a particular OA (Bastida *et al.*, 2008). Soil amendments can affect soil microbial functional diversity and activities (such as microbial biomass quotient [C_{mic}:C_{org}] and metabolic quotient [qCO_2]) and community structure which in turn affect soil health through OM decomposition and nutrient recycling (Amaral and Abelho, 2016). This is because microbial enzyme activities can be affected by both the quantity and type of organic or inorganic inputs (Yu *et al.*, 2016). Soil microbes vary in diversity and function and are influenced by the organic matter content, soil fertility, and the physical and chemical properties of the soil (Aspray, 2008; Amaral and Abelho, 2016; Yu *et al.*, 2016).

Application of OAs or inorganic fertilizers can enhance microbial activity. OA is a major driving force for changes in soil microbial community composition (Yu *et al.*, 2016). Soil enrichment through OA and/or inorganic fertilizer input is a source of anthropogenic disturbance for soil habitats (Suleiman *et al.*, 2016). This suggests that the soil microbes and biological properties are influenced by management techniques, hence changes in the management practices can have significant effects on the soil microbial properties (community, population and diversity) and soil processes (Amaral and Abelho, 2016). For example Amaral and Abelho (2016) found that the amount (level) of microbial biomass in soils subjected to conventional farming was lower than that in organically farmed soil due to greater improvement in N and P as a result of compost application. Further, composted sewage and sludge treatments were found to enhance the mycorrhizal community more than un-amended treatments (Bastida *et al.*, 2008). Continual addition of farmyard manure increases microbial biomass (Haynes and Naidu, 1998).

2.8.1 Microbial biomass carbon (MB_C)

Microbial biomass C (MB_C) is a measure of the mass of the living component of soil organic matter (Hoyle *et al.*, 2015). It mostly consists of bacteria and fungi that decompose plant and animal residues and SOM to release carbon dioxide and plant available nutrients (Hoyle *et al.*, 2015). Further, soil microbial biomass plays an active role in the immobilization-mineralization soil processes (Figures

5 and 6, Sections 2.7.3 -2.7.4). MB_C provides information on the size of soil microbial communities and has also been regarded as an indicator of microbial abundance in the soil (Biau *et al.*, 2012). Large amounts of organic carbon are transformed, stored, and respired by micro-organisms in soil (Spohn, 2014). The soil microbes have direct interactions with plants and soil with regard to nutrient and organic matter cycling (Mandal *et al.*, 2007).

Cherif *et al.* (2009) reported significant differences in MB_C following the application of OAs (compost derived from municipal solid waste and farmyard manure) applied at 40 t ha^{-1}. They observed that the combination of inorganic fertilizer with the OAs significantly increased the MB_C as compared with the control. Similarly, Jannoura *et al.* (2013) reported that the application of OAs (horse manure and yard-waste compost [composted shrub and garden cuttings]) significantly increased MB_C, C, N, and P at all sampling periods (within the 124-day experimental period). They found that horse manure significantly increased the MB_C, N and P by 54%, 52%, and 67% respectively; while yard-waste compost increased MB_C, N and P by 23%, 23% and 60%, respectively, as compared with the control treatments. Further, compost treatment application increased MB_C by up to 100% as compared with un-amended controls (Diacono and Montemurro, 2010). A balanced application of adequate amounts of inorganic fertilizer and manures improved SOM and MB_C status (Mandal *et al.*, 2007). The authors observed that the application of 100% NPK + FYM had significantly higher (517 mg kg^{-1}) MB_C as compared with the control un-amended treatment (261 mg kg^{-1}).

Masto *et al.* (2006) found significantly higher MB_C with FYM + 100% NPK fertilizer application as compared with the control treatment (no manure or NPK application). The authors linked the higher MB_C to the increases in plant root biomass and higher root exudations which provided the MB_C with readily metabolizable carbon and N. Lupwayi *et al.* (2005) found that applying cattle manure at 17 t ha^{-1}, the MB_C in the bulk soil increased by 26%, while the application of 39 t ha^{-1} inorganic fertilizer (NPK) reduced the MB_C by 20% as compared with the control. In another study, Lupwayi *et al.* (2014) found that within one year of applying 160 t ha^{-1} and 80 t ha^{-1} fresh cattle manure, the MB_C in the amended bulk soil was significantly higher as compared with the un-amended control and NP fertilizer treatments, respectively. Further, they observed that subsequent application of fresh cattle manure for 3 years (at either application rate) continued to increase MB_C as compared with the NP fertilizer and control treatments, respectively.

Bastida *et al.* (2008) evaluated the effect of OAs (composted sewage sludge and anaerobic digested sewage sludge which differ in their degrees of stabilization) on the biochemical and microbial properties of a soil. They observed a significantly higher MB_C in the composted sewage sludge treatment as compared with the anaerobic digested sewage sludge and control treatments. This was attributed to the composition of the incorporated compost which influenced the size and type of the microbial community. Further, Bastida *et al.* (2008) observed that compost amended treatment produced a greater mycorrhizal community than anaerobic digested sewage sludge treatment.

2.8.2 Soil microbial activity

Soil microbes and microbial activities play an important role in soil biological and biochemical processes and influence the transformation of nutrients and OAs (Vinhal-Freitas *et al.*, 2010). Microbial activity and biomass are closely linked to N mineralization in soils (Hart *et al.*, 1994; Tietema, 1998). Soil respiration reflects the availability of carbon for microbial maintenance (Masto *et al.*, 2006). In addition, microbial respiration represents the primary mechanism for degradation of carbon fixed by plants (Allen and Schlesinger, 2004). However, soil respiration is highly variable and highly dependent on soil moisture and temperature (Masto *et al.*, 2006; Bhaduri *et al.*, 2015).

In this present study microbial respiration is synonymously used to indicate soil microbial activity. It is suggested that microbial biomass alone does not provide detailed information on microbial activity. Thus, measures of microbial biomass turnover, such as respiration, are required for an accurate assessment of microbial activity (Masto *et al.*, 2006). Bhaduri *et al.* (2015) suggested that the use or interpretation of soil respiration results should be treated with caution.

This is because soil respiration results could have both negative and positive meanings. For instance, release of CO_2 due to rapid decomposition of organic matter may not be considered desirable from the soil health perspective because of the important roles organic matter plays in the soil. On the other hand, organic matter decomposition releases plant nutrients and this may be considered desirable (Bhaduri *et al.*, 2015).

2.8.2.1 Microbial respiration

Soil respiration rate is commonly determined either on the basis of the rate of CO_2 evolution or on the rate of O_2 uptake (Dilly, 2003). Soil microbial respiration (MResp) measured through CO_2 production is regarded as a direct indicator of microbial activity and an indirect measure of organic C availability, since organic C is source of energy for the soil microbes (Ferreras *et al.*, 2006; Tejada *et al.*, 2008). Soil amended with OAs increase CO_2 emissions due to microbial decomposition processes in the soil (Terhoeven-Urselmans *et al.*, 2009). Tejada *et al.* (2008) obtained higher CO_2 release from an organically amended soil as compared with an un-amended control treatment. In addition, the authors found that CO_2 released decreased over time as the SOM decreased due to mineralization.

Bastida *et al.* (2008) observed significantly higher basal MResp in a composted sewage sludge treatment as compared with anaerobic digested sewage sludge and control treatments. Lupwayi *et al.* (2014) reported that CO_2 evolution correlated positively with uptake of nutrients N, P, K, but not with grain yield. Further, they observed that CO_2 evolution correlated positively with soil inorganic N, available P, and exchangeable K. Compost application had positive effects on C mineralization and influenced cumulative soil respiration after 15 days of incubation and significantly increased microbial activity (Vinhal-Freitas *et al.*, 2010). According to the authors, microbial activity increased due to the contributions of organic C and nutrients available to soil microbes via the OAs applied.

2.8.2.2 Soil microbial biomass quotient (C_{mic}:C_{org})

Soil organic matter dynamics and nutrient cycling have been linked to microbial activities (Vjatráková *et al.*, 2003). Soil microbial biomass quotient (C_{mic}:C_{org}) expressed as a ratio of the microbial biomass to total SOC has been used as indicator of stress on soil microbial populations (Godley, 2007) and also as an indicator of SOM quality, since C_{mic}:C_{org} is sensitive to changes in the quality of SOM (Maková *et al.*, 2011). A low C_{mic}:C_{org} ratio suggests a microbial high stress level, for example metal toxicity following OAs application to soil (Godley, 2007) or due to a lack of nutrient availability. High or low C_{mic}:C_{org} values may represent losses or accumulation of carbon in the soil (Vjatráková *et al.*, 2003).

2.8.2.3 Soil metabolic quotient (qCO_2)

Soil metabolic quotient (qCO_2) has been used as a reliable biological indicator of stress and microbial efficiency, and is used as a measure of the energy required to maintain the metabolic activity in relation to the energy required to synthesize biomass (Gibbs *et al.*, 2006; Vinhal-Freitas *et al.*, 2010). Changes in nutrient availability can modify microbial maintenance energy requirements. Thus, high qCO_2 indicates less efficient use of organic substrates by microbial biomass (Moscatelli *et al.*, 2005). However, most SOM are poorly degraded (due to low labile content) and does not support microbial growth (Godley, 2007). This can induce stressed conditions on the soil microbes and thus affect soil microbial activities. It is reported that qCO_2 is influenced by factors such as the pH, clay content and amounts of SOM and these factors can create varying stressed conditions for the soil microbes (Wardle and Ghani, 1995).

The biodegradability of OAs, plant organic carbon inputs (root exudates) into the soil, and natural variations in the microbial population sizes can affect the qCO_2 (Godley, 2007). Soil fertilization and liming have been reported to either increase or decrease qCO_2 depending on whether the treatments lower microbial stress (low qCO_2) or increases microbial stress (high qCO_2) (Wardle and Ghani, 1995; Maková *et al.*, 2011) due to increase or decrease in available nutrients or other environmental stressors, such as soil moisture content and temperature (Godley, 2007). OA application affects soil microbes activity, depending on the type of OA applied, the type of microbes dominant in the OAs applied and on the nutrient status of the soil prior to OA application (Maková *et al.*, 2011; Bhaduri *et al.*, 2015).

2.9 Potential Effects of Organic Amendments on Crop Growth and Yield Performance and Selection of Crop Performance Indicators

As stated in the previous Sections, OAs are a source of macro and micro nutrients essential for plant growth and development. Evanylo *et al.* (2008) advocated that OAs should be applied at the rates that meet crop nutrient needs. This is because OAs applied at rates that do not meet plant nutrient needs are not economically feasible for crop production. Krey *et al.* (2013) found that OA treatments (bio-waste compost and cattle manure applied at 30 t ha^{-1} in combination with triple super phosphate [TSP] applied at 21.8 kg P ha^{-1}) resulted in 1 t ha^{-1} higher maize yields than the un-amended control treatment. Adding OAs to soil affects crop growth and yield, either directly by supplying nutrients, or indirectly by modifying soil physical (Hati *et al.*, 2007), chemical and biological properties (Giacometti *et al.*, 2013; Unagwu *et al.*, 2013).

In addition to increasing the SOM, OAs provide additional benefits by supplying other nutrients which farmers seldom apply (e.g. Mn, Zn, and S) as insurance against potential yield limitations (Bulluck *et al.*, 2002). In a correlation analysis study on forage yield in corn hybrids, Ahmadi *et al.* (2014) considered the stem diameter, ear weight, and plant height as effective components of forage yield and thus these parameters were retained in the final regression analysis model. Similarly, Carpici and Celik (2010) observed positive and significant relationships between plant height and stem diameter, leaf number per plant, ear number per plant, and light interception; and between stem diameter and leaf number per plant. They, however, suggested that relationships between yield and yield components of maize, such as first ear height, leaf ratio, and light interception, should be considered for increasing the dry forage yield of maize. Application of 30 t ha^{-1} bio-waste compost recorded the greatest crop height and was 30 cm higher than the control treatment, due to higher P uptake

(Krey *et al.*, 2013). The authors regarded bio-waste compost an adequate substitute for commercial inorganic P fertilizer; since bio-waste compost applied every third year had a similar impact on plant available P as much as the inorganic P fertilizer applied annually.

2.9.1 Effects of SQIs on plant performance

Nitrogen is the nutrient most required by plants in large quantities (Biau *et al.*, 2012). Thus, N inputs and other nutrients, such as P and K, are crucial to achieve high productivity of maize (Biau *et al.*, 2012). However, the levels of N in soils are rarely sufficient for crops to achieve optimal yield. Thus, farmers often apply inorganic fertilizers and/or OAs (manures and composts) that can provide sufficient available nutrients (N, P, and K, Zn, S, Cu, Mn) to enhance crop productivity (Ahmad *et al.*, 2009; Maltas *et al.*, 2013).

Studies have shown a close relationship between the MB_C and crop yields both in the greenhouse (Chen *et al.,* 2000) and under field conditions (Mandal *et al.*, 2007). Lupwayi *et al.* (2014) found a positive correlation relationship between the MB_C, the nutrients (N, P, K, and Mn) and barley grain yield. However, Jannoura *et al.* (2013) found no correlation between the yield parameters and microbial biomass indices (MB_C, MB_N and MB_P). They reported that the short-term application of horse manure and compost greatly stimulated soil MB_C, MB_N and MB_P, but failed to increase productivity of the pea and oat crops grown. Although OAs (green manure, paddy straw, and poultry manure) improved the nutrient availability and soil biological activity (enzyme activities, soil respiration), Surekha *et al.* (2010) found no significant improvement in rice yields when compared with inorganic fertilizers. In contrast, Masto *et al.* (2006) found significantly higher root biomass and root exudates with the application of FYM + 100% NPK fertilizer as compared with the control treatment (no manure or NPK application).

In a 20-year study, Yang *et al.* (2014) reported a significantly higher maize yield with the application of crop residues (4.5 t ha^{-1} wheat stalk) + NPK and dairy manure applied at 20 t ha^{-1} + NPK, but found no significant increase in maize yield with application of only NPK fertilizer when compared with the untreated control. Relative to chemical fertilizers alone, OAs improved grain yields by 2%–13% under non-limiting N conditions, due to a diversified or higher availability of mineral nutrition (Maltas *et al.*, 2013). Combinations of OA and inorganic N improved soil nutrients and increased crops yields of a wheat-maize system (Yang *et al.*, 2014). Further, Srivas and Singh (2004) reported a significant and positive association between maize dry forage yield per plant and crop performance parameters, such as plant height, number of leaves per plant, and stem diameter. It is suggested that improvements in these plant performance parameters will help improve fodder yield both directly and indirectly (Carpici and Celik, 2010). Tejada *et al.* (2008) reported that green manures used as soil OAs improved production and quality of maize.

In addition, Agegnehu *et al.* (2015) observed a significant correlation between plant nutrient concentration and maize shoot and root biomass following compost addition with or without biochar + NPK. Biau *et al.* (2012) found higher maize grain yield with the application of inorganic fertilizer at 300 kg N ha^{-1} $year^{-1}$ (applied as a split dose); 65 kg P ha^{-1} $year^{-1}$; 207 kg K ha^{-1} $year^{-1}$ as compared with 315 kg N ha^{-1} $year^{-1}$ pig slurry applied as a full dose before sowing. The authors attributed the result obtained to the different fertilizer application strategies. They suggested that a significant proportion of N in the pig slurry may have been lost by volatilization before ploughing, resulting in the lower yield of maize. Higher plant yields increase soil carbon inputs from crop residues and root exudates (Biau *et al.*, 2012). High C:N ratio of crop residues reduces the decomposition rate, leading to an increase in the OM content (Biau *et al.*, 2012). Annual application of FYM at 4 t ha^{-1} + recommended dose of fertilizer (NPK) significantly increased grain yield of soybean by 14.2% and 50.3% as compared with the NPK only and un-amended control treatments (Bandyopadhyay *et al.*, 2010).

Reddy *et al.* (2000) found higher soybean and wheat yield with combined application of cattle manure and inorganic P fertilizer in a P-deficient vertisol than sole application of either treatment at the same application rate. Inorganic fertilizer improves crop yields and also leads to SOC accumulation in the soil due to the return of plant biomass (in the form of plant roots and residues) (Blanco-Canqui and Lal, 2004). Cherif *et al.* (2009) found significantly higher wheat grain yields with municipal solid waste compost applied at 40 t ha^{-1} and 80 t ha^{-1} as compared with the control plots (no fertilizer treatment). Horse manure and compost (composted shrub and garden cuttings) applied at 10 t ha^{-1} significantly increased crop yield (Jannoura *et al.*, 2014). For Roy *et al.* (2010), the application of OAs (mulch, compost and vermicompost) at the rate of 4.0 t ha^{-1}, 2.25 t $ha^{-1}$and 1.0 t ha^{-1}, respectively (≈60 kg N ha^{-1}) had a positive effect on maize biomass accumulation. The highest above-ground biomass (1134 kg ha^{-1}) was observed in vermicompost treated plots and lowest value was recorded in control plots (601 kg ha^{-1}). Mosaddeghi *et al.* (2009) found significant effects on maize root biomass and root length following dry weight application of 30 t ha^{-1} and 60 t ha^{-1} cattle manure. They concluded that cattle manure application had short-term beneficial effects on maize root length.

The combined application of appropriate rates of OAs and inorganic-N can improve soil nutrient status, which is crucial for sustaining desirable high yields of wheat and maize (Yang *et al.*, 2014). Further, Yang *et al.* (2014) observed that higher levels of manure + NPK application rate increased the soil nutrients by 50%, but did not result in significantly higher maize yields as compared with the yields obtained in lower treatment application rates. The non-significant difference in maize yield implied that the lower rate of application provided enough nutrients such that nutrient supply to the plant was non-limiting. Application of 22.5 t ha^{-1} of compost (vegetable, fruit and garden waste [VFG]) had a significantly higher maize yield compared with the un-amended control treatment due to a higher amount of total plant available (i.e. mineral) N applied (Leroy *et al.*, 2007).

Compost and slurry applied at 45 t ha^{-1} once in two years had significantly higher dry matter yield than the control (Leroy *et al.*, 2007). A pot study on the ameliorating effects of biochar and compost on soil quality and plant growth in a Ferralsol, Agegnehu *et al.* (2015) found that lone or combined application of compost and biochar together with fertilizer significantly increased maize growth when compared with the control (untreated) treatment.

2.9.2 Effects of SQIs on nutrient uptake

Maize stores its energy (food reserves) in the endosperm of the kernel and this provides the plant the nutrients its needs for a few days after germination. However, as the plant roots develop and begin to take charge of nourishing the young plant, shortages of nutrients, such as N, P and K, can slow growth and development (NSW DPI, 2009; Moore *et al.*, 2014). Nutrient uptake by plant depends on the ability of the plant roots to absorb nutrients and the nutrient concentration at the surface of the root (Jones and Jacobsen, 2001) and the availability of these nutrients in the soil solution.

According to Jones and Jacobsen (2001), plant nutrient uptake does not often correspond with plant growth. Hence, they suggested that plant access to sufficient K and N early in a crop's growth is more likely to increase plant performance than during the middle or later growth stages. This is because nutrient accumulation within plants is generally faster than biomass accumulation. Plant roots release about 17% of the photosynthate captured, most of which is available to soil organisms (Nguyen, 2003). However, deficiency of micronutrients is often related to soil type, soil pH, soil structural conditions and their effect on root growth, and crop susceptibility (Defra 2010).

Based on literature research, the following plant performance indicators were selected: number of plant leaves, plant stem diameter, plant height, vegetative growth stages, above and below ground dry biomass, and Cob Yield.

2.10 Summary

Following a detailed literature search on OA application and its effects on SQIs; it was observed that soil properties are related in 'complex interconnecting webs' such that a change in one soil property can be associated with either direct or indirect changes in another soil property. For instance, increase in the SOM following OA application can influence the WHC [physical properties] which can either directly or indirectly influence soil nutrients (chemical properties) and MB_C (biological properties). Thus, following the interrelatedness (complex-web) of these soil properties, a Fuzzy Cognitive Mapping (FCM) exercise was carried out to understand and demonstrate how OA application can improve the health of a degraded soil (Figure 4, See Appendix A for methodology). Therefore, the complex relationship associated with the soil properties (Figure 4) suggests that to improve a degraded soil using OA application involves a concomitant (holistic) improvement in the soil physical, chemical and biological properties and not just improvement in either of the soil properties.

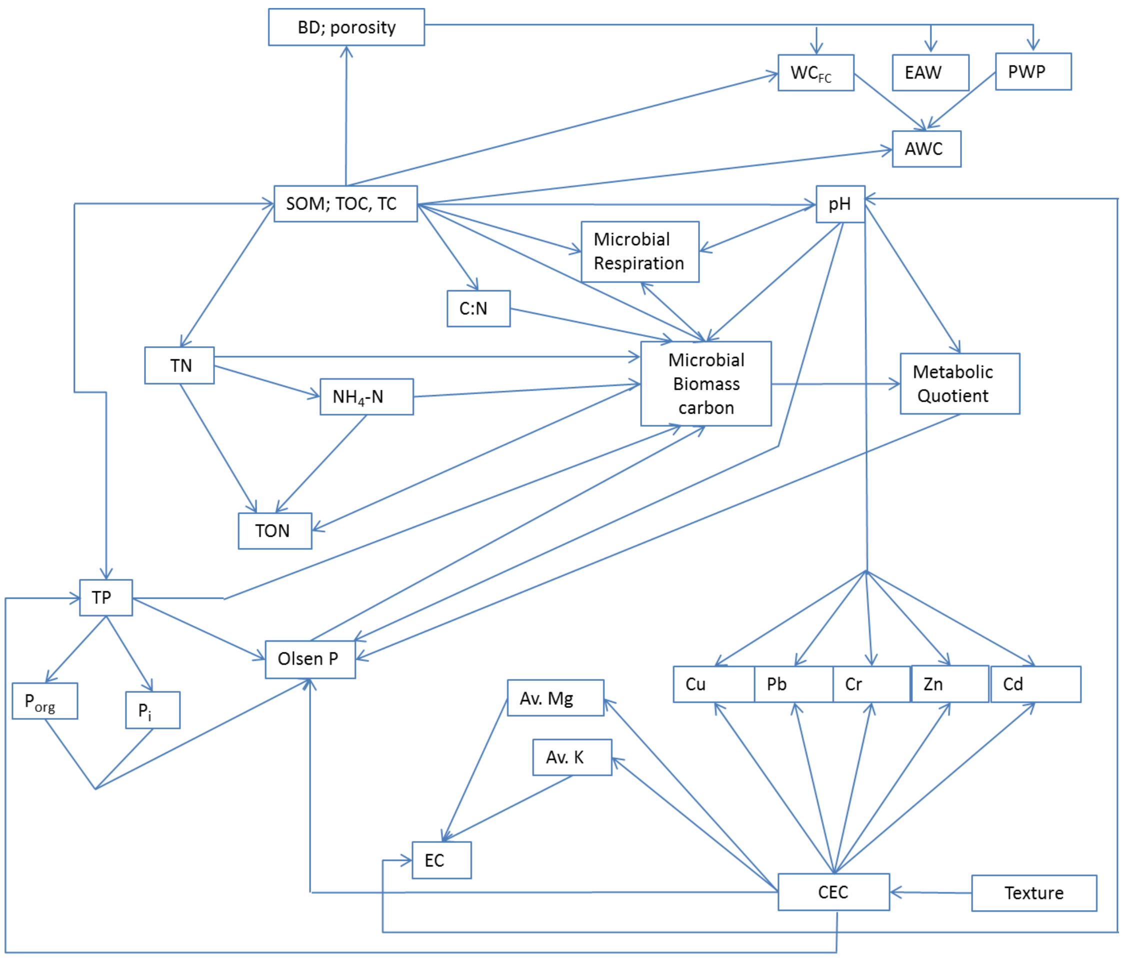


Figure 4 Relationship between key soil properties known to be influenced by soil OAs.

BD = Bulk density, WC_{FC} = Water content field capacity, EAW = Easily available water, PWP = Permanent wilting point, AWC = Available water capacity, SOM = Soil organic matter, TOC = Total organic carbon, TC = Total carbon, TN = Total N, NH4-N = Ammonium-N, TON = Total oxides of nitrogen, TP = Total P, P_{org} = Organic P, P_i= inorganic P, EC = Electrical conductivity, CEC = Cation exchange capacity, Av. = Available. The arrows show how OA affects the SQIs.

To further understand the effect of OA application on SQIs and the influence these have on the capacity of a degraded soil to perform its provisioning function, another FCM exercise was carried out (Figure 5). The FCM schematically demonstrates how crop performance is influenced by the effects OAs have on selected SQIs. Figure 5 indicates that higher crop yields depend on plant access to nutrients. This implies that to enhance crop yield, there is a need to increase soil nutrient levels, SOM content, WHC, MB_C and lower soil BD, thus creating an enabling environment for plant roots to gain access to soil nutrients and water.

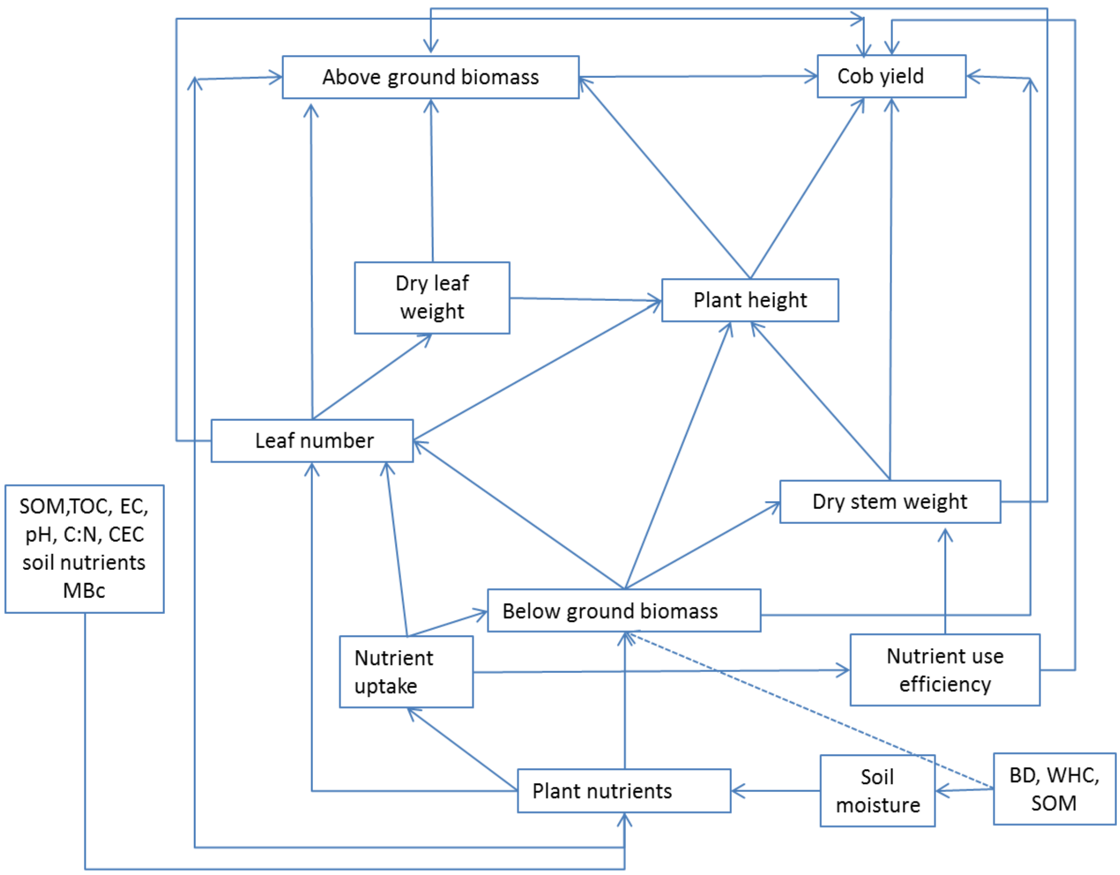


Figure 5 Relationship between selected SQIs and indicators of plant performance.

BD = Bulk density, WHC = Water holding capacity, SOM = Soil organic matter, TOC = Total organic carbon, EC = Electrical conductivity, C:N = Carbon to nitrogen ratio, CEC = Cation exchange capacity, MBc = Microbial biomass C.

In this present study, as evident in the FCM exercises (Figures 4 and 5), it is expected that OA application will improve the soil health of a degraded test soil through improvement in selected SQIs (See Section 2.11) and improvement in the SQIs will result in improved crop performance.

2.11 Minimum data set used in the present study

Marzaioli *et al.* (2010) and Epelde *et al.* (2012) suggested that in evaluating improvements in soil health, a reliable set of indicators of soil health is imperative. It is worth mentioning that measuring or testing all the physical SQIs listed by Merrington (2006) and other studies will in the context of this PhD be prohibitive in terms of time and budget. However, the following criteria have been suggested for consideration while selecting SQIs: potential costs (cost effective), practicality (availability of robust methodology) and simplicity (easy to analyse) of the indicators (Merrington, 2006). Thus, in this study and based on literature review, a minimum data set was selected to holistically investigate the effect of OAs on soil health, as measured by changes in the physical, chemical and biological soil quality indicators (SQIs) and also on plant growth and yield performance, which is used as a measure of soil productivity (Table 4).

Table 4 Key soil quality indicators used in assessing improvement in soil health

Minimum data set	Reasons for selection	References
	Physical SQIs	
Bulk density (BD)	It affects plant root penetration, soil porosity, runoff, soil compaction	Bandyopadhyay *et al.* (2010); Celik *et al.* (2010)
Total porosity	It influences water infiltration, runoff	Zhou *et al.* (2016);
Water release characteristics (WC_{FC}, EAW, AWC and WC_{PWP})	It affects availability of water for plant uptake and crop yield	Hati *et al.* (2007); Evanylo *et al.* (2008)
Soil moisture content (SMC)	SMC affects plant available water and crop performance	
	Chemical SQIs	
Soil organic matter/carbon	Affects soil nutrient, soil structure, BD and water retention, and soil processes, and soil microbes.	Celik *et al.* (2010); Rezig *et al.* (2013); Guo *et al.* (2016)
Nutrients: N, P, K, Mg, Zn, Cu	They influence the capacity of soil to support plant growth and yield, environmental quality indicator	Shen *et al.* (2011); Moharana *et al.* (2012); Cabilovski *et al.* (2014)
Metals	Influences environmental and plant performance	Nawab *et al.* (2016); Gondek (2010)
pH	It affects nutrient availability, heavy metal	Cabilovski *et al.* (2014)

Minimum data set	Reasons for selection	References
	mobility and absorption.	
Electrical conductivity (EC)	Used as a measure of the amount of salts in soil (salinity of soil). It Influences plant growth and productivity.	White (2006); Chang *et al.* (2007)
	Biological SQIs	
Microbial biomass C (MB_C)	It is a vital in nutrient cycling and organic matter decomposition.	Masto *et al.* (2006); Zhen *et al.* (2014)
Microbial respiration (MResp)	Used as a measure of soil microbial activities which play importance roles in soil biological and biochemical processes and the transformation of nutrients	Allen and Schlesinger (2004); Moscatelli *et al.* (2005); Vinhal-Freitas *et al.* (2010); Bhaduri *et al.* (2015)
Microbial quotient (qCO_2)	Used as indicator of stress and microbial efficiency	Godley (2007); Vinhal-Freitas *et al.* (2010)
Microbial biomass quotient (C_{mic}:C_{org})	Used as indicator of stress on soil microbial populations since C_{mic}:C_{org} is sensitive changes in the quality of SOM	Vjatráková *et al.* (2003); Godley (2007); Cheng *et al.* (2013)

2.12 Research gaps

From the detailed literature review, it was observed that OA have been used on soils to achieve different targets including: improving crop yield, re-establish vegetation cover on degraded soils, and increase soil nutrient content (Table 1). However, there are insufficient studies on the use of OAs to holistically improve the health of a degraded soil. In addition, there are very few studies (Table 1) that have an all-inclusive investigation on the effect of OA application on the physical, chemical and biological soil properties of a degraded soil and their impacts on crop productivity with specific reference to arable crop (maize) production. More information is needed on the use of OAs to restore the health of degraded soils (soils that are poorly structured, nutrient and organic carbon depleted, and have low biological activities) for maize production.

2.13 Aims and Objectives

This study aims to critically evaluate the effects of different OAs (Anaerobic digestate solid waste [AD_SW], mushroom compost [MC], PAS 100:2005 compost [PAS] and poultry manure [PM]) in:

(i) Improving the health of a degraded soil through improvements in the physical, chemical and biological properties through a critical evaluation of changes in selected soil quality indicators (SQIs).
(ii) Improving maize growth (plant height, number of plant leaves, vegetative growth, stem diameter) biomass [above biomass and below biomass], and yield performance (Cob Yield dry weight [Cob_{DW}]).

2.14 Hypotheses

To achieve the above stated aims, the hypotheses to be tested are that:

1. Application of OAs will improve the soil health by significantly affecting the physical, chemical and biological SQIs as compared with the control.
2. Higher rates of OAs applied will have greater significant effect on the physical, chemical and biological SQIs compared with the lower OAs rates.
3. OAs and the rates applied will significantly affect maize performance (biomass and cob yield) as compared with the control.

3 EXPERIMENTAL MATERIALS AND METHODS:

Test Soil

The test soil used in this study was supplied by Bourne Amenity Limited. It was a non-agricultural subsoil removed from between 50-150cm below the topsoil surface, in order to obtain a degraded soil in terms of the physical, chemical and biological properties. However, because soils can harbour pests, weed seeds, insects, fungi, and bacterial diseases (Phipps, 2013), the test soil was sterilised. This was done by heating the soil in a rotary kiln up to 200°C and allowing it to stay in the kiln for circa 10 minutes before being stored in an enclosed bay and allowed to cool down to ambient temperature. Thus, sterilizing the soil ensured that any significant changes in the soil physical, chemical and in particular the biological properties were due to the effects of the OAs applied.

3.1 Soil physical, chemical and biological analyses

The bulk soil (ca 1000 kg), was air-dried at the Cranfield University Soil Laboratory and sieved to <2.0 mm to remove stones and other non-soil particles, then mixed thoroughly to obtain a homogenous representative soil sample (Aggelides and Londra, 2000; Cherif *et al.*, 2009).

3.1.1 Post-incubation soil sampling

To evaluate the effects of OAs on key SQIs post-incubation, soil samples were taken from each of the experimental treatments (Table 13 Section 3.4.1) at the end of the 2-week incubation period prior to planting the maize.

A hand-held fork was used to collect topsoil samples to a depth of 5-10 cm. Approximately 600 g of moist soil sample was collected from each pot. The sample was split into two: a 200g moist soil was bagged and preserved at 4°C in the fridge for the determination of total oxides of nitrogen (TON), soil microbial respiration and microbial biomass C (MB_C). The remaining 400 g was air-dried (25^0C), sieved to <2.0 mm and used for determination of the chemical SQIs. Bulk density rings (5 cm depth x 5 cm diameter) were used to collect undisturbed soil samples for the determination of bulk density (BD) and measurement of water release characteristics (water holding capacity at field capacity [WC_{FC}], available water capacity [AWC], easily available water [EAW], and permanent wilting point [WC_{PWP}]). Post-harvest, this soil sampling method was repeated. However, particle size distribution (PSD) was determined only for the baseline physical soil characterization and not repeated post-incubation and post-harvest. Soil baseline physical, chemical and biological properties and key SQIs post-incubation or post-harvest were analysed using standard analytical methods.

3.1.2 Physical analysis

Bulk density was determined on undisturbed soil cores (5.0 cm deep x 5.0 cm internal diameter) using British Standard (BS) 7755 Section 5.6:1999 (Blake, 1965). Subsequently, total soil porosity was derived from the BD, calculated thus:

$$\text{Total porosity} = \left({}^{(1-\rho_b)}/_{\rho_s} \right) * 100 \qquad \textbf{(2)}$$

Where $\boldsymbol{\rho}_b$ is the bulk density and $\boldsymbol{\rho}_s$ is the particle density of soil solids (2.65 Mg m^{-3}) (Hati *et al.*, 2007).

In addition, soil water retention characteristics were determined on the undisturbed BD cores following BS 7755 Section 5.5:1999. To determine the water holding characteristics at 5 kPa suction (WC_{FC}), the samples were placed on a sand tension table set up to allow water suctions between 1 kPa to 10 kPa. Thereafter, the samples were weighed at intervals until a constant weight was obtained. To determine the water holding characteristics between 20 kPa [2 bar] and 1500 kPa [15 bar] points (i.e. EAW and WC_{PWP}, respectively) the samples were placed in a pressure cell (Figure 6).

Figure 6 Photo of pressure cells used for determining water retention characteristics.

Again, the samples were weighed at intervals until a constant weight was obtained. Thereafter, the constant weights of the samples were recorded and the samples oven dried at 105^0C for the determination of the dry mass of the sample. Further, particle size distribution (PSD) was determined using the sieving and sedimentation method (ISO 11277:1998) for three fractions namely sand (0.063–2 mm) silt 0.002–0.063 mm) and clay (<0.002 mm), following the particle size classification of the Soil Survey of England and Wales (Gee and Bauder, 1986).

3.1.3 Chemical analysis

Soil pH and EC were determined on a 1:5 (w/w) soil: deionised water suspension with a Mettler Toledo MA 235 pH analyser and a Jenway 4310 Conductivity Meter respectively (BS ISO 10390:2005; BS 7755 Section 3.4:1995). Soil organic matter (SOM) was determined following loss on ignition (BS EN 13039:2000) using a Carbolite AAFF 1100 Muffle Furnace at 450°C temperature overnight (about 16 hours). Total organic carbon (TOC) and Total-C were determined following BS 7755 section 3.8:1995 (ISO 10694:1995) and analysed using a Vario EL III CHNOS Elemental Analyser system, Germany. Total-N was also determined on the Vario EL III CHNOS Elemental Analyser, Germany following British standard BS EN 13654-2:2001. In addition, Olsen-P was determined in a sodium hydrogen carbonate solution using a Nicolet Evolution 100 atomic absorption spectrophotometer (AAS) at 880nm absorbance following BS 7755 Section 3.6:1995 (ISO 11263: 1994), Total-P was determined via microwave acid digest. Soil Available-Mg and Available-K were determined following BS 3882:1994 on an 1:5 air-dried soil to 1 M ammonium nitrate solution ratio. Filtrates were analysed for Mg and K using a Perkin Elmer Atomic Absorption Spectrometer (AAS) Analyst^{TM} 800. Ammonium-N (NH_4-N) and total oxides of nitrogen (TON) were determined on a fresh soil sample by potassium chloride extract following Method 53 of the MAFF (MAFF, 1986). Both NH_4-N and TON were auto-analysed using a Burkard Series 2000 Segmented Flow Analyser. In addition, soil Cation Exchange Capacity (CEC) was determined following the 1M ammonium acetate extraction method (MAFF, 1986b) on a 5.0 g <2.0 mm air-dried soil sample. Cadmium (Cd), Cu, Zn, Ni and Pb were determined by AAS Perkin Elmer Microwave AAnalyst^{TM} 800 following digestion in Anton Paar Multiwave 3000 microwave oven fitted with a 48MF50 rotor (BS EN ISO 7755-3.13:1998).

3.1.4 Biological analysis

Microbial biomass C (MB_C) was determined on moist fresh soils in triplicate for each treatment by the fumigation-extraction method (BS EN ISO 14240-2:2011). For each treatment, another three replicates were weighed out (the same mass) but not fumigated (serving as the control). The soil samples were mixed with 50 ml ± 2 ml 0.5 M K_2SO_4 for 30 minutes at 300 rpm in a Sorvall Legend RT oscillator to extract organic C. In addition to MB_C, microbial respiration was also determined on moist fresh soil by the alkali absorption method (British Standards Institute, 2011b).

The metabolic quotient (qCO2) was calculated as the ratio of respiration (mg CO_2-C g^{-1} h^{-1}) to MB_C (Thirukkumaran and Parkinson, 2000; Spohn, 2014). In addition, the microbial biomass quotient [C_{mic}:C_{org}] was calculated as the ratio of MB_C to TOC (Yan *et al.*, 2003; Almeida *et al.*, 2011).

3.2 Baseline characterisation of the test soil

The textural characteristics of the test soil are shown in Table 5. The soil is a sandy loam dominated by medium sand (46%). Sandy soils (>80% sand, <10% clay) are associated with poor physical condition (soil structure) and low chemical fertility (Arthur *et al.*, 2011). These properties affect the potential use of such soils for agricultural purposes, unless they are supplemented with chemical (inorganic) and/or organic fertilizers (Arthur *et al.*, 2011).

Table 5 Baseline physical properties of the test soil

%w/w total sand	%w/w Coarse sand	%w/w Medium sand	%w/w Fine sand	%w/w silt	%w/w clay	Texture
77.0 (± 1.24)*	8.0 (± 1.56)	46.0 (± 2.11)	23.0 (± 1.15)	17.0 (± 0.9)	6.0 (± 0.88)	Sandy loam

% w/w total sand = Coarse + Medium + fine sand, % w/w Coarse sand = 0.6 mm – 2.0 mm, % w/w Medium sand = 0.212 mm - 0.6 mm, % w/w Fine sand = 0.063 - 0.212 mm, % w/w Silt = 0.002 - 0.063 mm, % w/w Clay = < 0.002 mm. * = Values in parentheses represent +/- 1 standard error of the mean. Number of samples (n) = 6

The baseline soil chemical properties (Table 6) indicate that the test soil is alkaline with a pH of 8.2. Such a high pH suggests that the test soil will be associated with high calcium (Ca) or Mg carbonates (Brandy and Weil, 2010) which can affect P availability due to a reaction with the carbonates (P-adsorption) (Figures 5, Section 2.7.3) to form an insoluble compound $Ca_3(PO_4)_2$ (Wang *et al.*, 2006). The high pH would also affect the bio-availability of micronutrients such as Bo, Fe, Zn and Cu, due to precipitation as insoluble minerals (Wang *et al.*, 2006; Zeng *et al.*, 2011). This can affect plant nutrient uptake and performance. The test soil was associated with low levels of TON, available-P (measured as Olsen-P) and Available-K. Based on the Fertilizer Manual RB209 recommendation (Table 8, Section 3.2.1), the test soil's NPK content (Table 6, Section 3.2) is inadequate for optimum maize performance production (Defra, 2010) unless organic amendments and/or inorganic fertilizers are applied to provide adequate nutrients required for maize crop production (Alley *et al.*, 2009; Arthur *et al.*, 2011). The SOM was 2.33%; this appears to be high for a degraded soil. However, the Total-C content was less than 0.3%. The high SOM content is attributed to the volatilization of carbonates during the SOM analysis by loss on ignition by heating the soil to 450ºC for 4 hours (Nelson and Sommers, 1996).

Table 6 Baseline chemical and biological characteristics of the test soil

Olsen-P (mg kg^{-1})	EC (µS cm^{-1})	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available-K (mg kg^{-1})	Available-Mg (mg kg^{-1})	CEC (cmol kg^{-1})	SOM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	C:N	TOC (mg kg^{-1})	Total-P (mg kg^{-1})	MB_C (µg g^{-1})
32.9	130	8.2	0.45	4.17	87.3	179	15.9	2.33	22700	2560	0.113	2470	1643	5.51
(± 0.6)*	(± 0.003)	(± 0.03)	(± 0.08)	(± 0.33)	(± 1.96)	(± 2.3)	(± 2.06)	(± 0.08)	(± 0.093)	(± 0.01)	(± 0.03)	(± 0.01)	(± 22.1)	(± 0.33)

* = Values in parentheses represent +/- 1 standard error of the mean.

EC = Electrical conductivity, TON = Total oxides of nitrogen, NH_4-N = Ammonium-N, CEC =Cation exchange capacity, SOM = Soil organic matter, C:N = Carbon to Nitrogen ratio, TOC = Total Organic C, MB_C = Microbial biomass C. Number of samples (n) = 6.

The baseline soil heavy metals results indicate that the metal concentrations are within the EU maximum permissible levels [Table 7] (Nicholson *et al.*, 2010). From a regulatory point of view, this implies that the test soil is safe to receive the OA application. However, depending on the concentrations of heavy metals in the OAs, application of OA may result in the amended soil exceeding the permissible levels.

Table 7 Baseline heavy metals concentrations in the test soil

Cr (mg kg^{-1})	Cu (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	Cd (mg kg^{-1})
172 (± 3.34)	25.3 (± 4.09)	62.7 (± 2.4)	26.8 (± 10.3)	109 (± 3.39)	0.03 (± 0.003)
***EU Maximum Permissible heavy metals levels in soil**					
200 – 400	50 – 400	30 – 75	50 – 300	150 – 300	1 – 3

Values in parentheses represent ± 1 Standard Error (SE), Number of samples (n) = 6
*source: (Nicholson *et al.*, 2010).

3.2.1 Inorganic Fertilizer Application Rate

In this study, 50% of the RB209 recommended inorganic fertilizer application rates were applied to the test soil with the expectation that the application of OAs (AD_SW, PAS, PM and MC [see Section 3.3]) will make up the remaining NPK requirements of maize. This is because studies have shown that OA application has positive effects in improving nutrient availability (Surekha *et al.*, 2010; Jannoura *et al.,* 2013). Further, the application of 50% of the Fertilizer Manual RB209 recommended NPK rates was intended to replicate the low (and insufficient) levels of inorganic fertilizer that farmers in Nigeria and other developing countries can afford (FARA, 2009; CIMMYT and IITA, 2011).

Single N, P and K inorganic fertilizers were used in this study due to the inherently low nutrient status of the test soil (Table 6, Section 3.2). In such situations, application of N, P and K fertilizers are recommended to boost the soil nutrient levels required for maize production (Defra, 2010; IITA, 2010). The inorganic NPK fertilizers were applied as Nitram (34.5% N), Tri-single super phosphate (46% P_2O_5) and Murate of potash (60% K_2O), respectively. The quantity of inorganic fertilizer applied was based on the test soil's NPK indices, which were calculated following the Fertilizer Manual RB209 recommendations (Defra, 2010; Appendix B).

The P, K, and Mg indices of the test soil were 3, 1 and 4, respectively (Table 8, Section 3.2.1). However, due to the high pH associated with the test soil, a P-Index of 2 was used in calculating the inorganic P fertilizer to be applied. This is to account for the effects P-adsorption by the calcium carbonates which will affect P availability for plant uptake (Fontes and Weed, 1996; Fink *et al.*, 2016). Due to the complex dynamics and transformations processes associated with N (Figure 6, section 2.7.4), the soil N index was not calculated, but an index of 1 was assumed. This is due to the low N, P and K concentrations of the test soil.

Based on Fertilizer Manual RB209 for maize, the recommendation is to apply 100 kg N ha^{-1} on soil with an SNS (Soil Nitrogen Supply) index of 1. For soils with a P-Index of 2, 55 kg P ha^{-1} of Tri-single super phosphate (46% P_2O_5) is recommended. For soils with a K-index of 2, 205 kg N ha^{-1} of Muriate of potash (60% K_2O) is recommended (Table 8, Section 3.2.1). Table 8 (Section 3.2.1) illustrates how the soil indices were used to obtain the recommended fertilizer rates based on the Fertilizer Manual RB209 (Defra, 2010; Appendix B).

Table 8 Soil P, K and Mg Nutrient Indices

Index	Phosphorus (P)	Potassium (K)	Magnesium (Mg)
	Olsen-P (mg l^{-1})	Ammonium nitrate extract (mg l^{-1})	
0	0 – 9	0 – 60	0 - 25
1	10 – 15	**61 – 120**	26 - 50
2	16 – 25	121-180 (2-) 181-240 (2+)	51 - 100
3	**26 – 45**	241 - 400	101 – 175
4	46 – 70	401 – 600	**176 – 250**
5	71 – 100	601 – 900	251 – 350
6	101 – 140	901 -1500	351 – 600
7	141 – 200	1501 – 2400	601 -1000

Source: Fertilizer Manual RB209 recommendation (Defra, 2010).

The highlighted/bolded figures indicate the P, K, Mg indices of the test soil.

Based on the baseline characteristics and weight of the test soil (Table 6, Section 3.2), the inorganic fertilizers applied per pot were 2.70 g N, 1.41 g P and 4.01 g K which represented 50% of the Fertilizer Manual RB209 recommendation rates required for maize.

Table 9 RB209 recommended fertilizer application rates for forage maize based on SNS, P and K indices for soils in the UK

Nutrient elements	SNS, P or K Index					
	0	1	2 (kg ha^{-1})		3	≥4
Nitrogen (N) for all mineral soil	150	**100**	50		20	0
Phosphate (P_2O_5)	115	85	**55**		10	0
Potash (K_2O)	235	205	175 (2-)	**145 (2+)**	110	0

Modified from Fertilizer Manual RB209 (Defra, 2010).

The highlighted/bolded figures indicate the NPK fertilizer rates applied to the test soil.

3.3 Organic amendment (OA) chemical and biological analyses

Approximately 600 g fresh (un-dried) OAs were bagged and preserved at 4°C in the fridge for the determination of TON, MResp and MB_C. About 1 kg of the remaining OAs were air-dried in an oven set at 30 °C for 24 hours, ground and sieved to < 2.0 mm and used for determination of the chemical SQIs following the same standard laboratory procedure used for soil chemical analysis (Section 3.1).

3.3.1 Organic Amendments characterisation

3.3.1.1 Descriptions of the OA types

The Poultry manure (PM) was supplied by Cobrey Farms, Ross-on-Wye Herefordshire and PAS 100 Compost (PAS), by MEC Re-cycling, Lincoln, Lincolnshire. The mushroom compost (MC) and anaerobic digestate solid waste (AD_SW) were supplied by the Gs Fresh, Ely; Cambridgeshire. Poultry manure is an organic waste material, which consists of birds' faeces, urine and sometimes contains some of the bedding material or litter (e.g. wood shavings or sawdust) and feathers. Poultry manure is regarded as a good organic fertilizer because of its high nutrient content, especially N, P, and K (Hochmuth *et al*, 2013). The PAS refers to the Publicly Available Specification for composted material. It is green waste compost derived from garden cuttings and meets the British Standards Institution (BSI) specifications for composted materials used for agricultural purposes to ensure that they are pest and disease free.

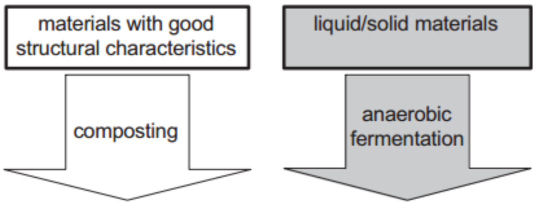
MC is a by-product obtained from mushroom farms and is a slow nutrient release OA (RHS, 2017). It is made by composting organic materials such as hay, straw, corn cobs and hulls, and poultry or horse manure for mushroom production. This by-product also called spent mushroom compost is used as a soil conditioner as it is an organic material used to increase the soil nutrient status and pH levels (RHS, 2017). The AD_SW is a by-product of the anaerobic digestion which is a process by which micro-organisms break down organic materials, such as food scraps, manure, and sewage sludge, in the absence of oxygen (USEPA, 2014). Semi solid (sludge) and liquid residues are by-products from anaerobic digestion plants and can be applied to land or composted and used as a soil amendment (USEPA, 2014).

3.3.1.2 Baseline chemical characteristics of the OAs

The OAs varied significantly in their chemical composition (Table 10, Section 3.3.1) due to their inherently different feedstock and the different processes that each OA goes through. For example, MC and PAS were composted organic materials. The AD_SW was anaerobically digested and the PM was air-dried. According to Gutser *et al.* (2005), composted OAs are associated with lower levels of NH_4-H compared to anaerobic fermented OAs. Fermented OAs are associated with higher pH than composted organic materials (Figure 7, Section 3.3.1). The present analysis showed similar findings (Table 10, Section 3.2.1.2).

The results (Table 10) indicate that PM had significantly higher Olsen-P concentration (2,417 mg kg^{-1}) compared with all other OAs. The pH (10.3) of AD_SW was significantly higher than the other OAs. The pH levels in the OAs were in the order AD_SW > PAS > PM > MC. Soil pH has significant effects on soil functions, chemical solubility, soil organisms and microbial activity as well as the availability of essential plant nutrients (Thomas, 1996; Jones and Jeff Jacobsen, 2001). Further, soil pH affects P availability due to P-fixation on carbonates (Figure 5, Section 2.7.3); and also affects micronutrients [Bo, Fe, Zn and Cu] availability (Wang *et al.*, 2006; Zeng *et al.*, 2011), which in turn can affect plant growth and crop performance.

The MC had a significantly higher (10,300 µS cm^{-1}) EC level as compared with all other OAs (Table 10, Section 3.3.1.2), implying MC contains a high concentration of soluble salts. High EC can cause soil salinity problems which can affect plant uptake of water and nutrients and crop yield (Ayers and Westcott, 1985).



		composting	anaerobic fermentation
organic substance	amount	decrease	decrease
	stability	increase	increase
	humus reproducibility	increase	increase
C : N ratio		decrease	decrease
NH_4^+-N		decrease	sharp increase
pH value		increase	sharp increase

Figure 7 Impact of composting and anaerobic fermentation on N availability in organic amendments. Adapted from Gutser *et al.* (2005).

The NH_4-N content in AD_SW (900 mg kg^{-1}) and PM (700 mg kg^{-1}) were significantly higher as compared with the other two OAs. PAS had the lowest (96.7 mg kg^{-1}) NH_4-N level. The TON in the OAs was significantly higher for MC (96.2 mg kg^{-1}) as compared with all other OAs. The low levels of TON found in PM, AD_SW, and PAS, suggest that most of the available-N for plant uptake will either come from direct uptake of NH_4-N or from microbial conversion of NH_4-N to nitrate.

Available-K varied significantly ($p < 0.05$) (Table 10, Section 3.3.1.2) between OAs. The AD_SW had significantly higher Available-K (14,981 mg kg^{-1}) as compared with all other OAs, while PAS had the lowest (4,592 mg kg^{-1}). The organic matter (OM) content associated with the OAs was significantly ($p < 0.05$) higher for PM (83.8%) as compared with the PAS, MC and AD_SW amendments (Table 10). PM had significantly ($p < 0.05$) higher Total-N and Total-C as compared with the other OAs. Except for MC, PM had significantly lower C:N ratio (12.8) as compared with the other OAs (Table 10). The low C:N in PM suggests high mineralization of N nutrient (Spohn, 2014). PAS had significantly ($p < 0.05$) lower Total-N and Total-C as compared with the other OAs. AD_SW had a significantly higher C:N ratio (19.7) as compared with the other OAs. The high C:N ratio in AD_SW can impede nutrient mineralization (nutrient immobilization) by soil microbes (Spohn, 2014), especially N, which will affect nutrient availability for plant uptake (See Section 2.7.7). The MB_C associated with the PM and AD_SW amendments was higher ($p>0.05$) as compared with the PAS and MC amendments. This can be attributed to the higher OM associated with the PM and AD_SW amendments [Table 10, Section 3.3.1.2] (Drinkwater *et al.*, 1995; Amaral and Abelho, 2016).

The high nutrient content of the PM is because most of the nutrients (protein, carbohydrates fats and oil), vitamins, and minerals (Zn, Fe, Ca) in feed that are utilized by the poultry birds are passed out as urine/faeces (Rasnake, 2012). This would account for the high levels of NH_4-N and Olsen-P found in the PM.

Based on the differences in their chemical and biological characteristics, it is expected that the OAs will have varied effects on the SQIs, which subsequently will affect plant growth and crop yield performance. This is because studies have shown significant changes in soil properties following the application of OAs (Barzegar *et al.*, 2002; Shukla *et. al*, 2006; Epelde *et al.*, 2012; Kirkby *et al.*, 2013; Spohn, 2014).

Table 10 Chemical composition of the organic amendments

Amendments	Olsen-P (mg kg^{-1})	EC (µS cm^{-1})	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available-K (mg kg^{-1})	Available-Mg (mg kg^{-1})	OM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	C:N	TOC (mg kg^{-1})	Total-P (mg kg^{-1})	MB_C (µg g^{-1})
MC	383a*	10,300c	7.3a	96.2b	120b	13,679a	1552c	61.8c	19,000a	266,000b	14.1ab	257,000b	2,440a	1,358d
AD_SW	1195b	4,500a	10.3d	0.20a	700c	14,981a	126b	85.8a	19,900a	391,000c	19.7d	370,000c	4,420b	20,972b
PAS	255a	1,300b	8.7c	0.45a	96.7a	4,592b	610a	37.4b	9,800b	154,000a	15.6b	151,000a	2,120a	1,929c
PM	2417c	4,400a	8.0b	0.18a	900c	9,142c	516a	83.8a	31,400c	400,000d	12.8a	390,000d	5,400b	23,943a

MC = Mushroom compost, AD_SW = Anaerobic digestate solid waste, PAS = PAS 100:2005 Quality Protocol compliant compost, PM = Poultry manure. EC = Electrical conductivity, TON = Total oxides of nitrogen, NH_4-N = Ammonium-N, OM = Organic matter, C:N = Carbon to Nitrogen ratio, TOC = Total Organic C, MB_C = Microbial biomass C. Number of samples (n) = 16.

*Within each column values followed by a different letter denote statistical differences ($p \leq 0.05$) following One-way ANOVA, followed by *post-hoc* Fisher LSD analysis.

Repeated applications of OAs can increase heavy metal concentrations and toxicity in the soil, thus jeopardizing their use for agriculture (Nkoa, 2014). Metal toxicity can negatively affect crop growth and yield performance (Sato *et al.*, 2010; Singh and Agrawal, 2010). However, in the present study, heavy metal levels of the PM, PAS, MC, and AN_SW were within the EU permissible levels (Table 11). Thus, the application of these OAs is unlikely to cause any environmental hazards (soil contamination by metal concentration). It is of note that the concentrations of Cu and Zn were significantly higher in PM than in other OAs (Table 11). Such high concentrations are likely to come from the feed additives in the poultry feed (Rasnake, 2012).

Table 11 Heavy metal concentrations in the organic amendments

Amendments	Cu ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Cd ($mg\ kg^{-1}$)	Cr ($mg\ kg^{-1}$)	Ni ($mg\ kg^{-1}$)	Pb ($mg\ kg^{-1}$)
MC	19.7^{a}	75.9^{a}	0.13^{a}	2.73^{a}	9.5^{a}	32.3^{a}
AD_SW	7.8^{a}	39.1^{a}	0.06^{a}	0.47^{a}	8.1^{a}	21.3^{b}
PAS	32.5^{b}	119^{b}	0.4^{b}	19.5^{c}	5.9^{ab}	66.4^{c}
PM	142^{c}	594^{c}	0.17^{a}	9.0^{b}	1.0^{b}	39.3^{a}
*EU Maximum Permissible levels in organic amendments	1000 - 1750	2500-4000	20 - 40	-	300 - 400	750 - 1200

MC = Mushroom compost; AD_SW = Anaerobic digestate solid waste, PAS = PAS 100:2005 Quality Protocol compliant compost; PM = Poultry manure. Within each column values followed by a different letter denote statistical differences ($p \leq 0.05$) following One-way ANOVA, followed by *post-hoc* Fisher LSD analysis. Number of samples (n) = 16
*source: (Nicholson *et al.*, 2010).

3.3.2 Organic amendment application rates

Different rates of OAs ranging from 8 t ha^{-1} to 160 t ha^{-1} have been used by various authors to evaluate their effects on soil physical, chemical and biological properties (Table 1 Section 2.2). Kanchikerimath and Singh (2001) evaluated the changes in SOM and biological properties due to the long-term application of manure and inorganic fertilizer in a maize–wheat–cowpea cropping system by applying 15 t ha^{-1} of cattle manure. Krey *et al.* (2013) used 30 t ha^{-1} cattle manure and 30 t ha^{-1} bio-wastes to assess the impact of a ten-year continuous application of organic and inorganic P fertilizer on P nutrition of maize. A review of the application of OAs as soil amendments shows that different OA rates have been used to achieve different targets (Table 1, Section 2.2). In the present study, inorganic NPK fertilizer was applied at 50% RB209 Fertilizer recommended rates while the remaining 50% of the nutrients were expected to come from the OAs. In the present study, the OAs were applied at 10 t ha^{-1} and 30 t ha^{-1} rates to represent low and high application rates (Table 12).

Table 12 Quantity of air-dry organic amendment required to achieve target application rates (10 t ha^{-1} and 30 t ha^{-1}).

Organic amendment types	10 t ha^{-1} (low rate)	30 t ha^{-1} (high rate)
Mushroom compost	235 g[a]	706 g[b]
Anaerobic digested solid waste	235 g	706 g
PAS 100 compost	235 g	706 g
Poultry manure	235 g	706 g

[a] = Organic amendment in g per pot equivalent to 10 t ha^{-1};
[b] = Organic amendment in g per pot equivalent to 30 t ha^{-1}.

The estimated P and K nutrient supplied via the OAs is presented in Figures 11-13 (Section 3.3.2). The results show that the available-P supplied via the PM and AD_SW applied at 10 t ha^{-1} and 30 t ha^{-1} with or without inorganic fertilizer addition [PM1N/1F, PM2NF/2F, AD_SW1F, and AD_SW2NF/2F] was higher than the recommended 24 kg P ha^{-1} rate (equivalent amount of elemental P supplied via 55 kg P_2O_5 ha^{-1}) [See Appendix B for more details on fertilizer calculations]. The result hypothetically suggests that the PM and AD_SW amendments at both application rates with and without inorganic P fertilizer addition (except for AD_SW1NF treatment) achieved the P recommended rates for maize (Table 9, Section 3.3.2). In contrast, the PAS and MC amendments at both application rates with and without inorganic P fertilizer addition did not achieve the P target via their Olsen-P supply (Figure 11). Unlike PM and AD_SW amendments, this result suggests that available-P supply from the PAS and MC amendments is limiting and can negatively affect plant growth and yield performance if no additional P is supplied/provided or if P is not made available by microbial activities (Figure 5, Sections 2.7.3).

Based on the Total-P concentration associated with the OAs, the results indicate that with exception of PAS1NF (which had <14% less P supply than the recommended rates), all other OA treatments had 36-86% higher P supply via their Total-P concentration than the recommended (24 kg P ha^{-1}) rates (Figure 12). However, Total-P comprises other forms of P not available for plant uptake. Thus the quantity of P in the Total-P implies that more P will be made available via microbial mineralization of organically bound P to increase P supply (Figure 5 Section 2.7.3). This suggests that the release of available-P from the Total-P will be a function of the type of OA, quantity of microbial biomass present (microbial population) and how effective the microbial activities are in degrading (mineralizing) the OAs. Therefore, the varied P supplied via the OAs is expected to have a varied effect on plant growth and yield performance (See Chapter 7 for more discussion).

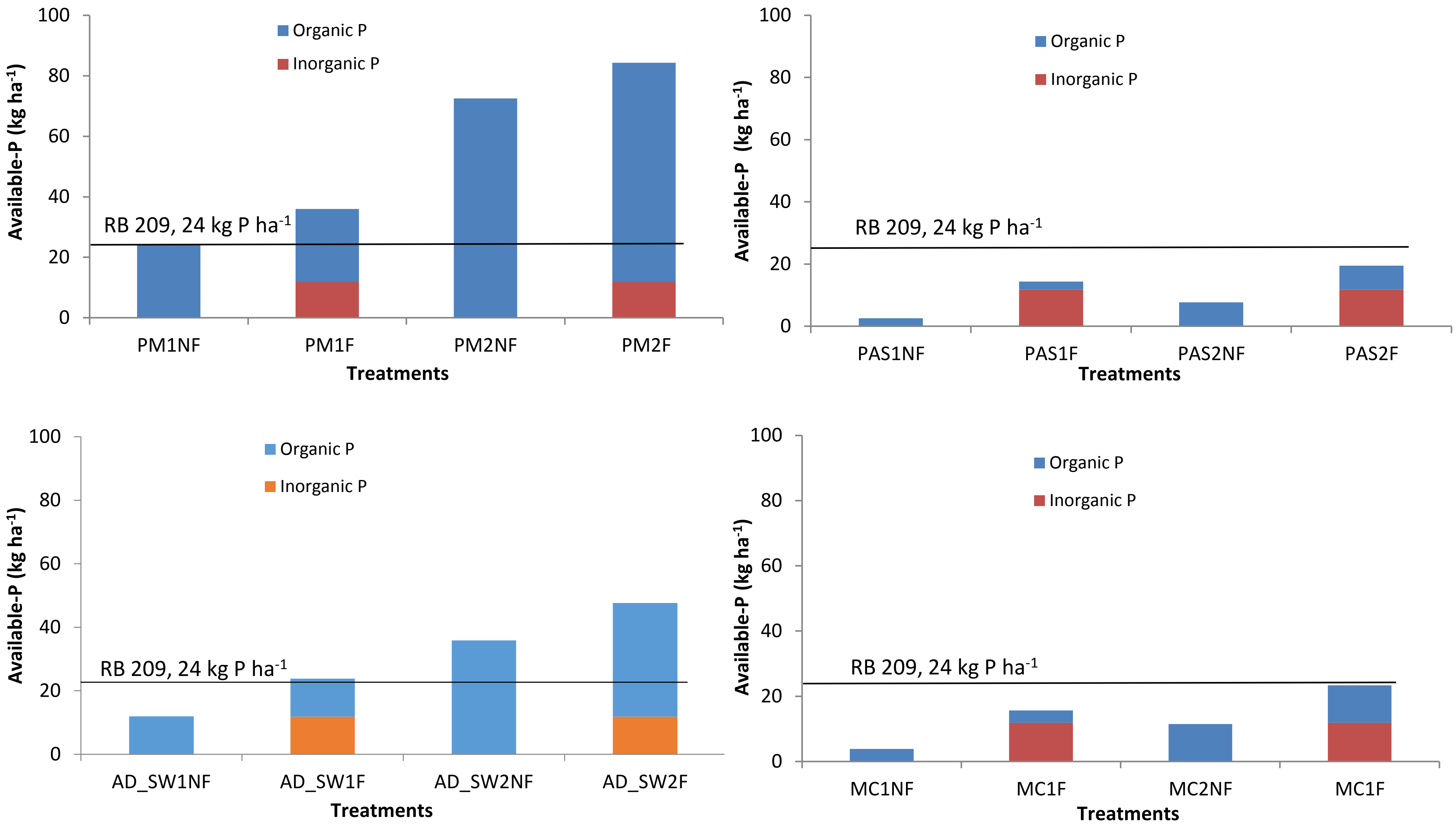


Figure 8 Estimated amount (kg ha^{-1}) of Available-P supplied via OA treatment application.

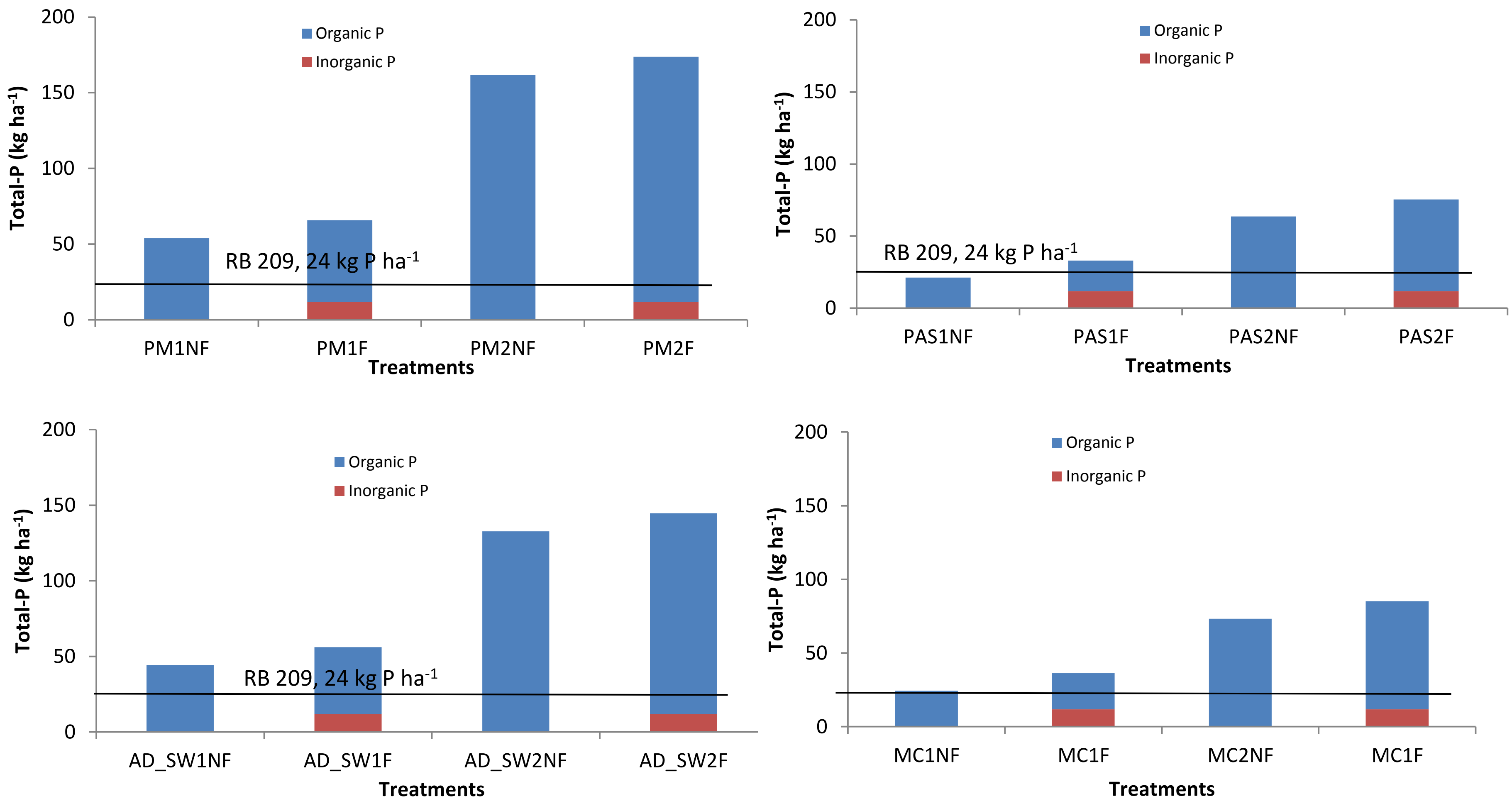


Figure 9 Estimated P supplied by the OAs via Total-P.

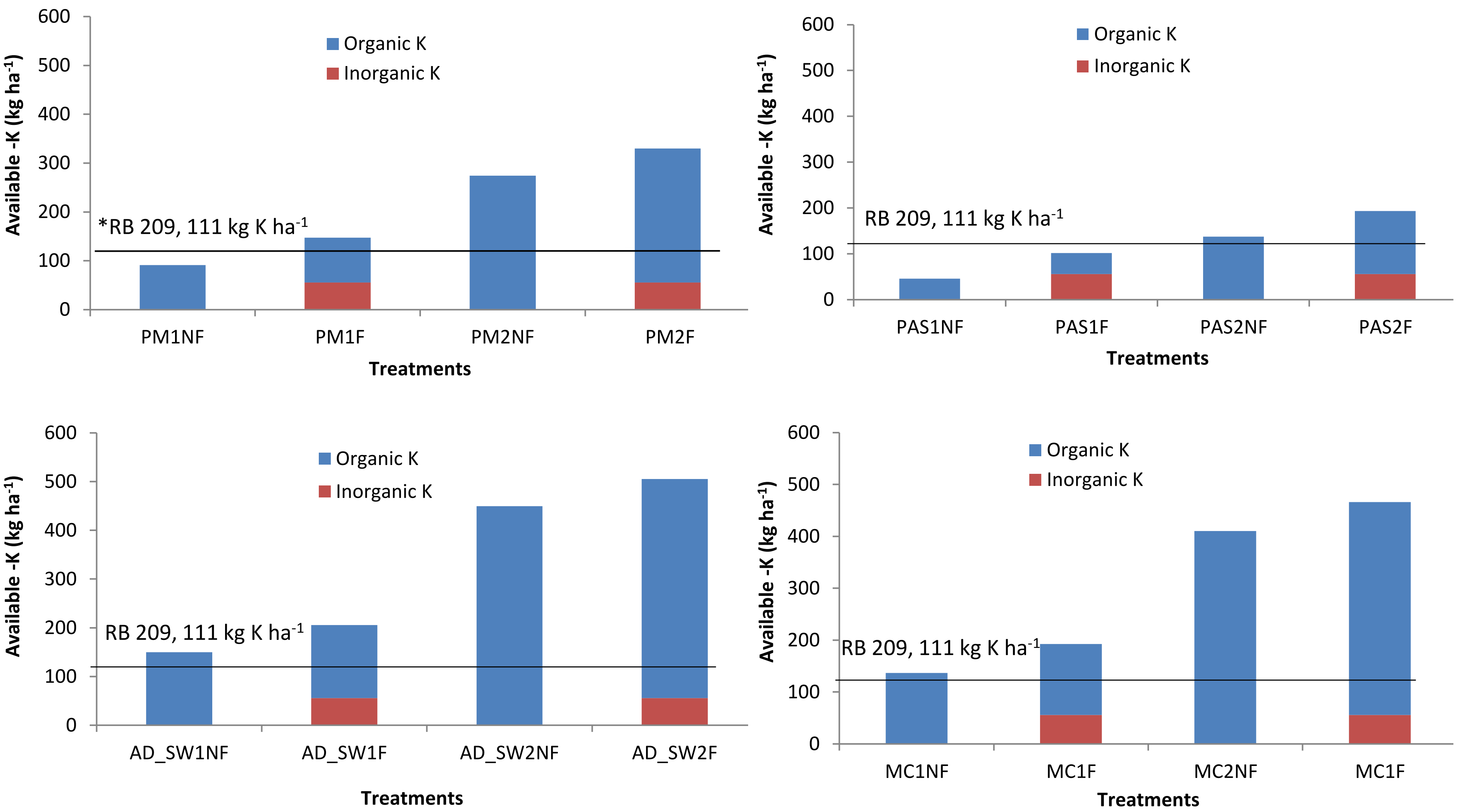


Figure 10 Estimated amount of Available-K supplied via OA treatment application.

The estimated results show that with the exception of PM1NF all PM treatments supplied more K than the recommended rate (Figure 10). In contrast, the estimated Available-K supplied via PAS1NF and PAS1F treatments were 59% and 9% less than the recommended K rate. However, at higher application rates (30 t ha^{-1}), the PAS2NF and PAS2F treatments had 20% and 42.3% higher K than the recommended rates. This suggests that PAS treatments achieved the RB209 K target only at higher application rates with or without inorganic K fertilizer addition (Figure 10). This has implications for plant growth and yield performance.

The result indicates that AD_SW and MC at both application rates with or without inorganic fertilizer addition were associated with greater supply of K than the OAs. Overall, with the exception of PM1NF and PAS1NF/1F treatments, all other OA treatments are expected to provide the K recommended rate. This suggests that K is not limiting to plant performance (See Chapter 7 for more discussion).

3.4 Experimental design

3.4.1 Glasshouse experimental set up

The experiment was set up in July, 2014 in a glasshouse at Cranfield University following a completely randomized design. For each treatment 10 kg of air-dried homogenised test soil was weighed into polythene bags containing a pre-weighed amount of OA (Table 13). Subsequently, the appropriate amounts of inorganic fertilizer were added and the treatments were thoroughly mixed in the polythene bag and transferred into the experimental plastic pots. This procedure was used for all the treatments (Table 13) with the exception of the CNF control treatments. A total of 72 [10 litre] plastic pots (Figure 11) with drainage holes in their base were used in this study. The holes at the base of the pots were covered with permeable material to prevent soil loss through the openings and allow free movement of water and air. Each pot was placed in a saucer for irrigation and drainage, as required.

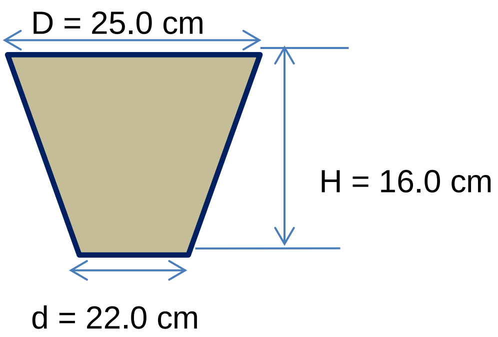


Figure 11 Pot dimensions used for the glasshouse trial

Note: the above diagram is not drawn to scale.

Where: ‘D’ and ‘d’ = pot diameters and H = pot height.

3.4.2 Soil and Amendments application and Incubation period

Treatments were incubated for two weeks with 300–500 ml of water added to all treatments to achieve 45% soil moisture content (SMC). The SMC was measured using a soil moisture Delta-T sensor probe (SM 150 model). During the experimental set up, it was observed that above 45% SMC, the pots tended to be water logged and this could result in anaerobic conditions, unfavourable for beneficial soil microbes. Thus, 45% SMC was adopted to avoid nutrient loss since inorganic fertilizers, especially N, are soluble in water and can easily be lost by leaching.

It is important to note that the volume of OAs differed even though the mass of OAs was the same for each treatment. This is because some OAs were less dense (especially AD_SW) than others, which increased their volume. The differences in the volume of the OAs applied are expected to have significant effects on the physical SQIs (Chapter 4).

Table 13 Experimental Treatments used for the study

Treatments	Organic amendment Rates g pot^{-1}	Fertilizer level	Replications
AD solid waste [AD_SW1NF]	235.2[a]	No fertilizer	4
AD solid waste [AD_SW1F]	235.2	Low fertilizer	4
AD solid waste [AD_SW2NF]	705.6[b]	No fertilizer	4
AD solid waste [AD_SW2F]	705.6	Low fertilizer	4
Mushroom compost [MC1NF]	235.2	No fertilizer	4
Mushroom compost [MC21F]	235.2	Low fertilizer	4
Mushroom compost [MC2NF]	705.6	No fertilizer	4
Mushroom compost [MC2F]	705.6	Low fertilizer	4
PAS 100 compost [PAS1NF]	235.2	No fertilizer	4
PAS 100 compost [PAS1F]	235.2	Low fertilizer	4
PAS 100 compost [PAS2NF]	705.6	No fertilizer	4
PAS 100 compost [PAS2F]	705.6	Low fertilizer	4
Poultry manure [PM2NF]	235.2	No fertilizer	4
Poultry manure [PM2F]	235.2	Low fertilizer	4
Poultry manure [PM2NF]	705.6	No fertilizer	4
Poultry manure [PM2F]	705.6	Low fertilizer	4
Control (untreated) [CNF]	0	No fertilizer	4
Control (fertilizer only) [CF]	0	Low fertilizer	4

[a] Organic amendment in g pot^{-1} equivalent to 10 t ha^{-1}

[b] Organic amendment in g pot^{-1} equivalent to 30 t ha^{-1}.

3.5 Maize planting and measurement of crop performance indicators

3.5.1 Seeding of treatments

Before sowing, the maize seeds (Severus variety) were chitted in water for four days until the radicles (root tips) appeared (Mavi *et al*., 2010). This was to ensure that the seeds were viable and also to enhance early seedling emergence. Pre-sowing seed treatments, such as chitting, are known to improve and ensure uniform crop emergence (Parera and Cantliffe, 1992) and increase germination rate (Khan *et al.*, 1980, cited in Parera and Cantliffe, 1992). The maize seeds were sown on 7th July, 2014. Three seeds were sown per pot (Figure 12).

3.5.2 Method of thinning down to one seedling per pot

The heights of the three seedlings in each pot of the four treatment replicates (total = 12 plants) were measured (Figures 13 and 14, Sections 3.5.2 and 3.5.4). The height was taken from the soil surface to the tallest leaf of each plant (assuming an imaginary horizontal plane is placed over the plant). The mean height of the 12 seedlings for each treatment was obtained. Only seedlings closest to the mean treatment seedling height were selected, while the other seedlings were thinned out. Maize thinning was done ten (10) days after planting (DAP) to ensure that the maize seedlings had completely emerged.

Figure 12 Glasshouse experimental set up at Cranfield University.

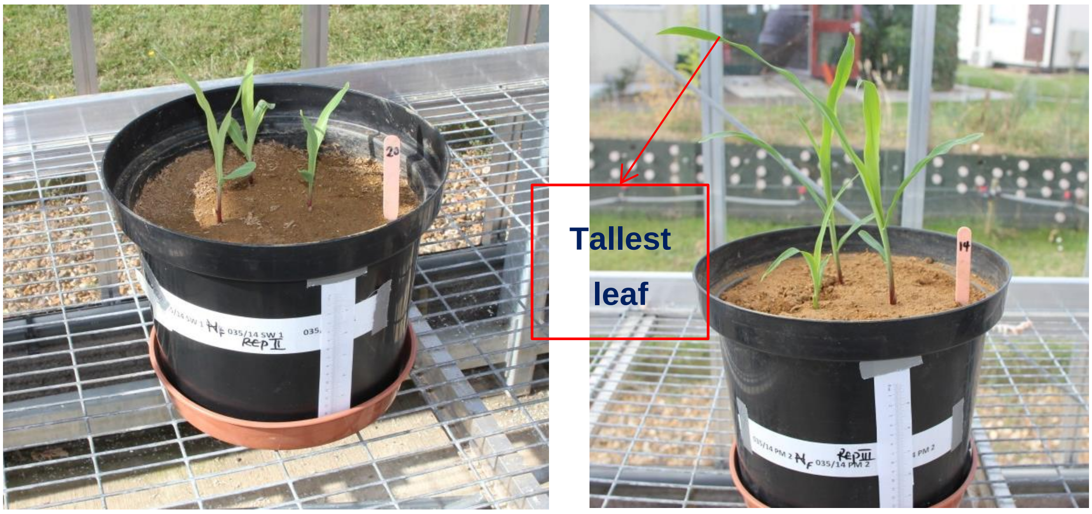


Figure 13 Maize seedlings (3 per pot) before thinning.

3.5.3 Method of irrigating the maize plants

The maize plant is sensitive to drought and water logging (NSW DPI, 2014). To ensure that the maize plants were not water stressed, 500–1000 ml of water was applied manually every day to meet the crops' water demands and also to make up for moisture losses that may have occurred due to evapo-transpiration. A soil moisture theta sensor probe (Delta T-model SM 150) was used to measure the SMC in each of the treatments.

3.5.4 Plant parameters measured

To evaluate the effect of OA application on maize plants and yield, plant performance indicators were measured at weekly intervals after emergence. The maize stem diameter was measured with a digital Vernier gauge. The measurements were taken at 5.0 cm above the soil surface (Figure 14). The maize plant height was measured weekly using a metre rule, as described in Section 3.5.2

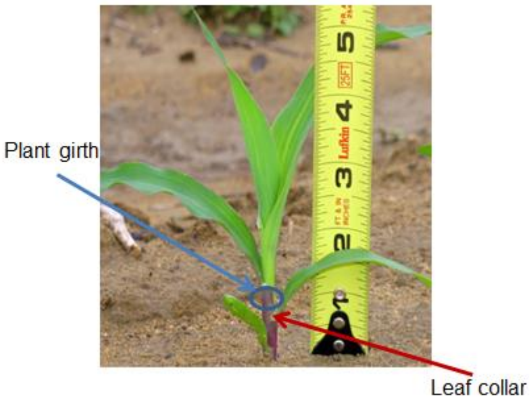


Figure 14 Measurement of maize plant height and stem diameter.

Modified from: http://www.mississippi-crops.com/2016/05/28/how-to-determine-growth-stages-of-young-corn-or-sorghum/

The vegetative growth stage was determined at weekly interval using the Leaf Collar method (O'Keeffe, 2009) which involved counting the number of visible leaf collars. The leaf collars were identified by the presence of a collar-like 'band' located at the base of the plant leaf (sheath) i.e. near the spot where the leaf blade comes in contact with the stem of the plant (Figure 14). Different growth stages relate to the number of visible leaf collars present (O'Keeffe, 2009). The following was used to describe the maize plant's vegetative growth stages otherwise called the 'V' stages (Table 14 Section 3.5.4).

Table 14 Plant developmental growth stages

Vegetative stages	**Description**
VE = Crop emergence:	This occurs between 6 to 10 days depending on the seed variety planted, soil and environment conditions (O'Keeffe, 2009)
V1 = First leaf stage	This was identified by appearance of the first of visible leaf collar.
V2 = Second leaf stage	This marked by appearance of the second of visible leaf collar (Figure 15).
Vn = The nth leaf stage	This is the nth number of fully developed plant leaf

Vegetative stages	Description
VT = Tasselling stage	This is identified by the appearance of tassel which is the male flowering structure of the maize plant. Tassels produce pollen to fertilize the female flowers (the plant ears) (NSW DPI, 2009).
R1 = Silking stage	The silk is visible thread-like material that comes out from the tip of the husk (the female reproductive structure). Pollen grains from the male flowers which pollinate the ovules (female flowers) are captured by the silk (Figure 15).

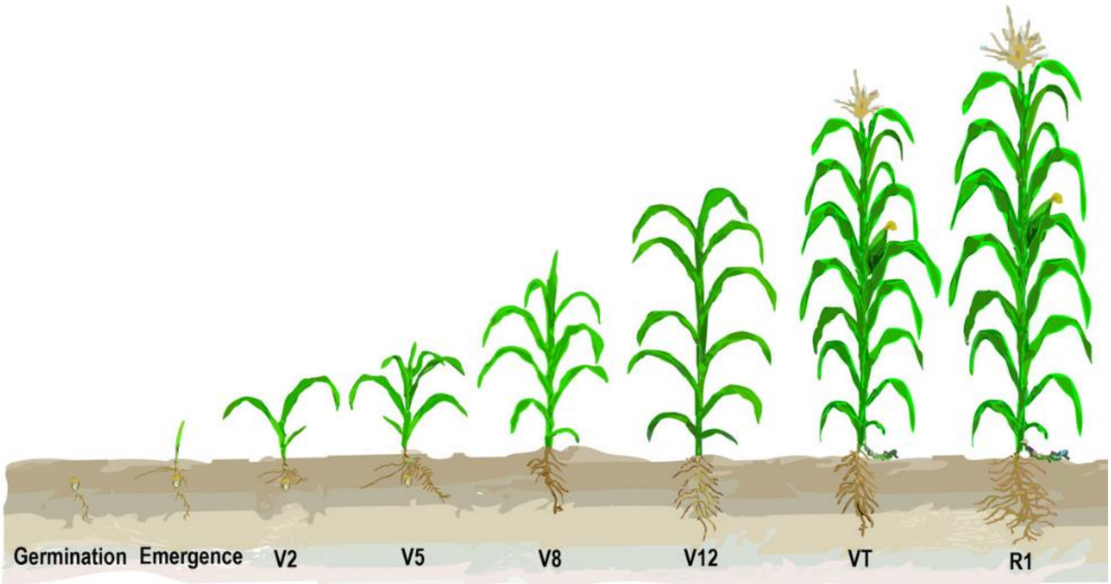


Figure 15 Maize vegetative growth stages.

Source: http://www.reganpdesigns.com/illustrations

Dry matter yield (above and below ground biomass) and cob yield data were measured after plant harvest by obtaining the dried weight (g pot^{-1}) of the plant samples.

3.5.5 Plant biomass and nutrient analysis

At 85 days after planting when more than 50% of the plants had attained maturity, above-ground [AG_{DB}] biomass was harvested, 5.0 cm above the soil surface to avoid any contamination with soil. Then, the below-ground biomass [root, BG_{DB}] was harvested. For each pot, the roots were judiciously separated out from the soil by rinsing them with clean water. Subsequently, each plant was separated into leaves, stems, cobs and roots and their fresh weights recorded using a 4-decimal place weighing balance. The individual plant parts were put into separate paper bags and oven-dried at 65^{0}C for 72 hours until constant weight was achieved and the dry weights (DW) taken. This was done to identify the contribution of each component to total plant biomass.

Plant nutrient analysis was carried out to determine the effect of the different OAs on plant nutrient concentration, plant nutrient uptake and nutrient use efficiency (NUE). The plant nutrient analysis was carried out on air-dried plant samples ground to <4.0 mm using a Retsch Muhle cutter mill and analysed for Total-N concentration by dry combustion using a Vario Elemental analyser (BS EN 1364-2:2001). Phosphorus was determined using the US EPA Method 3051 after extraction with a nitric/hydrochloric acid mixture. Potassium, Zn, Cu and Mg were determined by AAS after wet digestion with sulphuric acid with a Perkin Elmer AAnalyst^{TM} 800 (flame and furnace system) (BS EN ISO 11047:1998). The crop N and P uptake was calculated by multiplying the plant Total-N and Total-P concentration by the crop total above dry matter yield. For instance, N uptake was calculated by:

$$\text{Nitrogen uptake} = \text{Plant biomass} * \text{Total} - \text{N concentration in biomass} \quad \textbf{(3)}$$

In addition, NUE was calculated for both P and N thus:

$$\text{Nutrient utilization efficiency} = \text{Cob Yield} / \text{N uptake} \quad \textbf{(4)}$$

3.6 Statistical analysis:

The results from baseline soil, baseline OA, post-incubation, post-harvest and plant performance indicators were subjected to a one-way Analysis of Variance (ANOVA) using Statistica software version 12.1 with means compared at 5% probability following a *post-hoc* Fisher LSD analysis.

4 RESULTS AND DISCUSSION – Effect of OAs on Physical SQIs

In this Chapter, the effects of the OAs on the physical properties of the soil post-incubation are discussed.

4.1 Treatment effects on the physical (SQIs) post-incubation

Studies have shown that OA application increases soil WHC, porosity, infiltration capacity, and water stable aggregates and reduces soil BD due to the increase in SOM content (Haynes and Naidu, 1998; Aggelides and Londra, 2000; Hati *et al.*, 2006; Hati *et al.*, 2007). It is hypothesized that the OA treatments will improve the selected physical SQIs relative to the un-amended control treatment (CNF).

4.1.1 Water Content at Field Capacity (WC_{FC}) [5 kPa] associated with OA treatments without inorganic fertilizer

As described in Section 4.1, it is expected that the water content at field capacity (WC_{FC}) in the OA treatments will be higher as compared with the CNF treatment, due to increases in soil porosity and a corresponding decrease in soil BD (Zhang *et al.*, 2014).

10 t ha^{-1}: Contrary to expectation, no significant difference in the WC_{FC} was observed between the OA treatments (PM1NF, PAS1NF, AD_SW1NF and MC1NF) and the CNF control (Table 15, Section 4.1.1). Although the OAs had different effects on soil total porosity compared with the CNF treatment, the non-significant effect on WC_{FC} at 10 t ha^{-1} application rate suggests that this quantity of OA was insufficient to have had any significant effect on the WC_{FC} within the two-week incubation period.

30 t ha^{-1}: As expected, at the higher application rate the OA treatments had significantly higher WC_{FC} as compared with the CNF control (Table 15, Section 4.1.1). The AD_SW2NF treatment recorded the highest WC_{FC} (33.2 g g^{-1}) which was 45.5%, 15.7%, 14.2%, and 18.1% higher (p <0.05) as compared with the CNF, PM2NF, PAS2NF and MC2NF treatments, respectively (Table 15). The significantly higher WC_{FC} associated with the OA treatments at 30 t ha^{-1} is attributed to increased SOM content (Figure 17, Section 4.1.1) following OA application which lowered the soil bulk density and thus increased the soil total porosity (Table 15). Further, the significant ($p < 0.01$) negative correlation (r = -0.63) between WC_{FC} and soil BD (Figure 16) suggests that the reduction in the soil BD following OA application contributed to the higher WC_{FC}. This relationship is represented by the regression ($r^2 = 0.39$; $p < 0.01$) equation:

$$WC_{FC} = 62.8 - 26.3*BD \qquad \textbf{(5)}$$

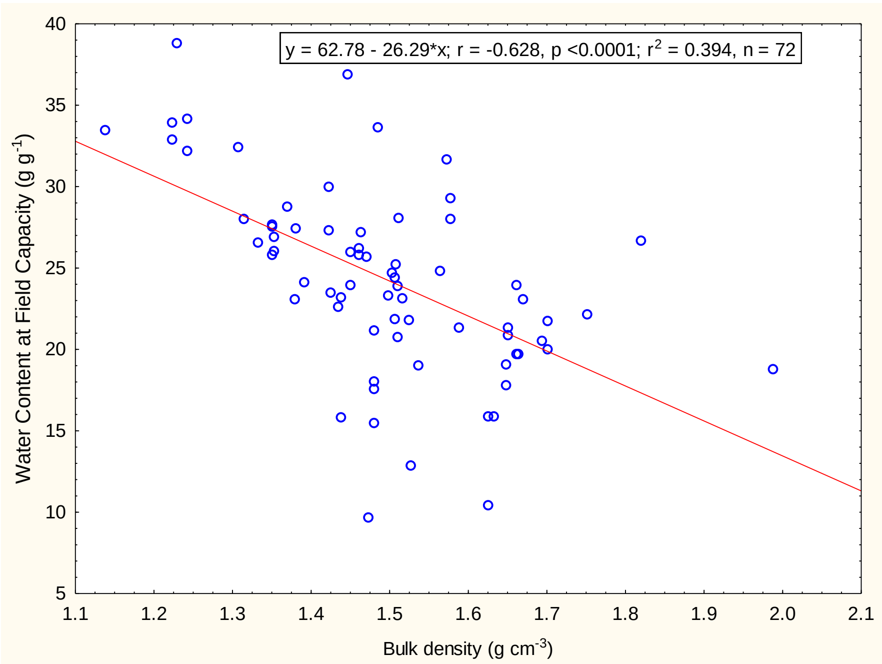


Figure 16 Correlation between soil BD and WC_{FC} across all treatment application rates with and without inorganic fertilizer.

The significant ($p < 0.01$) negative correlation (r = -0.63) between the soil BD and SOM content (Figure 17, Section 4.1.1) also suggests that the direct relationships established between BD and WC_{FC} are due to increases in SOM by OA application. The present result indicates that 1 g cm^{-1} reduction in BD due to increase in SOM following OA application, increased the soil WC_{FC} by 36.5 g g^{-1} (Figure 17, Section 4.1.1). This is remarkable considering that WC_{FC} significantly correlates (r = 0.83) with AWC, which is essential for better plant performance (See Chapter 7 for more discussion of plant performance).

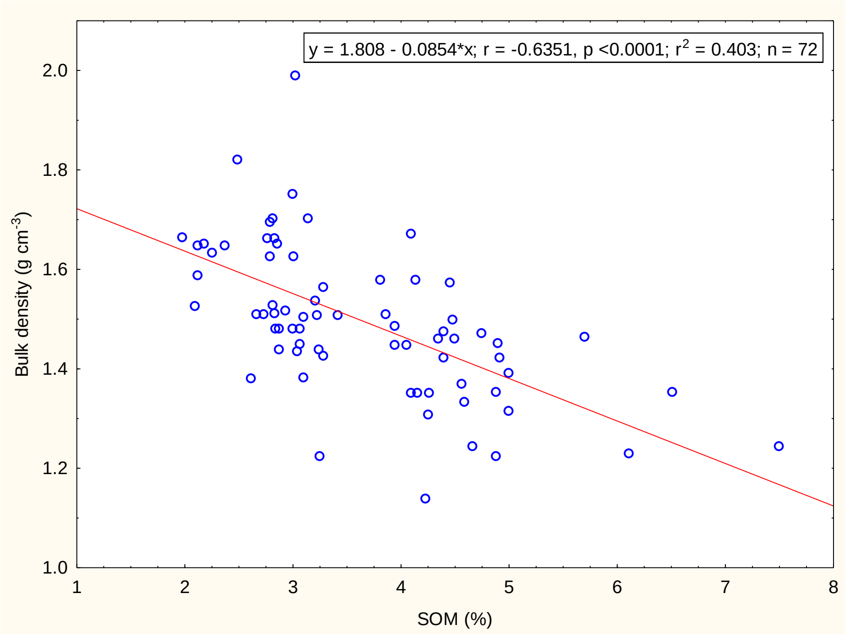


Figure 17 Correlation between soil BD and SOM content across all treatment application rates with or without inorganic fertilizer.

Similar findings were observed by Haynes and Naidu (1998). In addition, Hati *et al.* (2007) attributed the increase in WC_{FC} (0.033 MPa) following the application of NPK + FYM (farm yard manure) to the increased number of soil pores which increased soil water retention. Reichert *et al.* (2009) found a significant ($p < 0.05$) positive correlation ($r = 0.41$) between SOM and WC_{FC}. Increase in SOM has been reported to increase WHC (Saxton and Rawls, 2006).

Aggelides and Londra (2000) attributed a higher WC_{FC} to the effects of compost application. Soil BD was reported to have a negative ($r = -0.65$) effect on water retention due to a reduction in soil porosity associated with dense soil. Although initially increase in soil compaction increases the WC_{FC} (Archer and Smith, 1975), beyond a critical point, denser soils have a lower capacity for water retention at field capacity (Reichert *et al.*, 2009).

Application rates effect on WC_{FC}: The results indicate that the OA treatments at 30 t ha^{-1} application rate had significantly higher WC_{FC} as compared with the 10 t ha^{-1} treatments (Table 15, Section 4.1.1). The PM2NF treatment had 30% higher WC_{FC} than the PM1NF treatment. Similarly, the PAS2NF, AD_SW2NF, and MC2NF treatments had 38%, 35.8%, and 22.7% higher WC_{FC} as compared with the PAS1NF, AD_SW1NF, and MC1NF treatments, respectively.

Table 15 Effect of treatments on soil physical properties, post-incubation

Treatments	WC_{FC} (g g^{-1})	EAW (g g^{-1})	WC_{PWP} (g g^{-1})	AWC (g g^{-1})	BD (g cm^{-3})	Porosity (%)
OA treatments without inorganic fertilizer						
CNF	18.1^{b}	13.7^{cd}	10.1^{cef}	7.99^{a}	1.8^{g}	37.8^{ab}
PM1NF	19.7^{bc}	15.1^{def}	10.4^{cdefg}	9.36^{ab}	1.48^{de}	44.1^{cde}
PM2NF	28.0^{f}	17.8^{fghi}	7.78^{abcde}	20.2^{gh}	1.42^{cd}	46.3^{de}
PAS1NF	17.7^{ab}	10.7^{b}	7.24^{abcd}	10.5^{abc}	1.58^{ef}	40.5^{bc}
PAS2NF	28.5^{f}	19.5^{hi}	14.8^{h}	13.6^{cde}	1.48^{de}	44.1^{cde}
AD_SW1NF	21.3^{bc}	12.6^{bcd}	6.62^{a}	14.7^{def}	1.44^{cd}	45.7^{de}
AD_SW2NF	33.2^{g}	19.5^{hi}	10.7^{efg}	22.4^{h}	1.27^{ab}	52.2^{f}
MC1NF	21.3^{bc}	11.7^{bc}	7.15^{abcd}	14.1^{def}	1.70^{fg}	35.8^{a}
MC2NF	27.2^{ef}	15.7^{def}	10.0^{bcdefg}	17.2^{fg}	1.35^{bc}	49.0^{ef}
OA treatments with inorganic fertilizer						
CF	22.6^{bc}	11.2^{b}	7.42^{ab}	15.2^{ef}	1.65^{fg}	37.9^{ab}
PM1F	23.7^{cde}	13.7^{cd}	11.6^{fgh}	12.1^{bcd}	1.51^{de}	43.1^{cd}
PM2F	$26.2d^{ef}$	16.8^{efgh}	10.3^{defg}	15.9^{ef}	1.35^{bc}	48.9^{ef}
PAS1F	23.0^{cde}	15.4^{def}	11.6^{fgh}	11.5^{bcd}	1.63^{fg}	38.4^{ab}
PAS2F	33.0^{g}	18.6^{ghi}	13.3^{gh}	19.8^{gh}	1.49^{de}	43.6^{cd}
AD_SW1F	23.1^{cde}	11.4^{bc}	6.88^{ab}	16.2^{ef}	1.51^{de}	43.0^{cd}
AD_SW2F	33.1^{g}	20.8^{i}	11.0^{efg}	22.1^{h}	1.22^{a}	53.8^{f}
MC1F	13.7^{a}	7.55^{a}	5.96^{a}	7.70^{a}	1.68^{fg}	36.7^{a}
MC2F	25.9^{def}	15.3^{def}	5.98^{a}	19.9^{gh}	1.46^{cd}	44.9^{cde}

WC_{FC} = Water content at field capacity; EAW = Easily available water; WC_{PWP} = Permanent wilting point; AWC = Available water capacity. Number of samples (n) = 72. For each parameter, different letters within column indicate that treatment means are significantly different at p <0.05.

CNF = control; CF = inorganic fertilizer only (applied at 50% recommended rate)
PM1F = Poultry manure at 10 t ha^{-1} + Fertilizer; PM1NF = Poultry manure at 10 t ha^{-1} + No inorganic Fertilizer;
PM2F = Poultry manure at 30 t ha^{-1} + Fertilizer; PM2NF = Poultry manure at 30 t ha^{-1} + No inorganic Fertilizer;
PAS1F = PAS 100:2005 compliant compost at 10 t ha^{-1} + Fertilizer; PAS1NF = PAS 100:2005 compliant compost at 10 t ha^{-1} + No inorganic Fertilizer;
PAS2F = PAS 100:2005 compliant compost at 30 t ha^{-1} + Fertilizer; PAS2NF = PAS 100:2005 compliant compost at 30 t ha^{-1} + No inorganic Fertilizer;
AD_SW1F = Anaerobic digestate solid waste at 10 t ha^{-1} + Fertilizer; AD_SW1NF = Anaerobic digestate solid waste at 10 t ha^{-1} + No inorganic Fertilizer;
AD_SW2F = Anaerobic digestate solid waste at 30 t ha^{-1} + Fertilizer; AD_SW2NF = Anaerobic digestate solid waste at 30 t ha^{-1} + No inorganic Fertilizer;
MC1F = Mushroom compost at 10 t ha^{-1} + Fertilizer; MC1NF = Mushroom compost at 10 t ha^{-1} + No inorganic Fertilizer;
MC2F = Mushroom compost at 30 t ha^{-1} + Fertilizer; MC2NF = Mushroom compost at 30 t ha^{-1} + No inorganic Fertilizer.

As explained earlier, the higher WC_{FC} associated with the OA at 30 t ha^{-1} is attributable to the increase in SOM content. This result demonstrates that OA applied at 30 t ha^{-1} can retain more soil water/moisture at field capacity than the same OA applied at 10 t ha^{-1} rate. This can also have a significant impact on crop growth and development, especially in crops sensitive to drought conditions.

4.1.2 Water Content at Field Capacity (WC_{FC}) [5 kPa] associated with OA treatments + inorganic fertilizer

The OA treatments are expected to increase the soil WC_{FC} compared with the CNF treatment. However, it is not exactly clear, mechanistically, how inorganic fertilizer addition would affect soil water content just two weeks after application, since fertilizers are more associated with soil nutrient content. Nevertheless, it is reported that inorganic fertilizers do not only improve crop yields by providing adequate nutrients, but they also directly or indirectly induce changes in soil chemical, physical and biological properties (Zhong and Cai, 2007). According to Haynes and Naidu (1998), the degree of organic matter decomposition prior to its application to soil can have significant influence on soil aggregation. Thus, increase in microbial growth, especially fungi following OA application is accompanied with an increase in the physical entanglement of fungal hyphae and the production of extracellular polysaccharides and which can cause soil aggregation (Haynes and Naidu, 1998) and thus affect the WHC. This is because OAs affect the soil aggregates and soil pores through their binding or adhesion properties, which thus influence the WHC (Bot and Benites, 2005).

10 t ha^{-1}: With the exception of MC1F treatment, which recorded significantly lower (13.7 g g^{-1}) WC_{FC} as compared the CNF treatment, all other treatments, PM1F, PAS1F, and AD_SW1F recorded a significantly higher WC_{FC} compared with the CNF treatment (Table 15, Section 4.1.1). This is evident by the significant correlation ($r = 0.47$) that exist between MB_C and WC_{FC} (Table 16, Section 4.1.2).

30 t ha^{-1}: As anticipated, at 30 t ha^{-1} application rate, all the OA treatments (PM2F, PAS2F, AD_SW2F, and MC2F) had significantly higher WC_{FC} as compared with both the CF and CNF treatments, respectively. The PAS2F (33.0 g g^{-1}) and AD_SW2F (33.1 g g^{-1}) treatments recorded the highest WC_{FC} which were 31.7%, 20.8%, and 21.8% higher than the CF, PM2F and MC2F treatments, respectively (Table 15, Section 4.1.1). The significant increase in the WC_{FC} associated with the OA treatments is attributed to the increase in SOM content at the higher rates of OA. This lowered soil BD, increased the soil total porosity (Table 15, Section 4.1.1) thus resulting in greater WC_{FC} (Table 15).

Several studies suggest that soil WHC is predominantly controlled by the number of soil pores, their size distribution and the soil specific surface area (Haynes and Naidu, 1998; Hati *et al.*, 2007). Application of OA influences the number of soil pores and their size distribution and thus affects soil WHC (Hati *et al.*, 2007).

Table 16 Correlation between the physical SQIs, total organic carbon and microbial biomass C

Treatments	EAW ($g\ g^{-1}$)	WC_{PWP} ($g\ g^{-1}$)	AWC ($g\ g^{-1}$)	BD ($g\ cm^{-3}$)	TOC $mg\ kg^{-1}$	MB_C ($\mu g\ g^{-1}$)
Treatments without inorganic fertilizer						
WC_{FC}	0.86**	0.51**	0.83**	-0.63**	0.78**	0.53**
EAW		0.77**	0.49*	-0.45*	0.51**	0.35*
WC_{PWP}			-0.07^{ns}	-0.06^{ns}	0.2^{ns}	-0.08^{ns}
AWC				-0.69**	0.78**	0.66**
BD					-0.67**	-0.64**
TOC						0.99**
Treatments with inorganic fertilizer						
WC_{FC}	0.82**	0.48*	0.87**	-0.56**	0.53**	0.47*
EAW		0.72**	0.53**	-0.63**	0.52**	0.41*
WC_{PWP}			-0.02^{ns}	-0.23^{ns}	0.13^{ns}	0.03^{ns}
AWC				-0.51**	0.54**	0.52**
BD					-0.69**	-0.69**
TOC						0.70**

** = significant at $p < 0.01$, * = significant at $p < 0.05$, TOC = Total oxides of carbon, MB_C = Microbial biomass C. n = 72.

Application rates effect on WC_{FC}: As anticipated, the higher OA treatment application rate significantly increased the WC_{FC}. The WC_{FC} in the PAS2F, AD_SW2F and MC2F treatments was 30%, 30% and 47% higher ($p < 0.05$) than the PAS1F, AD_SW1F and MC1F treatments, respectively. In contrast, the

PM1NF and PM2NF treatments did not differ statistically in their WC_{FC}. This reflects the non-significant difference in their BD and total porosity (Table 15, Section 4.1.1). Evanylo *et al.* (2008) found higher WHC with compost treatments applied at much higher rates (144 t ha^{-1}). They also observed that application at rates similar to the present study (31 t ha^{-1}) of compost and poultry litter treatments did not add enough organic material to increase the soil WHC as compared with the control. In contrast, the present study found that the OA treatments applied at 30 t ha^{-1} significantly increased the WHC. This is due to the high OM content associated with the OAs applied relative to those Evanylo *et al.* (2008) applied. It can therefore be suggested that that the quality (OM content) of OAs applied can be as important as the function the OAs perform in the soil.

Overall, fertilizer addition increased the WC_{FC}. However, as stated earlier, the mechanisms behind this are unclear. The results, therefore, indicate that OA applied at 30 t ha^{-1} with or without inorganic fertilizer increased WC_{FC} two weeks after application. This implies that the rates of OA application have crucial effects on the WC_{FC}. An increase in WC_{FC} following OA application is expected to have a significant effect on maize plant growth and yield performance (Chapter 7), if water is limiting. Nonetheless, in this study water was not limiting (plants were irrigated at intervals). This may mask the benefits of the significantly higher WC_{FC} associated with the OA treatments.

4.1.3 Easily Available Water (EAW) [20 kPa] associated with OA treatments without inorganic fertilizer

Water that enters the soil is either stored (retained), drained or is lost to the atmosphere by evaporation and transpiration. Not all water in the soil is easily available for plant uptake: hygroscopic water is tightly held in the tiny void spaces between soil particles (Figure 4Figure 3). Easily available water (EAW) is the water that is readily available for plant uptake. Since OAs have the capacity to increase the soil WHC (Aggelides and Londra, 2000; Hati *et al.*, 2007), it follows that the OA treatments will have higher EAW as compared with the un-amended control treatment.

10 t ha^{-1}: Contrary to expectation, no significant difference in EAW was observed between the OA treatments and the CNF control, with the exception of PAS1NF which had 22% lower ($p < 0.05$) EAW as compared with the CNF treatment (Table 15, Section 4.1.1). The observed non-significant effect in the EAW is attributed to the non-significant difference in WC_{FC} (Table 15, Section 4.1.1). This is evidenced by the significantly ($p < 0.01$) strong correlation ($r = 0.86$) between EAW and WC_{FC} (Table 16, Section 4.1.2). Across the OA treatments, PM1NF had 29.1% and 22.5% higher ($p < 0.05$) EAW as compared with PAS1NF and MC1NF, respectively, but this was not statistically different from AD_SW1NF.

30 t ha^{-1} rate: With the exception of MC2NF which had no significant effect on the EAW relative to the CNF treatment, PM2NF, PAS2NF, and AD_SW2NF had 23%, 30%, and 30% higher ($p < 0.05$) EAW as compared with CNF, respectively. As suggested earlier, the higher WC_{FC} associated with the OA treatments contributed to the significantly higher EAW due to increased SOM content following OA application. This is evident by the significant ($p < 0.01$) and positive relationship ($r^2 = 0.74$) between the EAW and WC_{FC} (Figure 20). This relationship is predicted by:

$$EAW = 1.76 + 0.57 * WC_{FC} \quad (r^2 = 0.74;\ p < 0.01) \qquad \textbf{(6)}$$

The result indicates that increase in WC_{FC} by 1 g g^{-1}, increases the EAW by 2.33 g g^{-1}. This has a huge effect on AWC, since EAW is significantly correlated ($r = 0.49$) with AWC (Table 16, Section 4.1.2).

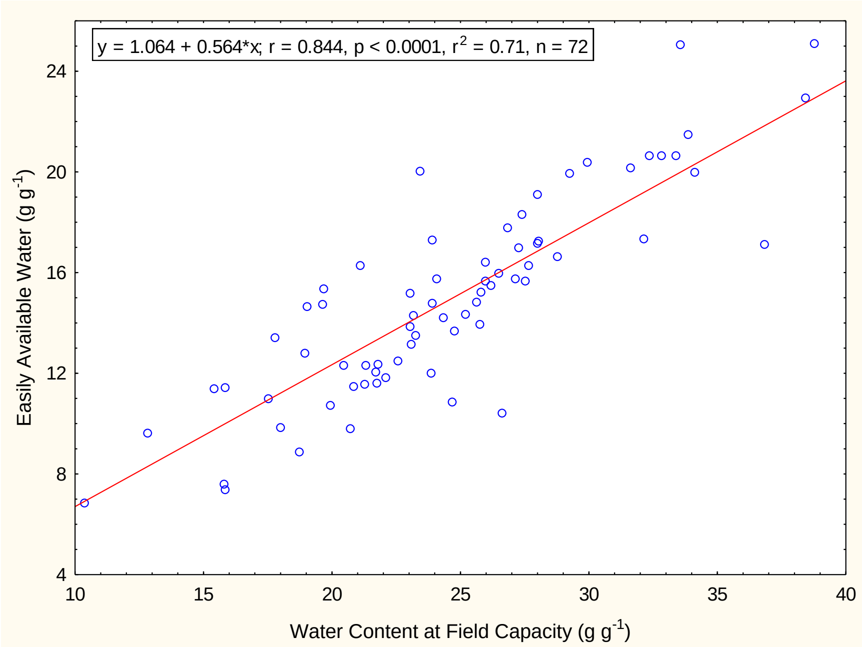


Figure 18 Correlation between water content at WC_{FC} and EAW across all treatment application rates with and without inorganic fertilizer.

Application rates effect on EAW: An increase in OA application rate significantly increased the EAW. The PAS2NF, AD_SW2NF and MC2NF had 45%, 35.4%, and 25.5% higher ($p < 0.05$) EAW as compared with PAS1NF, AD_SW1NF and MC1NF, respectively. In contrast, PM1NF and PM2NF showed no statistical difference in EAW, although PM2NF had 15% higher EAW than PM1NF. The non-significant difference in BD and total porosity associated with PM1NF and PM2NF can explain the non-significant difference in EAW observed between these treatments.

4.1.4 Easily Available Water (EAW) [20 kPa] associated with the OA treatments + inorganic fertilizer treatments

10 t ha^{-1}: The results indicate that MC1F recorded the lowest (7.55 g g^{-1}) EAW content, which was significantly ($p < 0.05$) lower than the CF and CNF treatments. MC1F had 81.5%, 104%, and 51% ($p < 0.05$) lower EAW as compared with PM1F, PAS1F, and AD_SW2F respectively. The PAS1F, PM1F and AD_SW1F treatments showed no statistical difference in their EAW levels as compared with CNF. In contrast, PAS1F had significantly higher ($p < 0.05$)

EAW which was 27%, 26%, and 50.1% ($p < 0.05$) higher than CF, AD_SW1F and MC1F, respectively. The varied effects on EAW associated with the OA treatments can be attributed to inherent differences in the OM content of the OAs (Table 10, Section 3.3.1). Further, as mentioned in Section 3.4.2, the differences in the volumes of OA applied can possibly contribute to the varied effects obtained.

30 t ha^{-1}: At the higher application rate, PM2F, PAS2F, AD_SW2F and MC2F were associated with significantly higher EAW as compared with CF. The EAW associated with AD_SW2F was 46.2%, 19.2% and 26.4% higher ($p < 0.05$) than CF, PM2F, PAS2F and MC2F, respectively. The higher EAW associated with AD_SW2F is attributed to the significantly lower BD compared with all other treatments. Therefore, increasing OA treatment application rates significantly increased SOM, with a concomitant decrease in BD, and increase in soil porosity, thus increasing the EAW. This is supported by the significant ($p < 0.01$) negative correlation ($r = -0.63$) between soil BD and EAW (Table 16, Section 4.1.2).

Application rates effect on EAW: The PM1F and PM2F treatments significantly vary in their EAW content, even though both treatments were not significantly different in their WC_{FC} (Table 15, Section 4.1.1). The results indicate that PM1F and PM2F significantly vary in their individual pore size distribution and pore spaces (micro- and macro- porosity). Further, PAS2F, AD_SW2F and MC2F had 17%, 45.2% and 50.7% higher ($p < 0.05$) EAW as compared with PAS1F, AD_SW1F and MC1F, respectively. This result suggests that rate of OAs applied is essential in improving the EAW of a degraded soil.

This result indicates that OAs applied at 30 t ha^{-1} significantly affected EAW and this can significantly affect plant performance, especially if water supply to the plants is limiting.

4.1.5 Water Content at Permanent Wilting Point (WC_{PWP}) [1500 kPa] associated with OA treatments without inorganic fertilizer

Water retained at WC_{PWP} is not available for plant uptake, so that in this state the plant permanently wilts and dies. Even so, this water can be beneficial to soil microbes by providing them a conducive environment for activity. It is expected that the OA treatments will lower the WC_{PWP} and make water more readily available for plant use, even at the driest point on the water release curve.

10 t ha^{-1}: Contrary to expectation, the WC_{PWP} associated with the OA treatments were not significantly different as compared with the CNF treatment, except for AD_SW1NF which had the lowest ($p < 0.05$) WC_{PWP} as compared with all other treatments (Table 15, Section 4.1.1). This is due to the low BD associated with AD_SW1NF, which increased the soil total porosity thus lowering the amount of hygroscopic water held in the soil. The 'noisy' data obtained prevented the treatments from being significantly different as compared with the CNF treatment.

30 t ha^{-1}: The results indicate that PM2NF, AD_SW2NF and MC2NF were not statistically different in their WC_{PWP} relative to CNF. In contrast, PAS2NF had significantly higher WC_{PWP} as compared with all other treatments. Since at WC_{PWP} water is unavailable for plant use, the high WC_{PWP} recorded for PAS2NF implies that plants grown in PAS2NF will be subjected to water stress more than the plants in other OA treatments due to low AWC. The effect of the high WC_{PWP} associated with the OAs will be more, especially where water is limiting (Haynes and Naidu, 1998; Moore *et al.*, 2014). This is evident by the significantly low AWC recorded for the PAS2NF treatment (Table 15, Section 4.1.1).**Application rates effect on WC_{PWP}:** The WC_{PWP} in PAS2NF and AD_SW2NF was significantly higher as compared with the PAS1NF and AD_SW1NF, respectively. However, PM2NF and MC2NF showed no statistical difference in their WC_{PWP} as compared with PM1NF and MC1NF, respectively.

4.1.6 Water Content at Permanent Wilting Point (WC_{PWP}) [1500 kPa] associated with OA treatments + inorganic fertilizer

10 t ha^{-1}: The WC_{PWP} associated with AD_SW1F and MC1F was not significantly different relative to CNF. In contrast, the AD_SW1F and MC1F treatments had significantly lower WC_{PWP} compared with the CNF treatment (Table 15, Section 4.1.1).

30 t ha^{-1}: With the exception of MC2F which had significantly lower WC_{PWP} as compared with CNF treatment, PM2F, AD_SW2F and CNF did not differ significantly in their WC_{PWP}. In contrast, PAS2F had a significantly higher ($p < 0.05$) WC_{PWP} as compared with the CNF control. As mentioned in Section 4.1.5, the high WC_{PWP} associated with the PAS OA can have a negative impact on plant performance due to reduction in AWC, especially where water supply is limiting.

Application rates effect on WC_{PWP}: The WC_{PWP} in AD_SW2F and AD_SW1F varied significantly. This is due to the different volume of OA applied. The WC_{PWP} associated with PM2F, PAS2F and MC2F was not statistically different compared with PM1F, PAS1F and MC1F, respectively. The result suggests that the OA rates applied were insufficient to significantly affect WC_{PWP}.

Overall, with the exception of PAS2NF and PAS2F, high rates OA application (30 t ha^{-1}) did not seem to change soil micro-pore distribution (though this was not directly measured) and hence the WC_{PWP} was unaffected.

Overall the differences in the WC_{PWP} observed across the treatments are attributed to the inherent differences in the OM content associated with the OAs applied (Table 15, Section 4.1.1).

4.1.7 Available Water Capacity (AWC) associated with OA treatments without inorganic fertilizer

Available water capacity (AWC) is a measure of the ability of soil to retain water over a period (Figure 4Figure 3). The AWC of a soil is the difference between WC_{FC} and WC_{PWP}. Therefore, it is expected that the OA treatments will have higher AWC as compared with the control treatment, due to the positive effects of OAs on soil WHC.

10 t ha^{-1}: As anticipated, AD_SW1NF and MC1NF had 45.6% and 43.3% higher ($p < 0.05$) AWC than CNF, respectively. However, the AWC associated with PM1NF and PAS1NF did not differ significantly as compared with CNF (Table 15, Section 4.1.1). The non-significant effect on the AWC observed for PM1NF and PAS1NF is attributed to their relatively high WC_{PWP} compared with AD_SW1NF and MC1NF.

30 t ha^{-1}: As predicted, the AWC in PM2NF, PAS2NF, AD_SW2NF and MC2NF were 60.4%, 41.3%, 64.3% and 53.5% higher ($p < 0.05$) than the CNF treatment. This is due to the higher SOM and TOC content associated with the OA treatments as compared with the CNF. This is evident by the significant positive ($p < 0.01$) correlation ($r = 0.83$) between the AWC and WC_{FC} (Table 16, Section 4.1.2).

The high AWC in the AD_SW2NF treatment can be attributed to the significantly lower BD associated with the AD_SW2NF treatment with the resultant increased in total porosity (Table 15, Section 4.1.1). Bandyopadhyay *et al.* (2010), Kirkby *et al.* (2013) and Jian-bing *et al.* (2014) reported similar findings. The present result suggests that AD_SW2NF is a better treatment with respect to AWC than all other OA treatments. Therefore, an increase in AWC suggests a greater capacity of soil to supply water to the plant over a time period. This will significantly affect plant performance and can also extend the irrigation scheduling period, particularly in regions where water is a limiting factor.

Application rates effect on AWC: In general, as expected, 30 t ha^{-1} OA treatments had higher AWC than the 10 t ha^{-1} OA treatments. Specifically, the PM2NF and AD_SW2NF treatments had 53.7% and 34.4% higher ($p < 0.05$) AWC as compared with PM1NF and AD_SW1NF treatments, respectively. In contrast, the AWC associated with MC1NF and MC2NF; and PAS1NF and PAS2NF were not significantly ($p < 0.05$) different. This is due to the high degree of within treatment variability (noisy data) associated with the PAS and MC treatments.

The present result indicates that for every 1% increase in SOM, the AWC increased by 5.31 g g^{-1}. This will have a huge effect on crop yield since, AWC is critical to plant performance. This suggests that OAs can directly influence the availability of water for plant uptake due to increased SOM (Gould, 2015). Overall, the variability in AWC observed across the treatments is due to the inherent differences in the SOM, TOC and MB_C associated with the OAs applied (Table 10, Section 3.3.1.2).

4.1.8 Available Water Capacity (AWC) associated with OA treatments + inorganic fertilizer

10 t ha^{-1}: With the exception of MC1F, the results indicate that PM1F, PAS1F, and AD_SW1F had over 30% higher AWC than the CNF treatment.

30 t ha^{-1}: As anticipated, the PM2F, PAS2F, AD_SW2F and MC2F had significantly higher AWC as compared with the CNF treatment. With the exception of PM2F, the AWC in PAS2F, AD_SW2F and MC2F was 23.2%, 31.2% and 23.6% higher ($p < 0.05$) as compared with the CF treatment. As mentioned in Section 4.1.7, the higher AWC associated with the OA treatments is attributed to the increased SOM content of the higher OA application rates. This is evident by the strong positive correlation (r = 0.80) between AWC and SOM (Figure 19). This result confirms the hypothesis that application of OA at higher application rate will result in higher AWC as compared with the CNF treatment. This result is similar to that of Hati *et al.* (2007) who reported a highly significant (positive linear correlation between AWC and SOC. In addition, application of compost (at 250 g kg^{-1} pot^{-1}) was reported to increase AWC due to greater organic C content (Nguyen *et al.*, 2012).

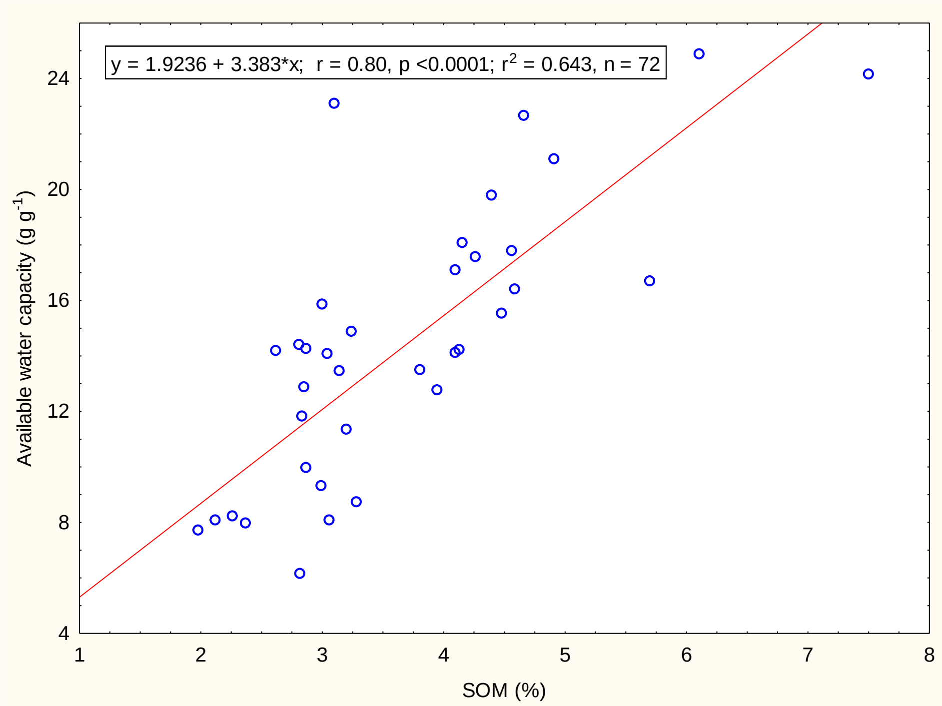


Figure 19 Correlation between AWC and SOM across all treatment application rates with and without inorganic fertilizer.

Application rates effect on AWC: As predicted, PM2F, PAS2F, AD_SW2F and MC2F had 24%, 42%, 27% and 61.3% higher ($p <0.05$) AWC as compared with the PM1F, PAS1F, AD_SW1F and MC1F treatments, respectively (Table 15, Section 4.1.1). This is due to the effect of higher rates of OA applied which increased the SOM content and total porosity; and lowered the soil BD thereby increasing the AWC. The present result suggests increase in SOM by 1% will increase the soil porosity by *ca* 36%. This is evident by the significant correlation ($r = 0.68$) between SOM and porosity which confirms that increasing the SOM content (due to increased OA application rates) significantly affects the soil porosity (Figure 20). Thus, this accounts for the higher AWC obtained. Further, OA types and the rates applied contributed to the varied effects the OAs had on the AWC (Nguyen *et al.,* 2012).

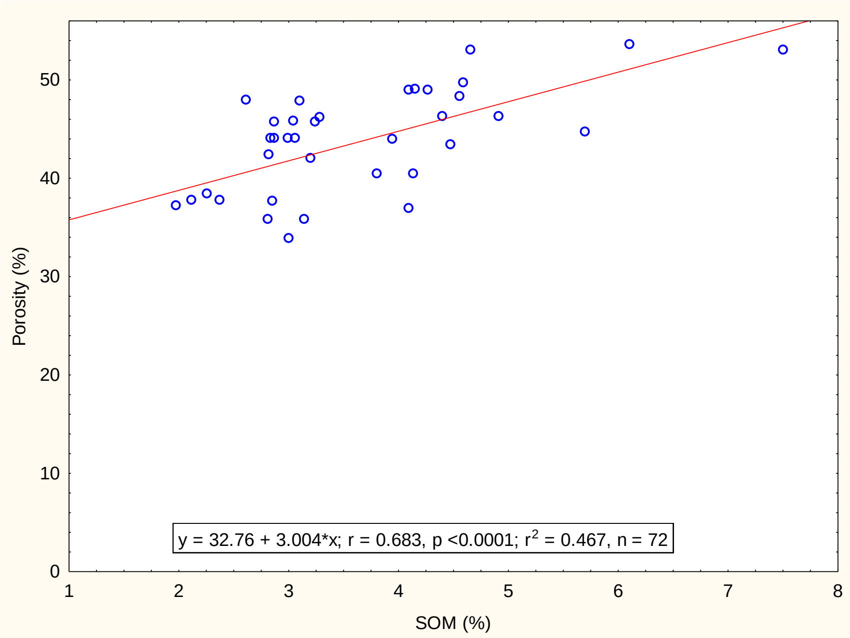


Figure 20 Correlation between SOM and porosity (%) across all treatment application rates with and without inorganic fertilizer

The result demonstrates that OA application has the potential to increase the AWC of a degraded sandy loam soil following OAs addition due to increase in the SOM, which lowered the soil BD and increased total porosity (Kirkby *et al.,* 2013 and Jian-bing *et al.*, 2014).

4.1.9 Effect of OA without inorganic fertilizer treatments on soil Bulk Density (BD)

The soil BD is an important soil physical property, as it affects seed germination, plant roots penetration into the soil, soil porosity and soil moisture retention. As an indicator of soil compaction, an increase in BD reduces porosity and impacts negatively on plant root growth due to reduced access to both water and nutrients (Celik *et al.*, 2010). Because OAs are less dense than the bulk soil, it is therefore expected that the OA treatments will significantly lower the soil BD as compared with the control treatment due to increased SOM content and associated soil porosity [Figure 17, Section 4.1.1] (Kirkby *et al.,* 2013; and Jian-bing *et al.*, 2014).

10 t ha^{-1}: With the exception of MC1NF, PM1NF, PAS1NF and AD_SW1NF had 17.8%, 12.2% and 20% lower ($p < 0.05$) BD than the CNF treatment, respectively. The lower BD associated with the OA treatments is attributed to the increase in SOM due to OA application. Figure 19 shows a significant negative correlation ($r = -0.68$, $p < 0.01$) between SOM and BD This is further supported by the significant positive correlation ($r = 0.68$) between the SOM and the soil porosity (Figure 20, Section 4.1.8), which suggests that increase in the SOM content increases the soil pore space (porosity), which in turn lowers the soil BD. This result is in line with the findings of Darwish *et al.* (1995), Miller *et al. (*2002*),* Bandyopadhyay *et al.* (2010), Jian-bing *et al.* (2014) and Zhou *et al.* (2016).

30 t ha^{-1}: As expected, the PM2NF, PAS2NF, AD_SW2NF and MC2NF treatments had 21.1%, 17.8%, 29.4% and 25% lower ($p < 0.05$) soil BD as compared with the CNF treatment. This is due to the increased rate of OA applied which further increased the SOM content (Bandyopadhyay *et al.* 2010; Zhou *et al.* 2016). Further, the BD in the AD_SW2NF treatment was not significantly ($p < 0.05$) different as compared with the MC2NF treatment but it was 10.7% and 14.2% lower ($p < 0.05$) as compared with the PM2NF and PAS2NF treatments. As mentioned in Section 3.4.3, the lower BD associated the AD_SW2NF treatment can be attributed to the OA's less dense characteristics relative to the other OAs (Section 3.4.3).

Application rates effect on soil BD: The results indicate that AD_SW2NF and MC2NF lowered ($p < 0.05$) BD by 11.8% and 20.6% as compared with the AD_SW1NF and MC1NF treatments, respectively. However, for the PM and PAS treatments, increasing application rate from 10 t ha^{-1} to 30 t ha^{-1} did not significantly lower the BD, although PM2NF and PAS2NF treatments had lower BD compared with PM1NF and PAS1NF treatments. This results suggest that the PM and PAS amendment at both application rates achieved the same effect on the BD.

4.1.10 Effect of OA + inorganic fertilizer treatments on soil Bulk Density (BD)

10 t ha^{-1}: With the exception of PASIF and MC1F treatments, the BD in the PM1F and AD_SW1F treatments was over 8% and 16% lower (p <0.05) than the CF and CNF treatments respectively. Hati *et al.* (2006) found significantly lower BD following the application of NPK + FYM treatment, which they attributed to the high organic matter content associated with OA applied. In a similar study, Bandyopadhyay *et al.* (2010) observed that the BD under integrated use of NPK (N:P:K = 30:26:25 kg ha^{-1}) + FYM (4 t ha^{-1}) was 5.6% lower than control treatment and this was linked to increased SOC content due to the OA applied. However, Bedada *et al.* (2014) found no significant effect on the BD following the application of 27 t ha^{-1} compost and 13.5 t ha^{-1} compost + 50% NPK fertilizer as compared with an un-amended control.

30 t ha^{-1}: The BD of PM2F, PAS2F, AD_SW2F and MC2F was significantly lower as compared with CNF by more than 20%. Similarly, PM2F, PAS2F, AD_SW2F and MC2F had significantly (p <0.05) lower soil BD as compared with the CF treatment by 18.2%, 9.7%, 21.6% and 11.5%, respectively. Across all OA treatments, AD_SW2F had the lowest (1.22 g cm^{-3}) BD and was 10.7%, 22.1% and 19.6% lower (p <0.05) than PM2F, PAS2F, and MC2F, respectively (Table 15, Section 4.1.1). The significantly lower BD of AD_SW2F is linked to the higher volume applied per unit mass, due to its low density (Section 3.4.3).

Application rates effect on soil BD: The PM2F, PAS2F, AD_SW2F and MC2F treatments significantly (p <0.05) lowered the BD by 12%, 9.4%, 23.8% and 15.1% as compared with PM1F, PAS1F, AD_SW1F and MC1F treatments, respectively.

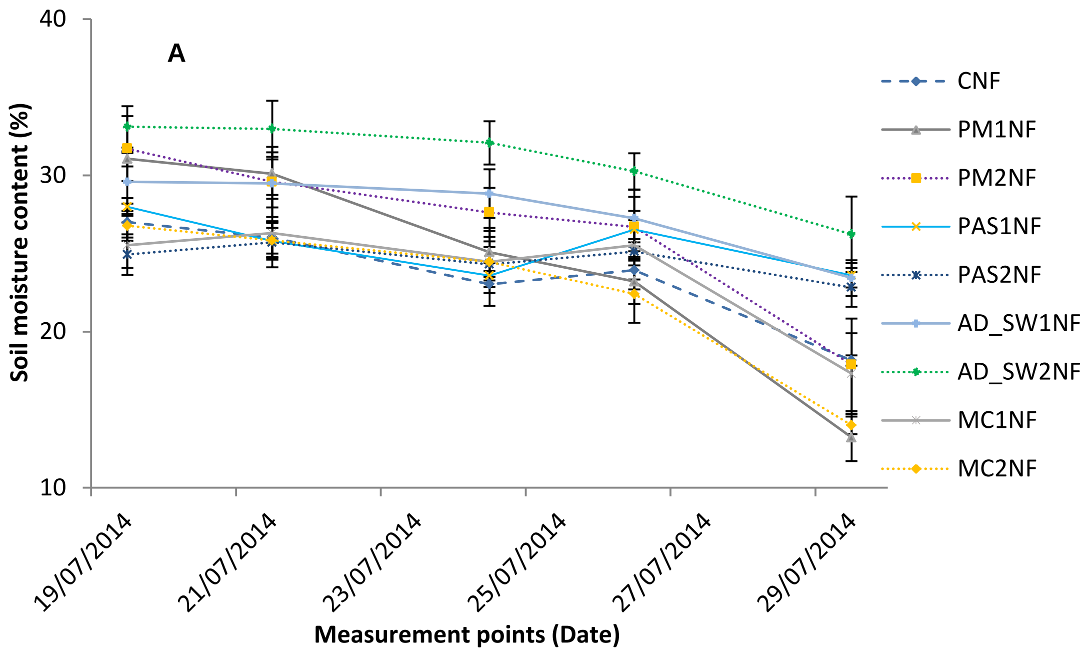
These results corroborate the findings of Mosaddeghi *et al.* (2009), Bandyopadhyay *et al.* (2010), Jian-bing *et al.* (2014) and Khaliq and Abbas (2015). The present result suggests that OAs and the rates applied provide soil BDs which can improve plant root growth and the overall plant performance with respect to root biomass, nutrient uptake and yield production (See Chapter 7).

4.1.11 Soil moisture content associated with OA without inorganic fertilizer

Application of OAs also had varied and significant effects on the soil moisture content (SMC) (Figure 21 A&B), with the exception of AD_SW2NF, and AD_SW1NF, which consistently recorded higher SMC compared with the other treatments. This is attributed to the high WC_{FC} associated with AD_SW due to the characteristically less dense nature of the AD_SW amendment.

4.1.12 Soil moisture content associated with OA treatments + inorganic fertilizer

Unlike the results above, the addition of inorganic fertilizer had significant effects in the SMC relative to the CNF treatment. However, it is not mechanistically clear why the addition of inorganic fertilizer to OAs had marked greater effects on the soil SMC as compared with the CNF than with sole application of OAs.



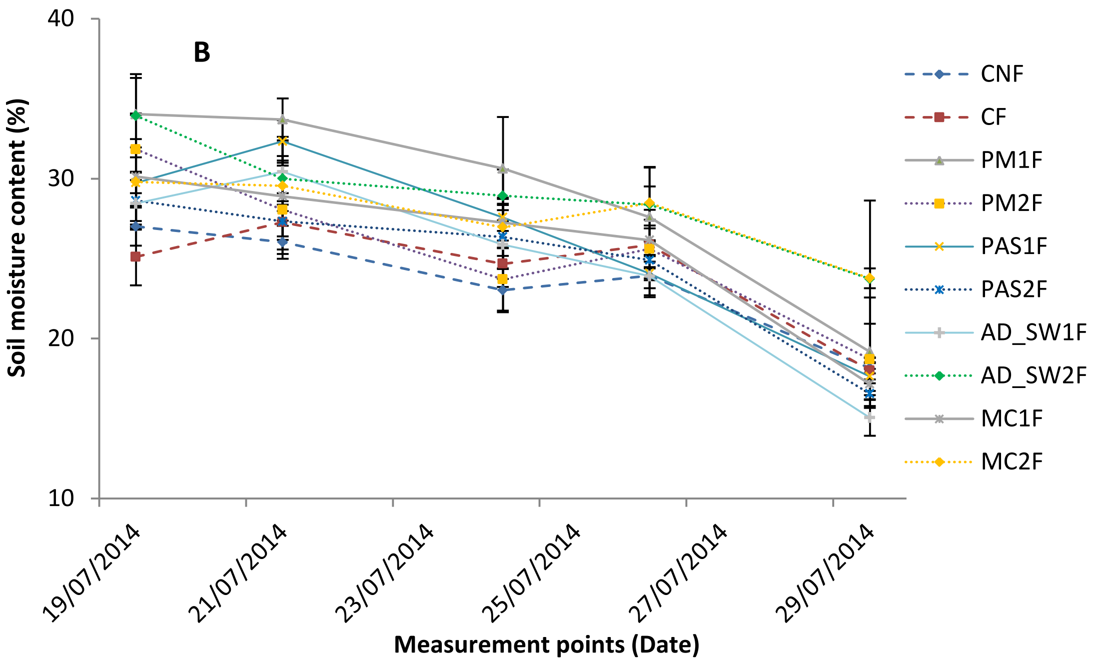


Figure 21 Soil moisture content (SMC) during the incubation period

Vertical bars denote +/- 1 standard error of the mean at 5% probability following a *post-hoc* Fisher LSD analysis, n = 72.
A = SMC of treatments with no inorganic fertilizer
B = SMC of treatments with inorganic fertilizer.

4.1.13 Conclusions

After 2 weeks incubation, the OAs at both rates had significant effects on the physical SQIs due to the inherent characteristics of each OA.

- OA treatments alone applied at 10 t ha^{-1} had no significant difference on WC_{FC}, EAW, and AWC as compared with the control treatment, with the exception of AD_SW1NF treatment.
- With the exception of MC1NF, all other OA treatments alone applied at 10 t ha^{-1} significantly lowered the BD as compared with the control treatment.
- OA treatments + inorganic fertilizer applied at 10 t ha^{-1} had significant effect on WC_{FC}, EAW, and AWC, except for MC1F treatment.
- With the exception of MC1F and PAS1F, all OA treatments had significantly lower BD as compared with the control treatment.

- OA treatments at 30t ha^{-1} application rates with or without inorganic fertilizer had significantly higher WC_{FC}, EAW, AWC and BD as compared with the control treatment.
- Generally, higher rates (30 t ha^{-1}) of OA treatments gave higher water retention than OA treatments at 10 t ha^{-1}.
- It was observed that 1% increase in SOM increased the AWC by 5.31 g g^{-1}.
- Reduction in BD by 1 g cm^{-1} increased the soil WC_{FC} by 36.5 g g^{-1}.
- The present result found that an increase in SOM by 1% increased the soil porosity by ca 36%.
- The result indicates that increase in WC_{FC} by 1 g g^{-1}, increases the EAW by 2.33 g g^{-1}.
- Changes in physical SQIs (by addition of OAs) that had impacts on crop growth and yield performances were masked because water was not limiting in this study.

Therefore, the results confirm the hypothesis that application of OAs improves the selected soil physical SQIs. Further research should study the mechanisms by which OAs + inorganic fertilizer addition had marked effects on the physical SQIs.

5 RESULTS AND DISCUSSION – Effect of OAs on Chemical SQIs at Post-incubation

Studies have shown that OA application affects key soil chemical SQIs (Bedada *et al.*, 2014; Cabilovski *et al.*, 2014). Thus, based on the earlier established hypothesis, it is expected that the OA treatments will be associated with significant positive effects on the chemical SQIs as compared with the control (CNF) treatment with subsequent impacts on maize plant performance.

5.1.1 Effect of OA treatments on Soil Electrical Conductivity (EC)

The soil electrical conductivity (EC) is a measure of ions (salts) present in the soil. A high or low EC indicates high or low levels of salt concentrations in the soil, but does not indicate or identify the type, concentration or relative proportion of salts present (Ayers and Westcott, 1985; Azeez and Van Averbeke, 2012). The results of OAs characterization (show that MC amendment had higher EC levels than all other OAs (Table 10, Section 3.3.1.2). Thus, it is expected that the soil EC levels associated with MC treatment will be significantly higher as compared with the un-amended CNF treatment, due to an increase in salt concentration from the OAs applied.

5.1.1.1 Soil EC associated with OA treatments (without inorganic fertilizer)

10 t ha^{-1}: The EC levels associated with the OA treatments were significantly higher ($p < 0.05$) as compared with the CNF treatment except for PAS1NF which was not significantly different from the CNF control (Figure 22, Section 5.1.1.1). As anticipated, the MC1NF treatment recorded the highest ($p < 0.05$) EC level, which was 62.5%, 47.5%, 65%, and 50% higher as compared with the CNF, PM1NF, PAS1NF, and AD_SW1NF treatments, respectively. The high EC in MC1NF treatment is due to the inherently high EC that is associated with the MC OA (Table 10, Section 3.3.1.2).

30 t ha^{-1}: Similarly at 30 t ha^{-1} the OA treatments had significantly higher EC as compared with the CNF treatment with the exception of PAS2NF treatment. Further, MC2NF had the highest ($p < 0.05$) EC levels (Figure 22, Section 5.1.1.1). The high EC associated with the MC2NF treatment is attributed to the inherently high level of

EC associated with the MC amendment (Table 10, Section 3.3.1.2). This supports the study of Carmo *et al.* (2016) that soil EC levels are affected by the type, composition and amount of OAs added to the soil. Further, significantly higher EC associated with the OA treatments, except PAS is due to the solubilization of soluble ions such as chloride, sulphate, sodium and other inorganic ions from compost and organic species, formed through organic matter mineralization (Chang *et al.* (2007).

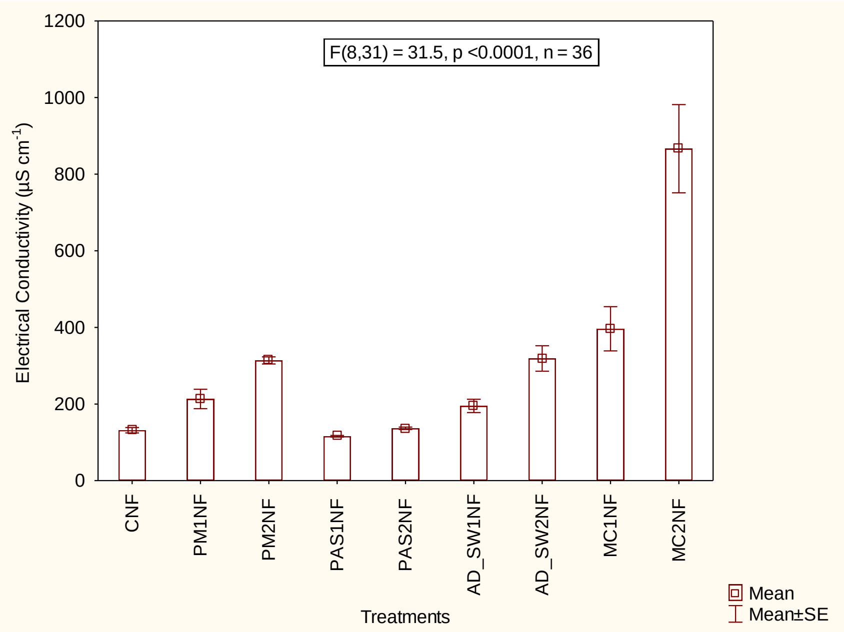


Figure 22 Effect of OA without inorganic fertilizer treatments on soil EC.

For Figures 24–26, 28–45, 52–68, vertical bars denote +/- 1 standard error of the mean at 5% probability following a *post-hoc* Fisher LSD analysis.
CNF = control; CF = inorganic fertilizer only (applied at 50% recommended rate)
PM1F = Poultry manure at 10 t ha^{-1} + Fertilizer; PM1NF = Poultry manure at 10 t ha^{-1} + No inorganic Fertilizer;
PM2F = Poultry manure at 30 t ha^{-1} + Fertilizer; PM2NF = Poultry manure at 30 t ha^{-1} + No inorganic Fertilizer;
PAS1F = PAS 100:2005 compliant compost at 10 t ha^{-1} + Fertilizer; PAS1NF = PAS 100:2005 compliant compost at 10 t ha^{-1} + No inorganic Fertilizer;
PAS2F = PAS 100:2005 compliant compost at 30 t ha^{-1} + Fertilizer; PAS2NF = PAS 100:2005 compliant compost at 30 t ha^{-1} + No inorganic Fertilizer;
AD_SW1F = Anaerobic digestate solid waste at 10 t ha^{-1} + Fertilizer; AD_SW1NF = Anaerobic digestate solid waste at 10 t ha^{-1} + No inorganic Fertilizer;
AD_SW2F = Anaerobic digestate solid waste at 30 t ha^{-1} + Fertilizer; AD_SW2NF = Anaerobic digestate solid waste at 30 t ha^{-1} + No inorganic Fertilizer;
MC1F = Mushroom compost at 10 t ha^{-1} + Fertilizer; MC1NF = Mushroom compost at 10 t ha^{-1} + No inorganic Fertilizer;
MC2F = Mushroom compost at 30 t ha^{-1} + Fertilizer; MC2NF = Mushroom compost at 30 t ha^{-1} + No inorganic Fertilizer;

5.1.1.2 Soil EC associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: The OA + inorganic fertilizer treatments had significantly higher EC as compared with the CNF treatment, with the exception of the PAS1F treatment (Figure 23, Section 5.1.1.2). The AD_SW1F and MC1F treatments showed no significant difference in their EC concentration, but were significantly higher as compared with the PM1F and PAS1F treatments, respectively.

30 t ha^{-1}: As expected, at 30 t ha^{-1} application rates, all the OA + inorganic fertilizer treatments had a significantly higher EC as compared with the CNF treatment (Figure 23, Section 5.1.1.2). The higher EC in the PAS2F treatment compared with the CNF treatment is attributed to increased PAS application rate + inorganic fertilizer addition. Again, the MC2F treatments recorded a significantly higher EC when compared with the CF, PM2F, PAS2F, and AD_SW2F treatments. However, the OA treatments at either application rates with or without inorganic fertilizer addition did not exceed the soil EC tolerance level for maize plant (Ayers and Westcott, 1985; White, 2006).

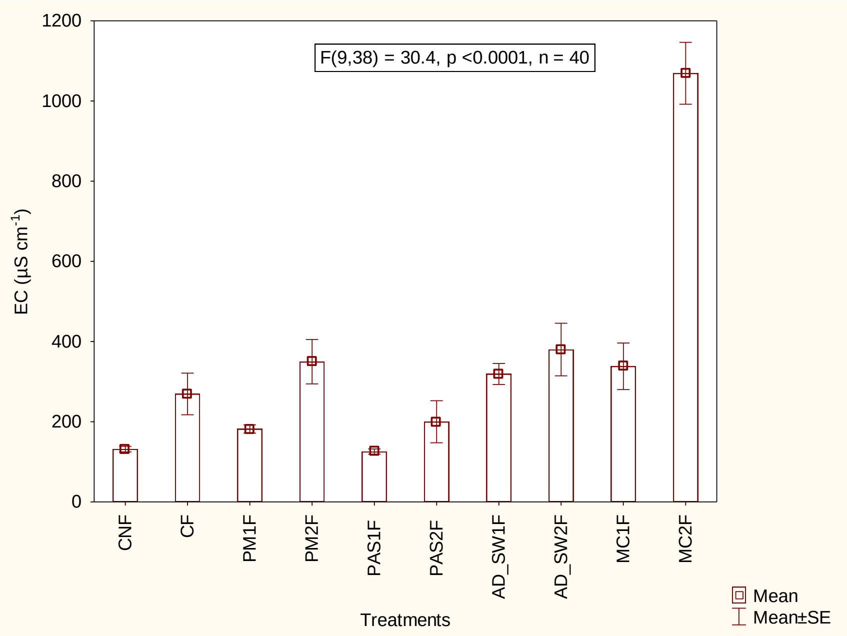


Figure 23 Effect of OA + inorganic fertilizer treatments on soil EC.

5.1.1.3 Application rates effect on EC:

With the exception of the AD_SW1F/2F and PAS1F/2F and PAS1NF/2NF treatments increasing application rate resulted in significant increase in soil EC. This is due to the inherently low EC associated with PAS amendment as compared with the other OAs (Table 10, Section 3.3.1.2). Ayers and Westcott (1985) and White (2006) reported that a soil EC level >4.0 dS m^{-1} (4000 µS cm^{-1}) can impede plant performance. However, Ayers and Westcott (1985) suggested that a soil EC of ≤1.7 dS m^{-1} is ideal for optimum (100%) maize yield, while a soil EC level of 2.5 dS m^{-1} and 3.8 dS m^{-}1 will result in 10% and 25% reduction in maize yield. In the present study, despite the high ($p < 0.05$) EC associated with PM, AD_SW and, in particular, the MC2NF treatments, the soil EC was below the critical soil EC level (Table 10, Section 3.3.1). This suggests that the EC concentrations of these treatments will not negatively affect the plant growth and yield performance (Ayers and Westcott, 1985; White, 2006).

5.1.2 Effect of OA treatments on Soil pH

The soil pH is an important soil property that not only indicates the acidity or alkalinity of a soil but also the availability of essential nutrients for plant uptake (Jones and Jeff Jacobsen, 2001; Ahmad *et al.*, 2009). Thus, it is expected that OA application will have a significant effect on the soil pH.

5.1.2.1 Soil pH associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: Contrary to expectation, only the PAS1NF treatment had significantly higher soil pH (8.55) ($p < 0.05$) as compared with the CNF, PM1NF, AD_SW1NF and MC1NF treatments (Figure 24). In contrast, the AD_SW1NF, MC1NF and PM1NF treatments had a significantly lower ($p < 0.05$) soil pH as compared with the CNF treatment. This is attributed to the high concentration of ammonium-N (NH_4-N) associated with the AD_SW1NF, MC1NF and PM1NF treatments (Table 10, Section 3.3.1.) which during ammonification processes release H^+ into the soil solution thereby lowering the soil pH due to increased levels of H^+ ion concentration (Nelson and Su, 2010). Chang *et al.* (2007) reported a significant decrease in soil pH following the application of compost. They suggested that mineralization of N from the compost was the major source of acidification. Decrease in soil pH with OA application is also in agreement with the results reported by Rezig *et al.* (2013) and Elhadi *et al.* (2016).

30 t ha^{-1}: The PAS2NF treatment recorded the highest pH though it was not significantly different from the AD_SW2NF treatment, but it was statistically higher compared with the CNF, PM2NF and MC2NF treatments. This is due to the inherently higher pH associated with the PAS amendment as compared with the PM and MC amendments (Table 10, Section 3.3.1.2).

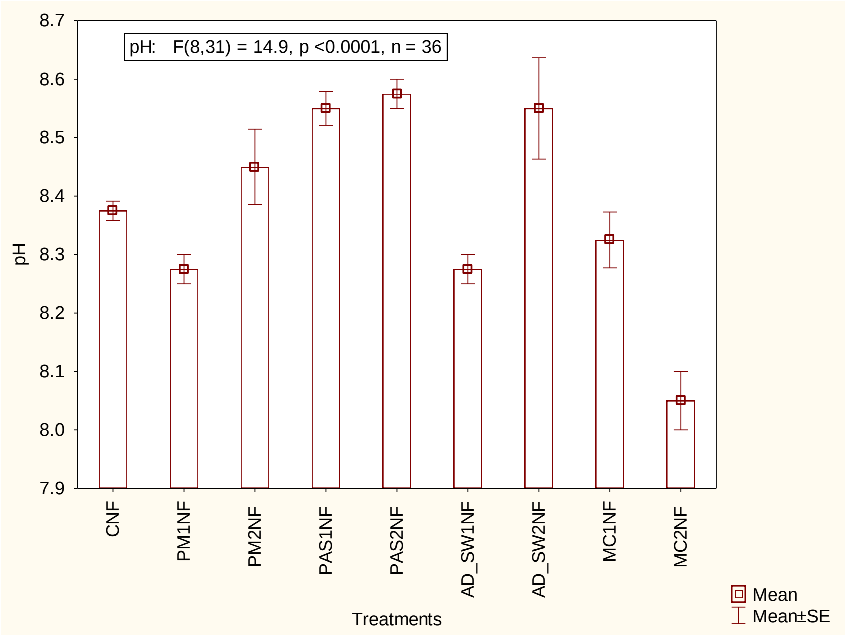


Figure 24 Effect of OA without inorganic fertilizer treatments on soil pH.

Although the AD_SW amendment was associated with significantly higher pH than all other OAs, the non-significant effect on the pH observed between the PAS2NF and AD_SW2NF treatments can be attributed to the high NH_4-N concentration in AD_SW amendment, which affected the pH during ammonification process due to release of H^+ (see Section 5.1.1.1). The high pH (>8.5) associated with the PAS and AD_SW treatments (Figure 27) suggests the likelihood of P-sorption to carbonates (Figure 5, Section 2.7.3). which can affect the availability of P for plant uptake (Fink *et al.*, 2016).

In contrast, MC2NF recorded the lowest soil pH as compared with all other treatments. The inherently high EC associated with the MC2NF treatment (Figure 22, Section 5.1.1.1) may in large part explain this finding. EC is a measure of ions (salt) concentration in the soil, acid forming cations such as Al^{3+}, Fe^{3+} and H^+, may be dominant ions in MC amendment such that by increasing MC application rate, the acidifying effects of these cations become more prominent thereby resulting in lower soil pH. The significant ($p < 0.01$) strong negative correlation ($r = -0.61$) between EC and pH suggests that the high EC in MC2NF contributed to the significantly lower pH obtained (Table 17, Section 5.1.2.2).

5.1.2.2 Soil pH associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: With the exception of MC1F, PM1F had the highest pH as compared with the CNF, CF, PAS1F, AD_SW1F and PAS1F treatments. The PM1F and PAS1F treatments had significantly higher pH as compared with the CNF treatment (Figure 25). No significant difference in pH was observed between the CNF and MC1F treatments. In contrast, the AD_SW1F recorded the lowest pH ($p < 0.05$) as compared with the PM1F, PAS1F and MC1F, CF and CNF treatments. Further, the pH in the CF treatment was 2.4% ($p < 0.05$) lower than the CNF treatment. This is attributed to the acidification effect of the inorganic fertilizer applied (Chang *et al.*, 2007; Nelson and Su, 2010).

30 t ha^{-1}: With the exception of PM2F treatment, at higher OA treatment application rate, the pH associated with CNF, PAS2F, and AD_SW2F were not significantly different. In contrast, MC2F had a significantly lower pH as compared with all other treatments.

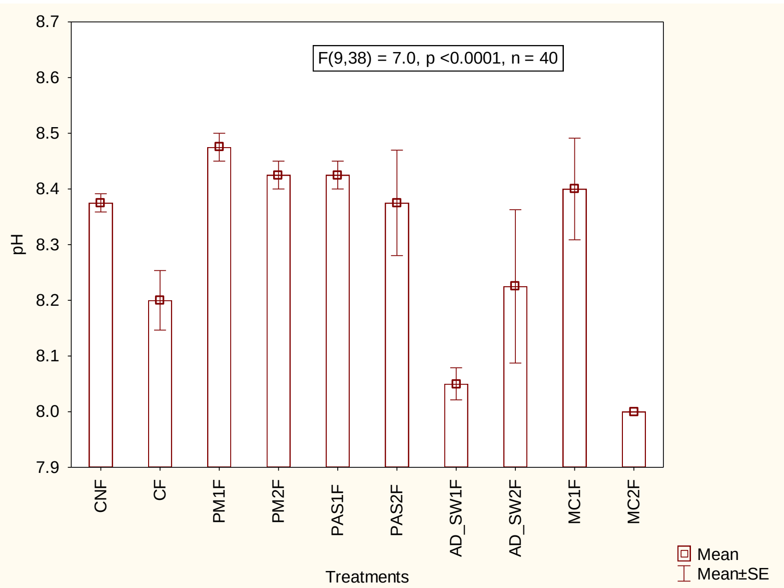


Figure 25 Effect of OA + inorganic fertilizer treatments on soil pH.

As explained earlier (Section 5.1.2.1), this is attributed to the high EC that is associated with MCF (Figure 23, Chapter 5.1.1.2) as evidenced by the significant strong ($p < 0.01$) negative correlation ($r = -0.66$) between the EC and the pH (Table 17, Section 5.1.2.2). Further, the regression ($R^2 = 0.822$, $p < 0.05$) result measured for the MC treatments confirmed that the high EC level associated with the MC amendment contributed to the significantly lower pH recorded for the MC2F treatment (Figure 26, Section 5.1.1).

5.1.2.3 Application rates effect on pH:

For the OA without inorganic fertilizer treatments, at 30 t ha^{-1} the pH associated with the PM2NF and AD_SW2NF treatments was 2.1% and 3.4% higher ($p < 0.05$) as compared with PM1NF and AD_SW1NF treatments, respectively. For all MC treatments, increasing application rate significantly reduced soil pH. This is linked to the higher EC associated with the MC2NF treatment (Figure 22, Section 5.1.1.1). For the OA with inorganic fertilizer treatments**,** with the exception of the MC1F and MC2F treatments, increasing OA application rate had no significant ($p < 0.05$) effect on soil pH.

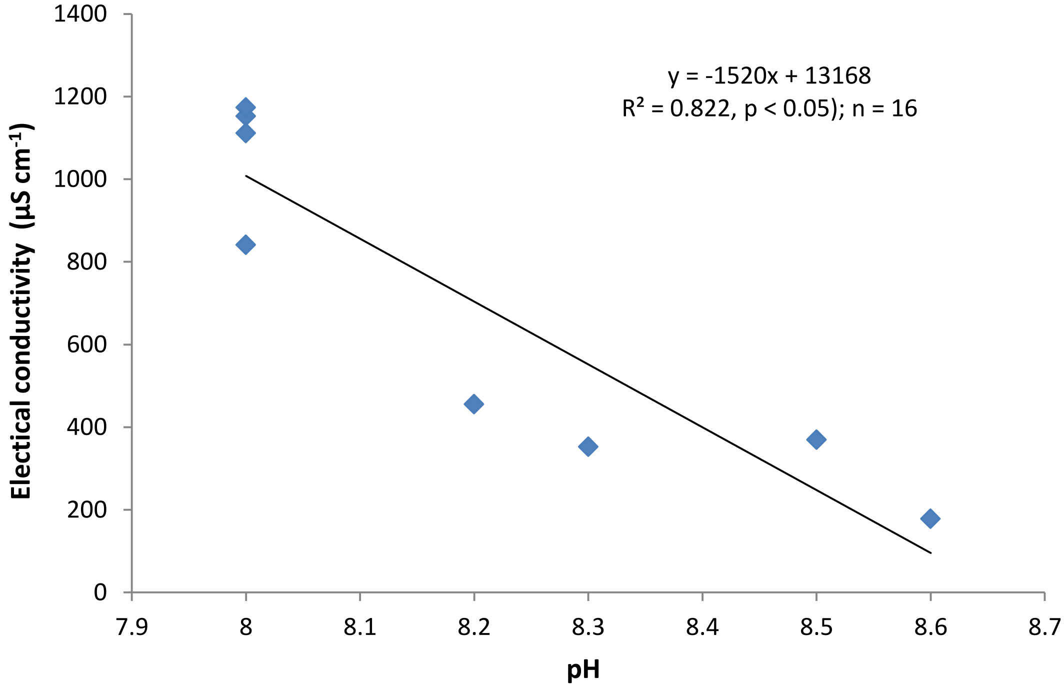


Figure 26 Relationship between EC and pH measured for the MC treatments across both application rates with or without inorganic fertilizer.

Table 17 Correlation between the post-incubation chemical and biological SQIs (n = 72)

Treatments	EC (μS cm^{-1})	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available -K (mg kg^{-1})	Available-Mg (mg kg^{-1})	SOM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	C:N	TOC (mg kg^{-1})	Total-P (mg kg^{-1})	MB_C (μg g^{-1})	C:P	Bio available-P (%)	Bio available-TOC (%)	C_{min}:C_{org}
								OA treatments without inorganic fertilizer									
Olsen-P	0.16^{ns}	0.25^{ns}	0.32*	0.35*	0.53**	0.86**	0.73**	0.79**	0.65**	0.26^{ns}	0.70**	0.86**	0.57**	0.39*	0.95**	0.37*	0.38*
EC		-0.61**	0.44**	0.27^{ns}	0.51**	0.05^{ns}	0.40*	0.48**	0.50**	0.36*	0.46**	-0.02^{ns}	0.42*	0.60**	0.26^{ns}	0.27^{ns}	0.34*
pH			-0.33*	-0.04^{ns}	0.01^{ns}	0.16^{ns}	0.21^{ns}	0.06^{ns}	0.08^{ns}	0.11^{ns}	0.16^{ns}	0.25ns	-0.11^{ns}	-0.06^{ns}	0.21^{ns}	0.10^{ns}	-0.20^{ns}
TON				0.53**	0.10^{ns}	0.21^{ns}	0.21^{ns}	0.35*	0.19^{ns}	0.07^{ns}	0.23^{ns}	0.37*	0.38*	0.11^{ns}	0.25^{ns}	0.33*	0.36*
NH4-N					0.11^{ns}	0.26^{ns}	0.31^{ns}	0.36*	0.23^{ns}	0.14^{ns}	0.28^{ns}	0.34*	0.58**	0.14^{ns}	0.28^{ns}	0.30^{ns}	0.53**
Available-K						0.34*	0.86**	0.72**	0.86**	0.63**	0.82**	0.24^{ns}	0.49**	0.83**	0.68**	0.36*	0.32*
Available-Mg							0.59**	0.65**	0.53**	0.23^{ns}	0.53**	0.77**	0.53**	0.30^{ns}	0.81**	0.32*	0.38*
SOM								0.86**	0.92**	0.67**	0.92**	0.49**	0.59**	0.81**	0.80**	0.56**	0.38*
Total-N									0.93**	0.56**	0.94**	0.62**	0.70**	0.81**	0.81**	0.55**	0.50**
Total-C										0.74**	0.97**	0.43**	0.64**	0.94**	0.73**	0.54**	0.45**
C:N											0.73**	0.07^{ns}	0.48**	0.79**	0.39*	0.75**	0.43**
TOC												0.46**	0.69**	0.91**	0.77**	0.61**	0.50**
Total-P													0.38*	0.13^{ns}	0.69**	0.25^{ns}	0.24^{ns}
MB_C														0.60**	0.62**	0.56**	0.95**
C:P															0.53**	0.54**	0.45**
Bioavailable-P																0.44**	0.45**
Bioavailable-TOC																	0.55**

Treatments	EC (µS cm^{-1})	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available -K (mg kg^{-1})	Available-Mg (mg kg^{-1})	SOM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	C:N	TOC (mg kg^{-1})	Total-P (mg kg^{-1})	MB_C (µg g^{-1})	C:P	Bio available-P (%)	Bio available-TOC (%)	C_{min}:C_{org}
								OA treatments with inorganic fertilizer									
Olsen-P	0.13^{ns}	0.22^{ns}	0.29^{ns}	0.66**	0.33*	0.88**	0.71**	0.72**	0.58**	0.26^{ns}	0.59**	0.65**	0.69**	0.39*	0.91**	0.36*	0.49**
EC		-0.66**	0.53**	0.10^{ns}	0.72**	0.06^{ns}	0.50*	0.52**	0.54**	0.32*	0.56**	0.27^{ns}	0.39*	0.52**	0.10^{ns}	0.28^{ns}	0.29*
pH			-0.64**	0.06^{ns}	-0.44**	0.28^{ns}	0.03^{ns}	-0.01^{ns}	-0.04^{ns}	0.03^{ns}	-0.05^{ns}	0.09^{ns}	-0.23^{ns}	-0.09^{ns}	0.20^{ns}	-0.01^{ns}	-0.30*
TON				0.51**	0.57**	0.18^{ns}	0.33*	0.39*	0.38*	0.29^{ns}	0.39*	0.22^{ns}	0.63**	0.33*	0.29*	0.32*	0.64**
NH4-N					0.31*	0.49**	0.47**	0.45**	0.39*	0.25^{ns}	0.38*	0.35*	0.49**	0.31*	0.66**	0.28^{ns}	0.39*
Available-K						0.31*	0.69**	0.66**	0.75**	0.61**	0.76**	0.36*	0.66**	0.71**	0.34*	0.50**	0.58**
Available-Mg							0.67**	0.72**	0.59**	0.30^{ns}	0.59**	0.62**	0.63**	0.42*	0.85**	0.30*	0.48**
SOM								0.95**	0.93**	0.67**	0.94**	0.67**	0.71**	0.81**	0.63**	0.59**	0.50**
Total-N									0.95**	0.63**	0.95**	0.72**	0.72**	0.80**	0.63**	0.58**	0.52**
Total-C										0.80**	0.99**	0.59**	0.70**	0.92**	0.53**	0.59**	0.54**
C:N											0.78**	0.20^{ns}	0.55**	0.89**	0.33*	0.63**	0.53**
TOC												0.59**	0.70**	0.91**	0.54**	0.64**	0.53**
Total-P													0.47**	0.25^{ns}	0.38*	0.28^{ns}	0.26^{ns}
MB_C														0.62**	0.67**	0.47**	0.94**
C:P															0.47**	0.61**	0.53**
Bioavailable-P																0.40*	0.53**
Bioavailable-TOC																	0.43**

*= significant at p <0.05; ** = highly significant at p <0.01.

5.1.3 Effect of OA treatments on Olsen-P

5.1.3.1 Olsen-P associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: The OA treatments (PM1NF, PAS1NF, AD_SW1NF and MC1NF) had significantly higher Olsen-P as compared with the CNF treatment (Figure 27). This is due to high concentrations of Olsen-P that are associated with the OAs applied (Table 10, Section 3.3.1.2) in addition to the release of organically-bound P. Further, the PM1NF treatment had 73%, 69.2%, 55% and 55% higher ($p < 0.05$) Olsen-P as compared with the CNF, PAS1NF, AD_SW1NF and MC1NF treatments respectively. This is attributed to the inherently high Olsen-P that is associated with the PM amendment (Table 10, Section 3.3.1.2).

30 t ha^{-1}: Similarly, the PM2NF treatment was associated with significantly higher Olsen-P as compared with the CNF, PAS2NF and MC2NF treatments but was not significantly different compared with the AD_SW2NF treatment due to some statistical 'noise' (Figure 27). The significant differences in the MB_C associated with the OAs (Table 10, Section 3.3.1.2) and that of the test soil (Table 6, Section 3.2) may also in part explain the significantly higher Olsen-P associated with the OA treatments through release of organically bound-P. This is supported by the significant correlation ($r = 0.57$) between the MB_C and Olsen-P (Table 17, Section 5.1.2.2) and demonstrate that OA application enhances mineralization of organically-bound P in soil, due to increases, in the soil microbial biomass and microbial activity. The present study also supports the findings of Cabilovski *et al.* (2014).

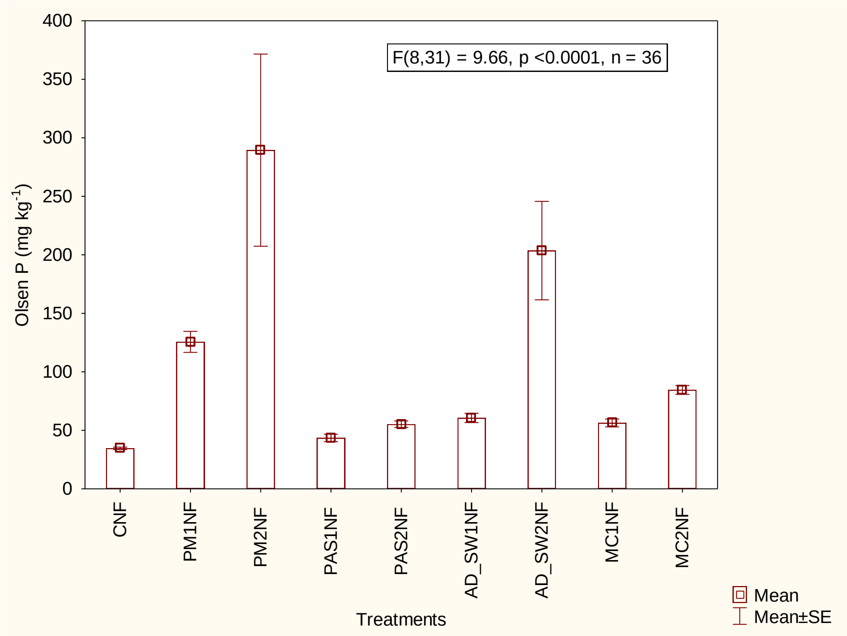


Figure 27 Effect of OA without inorganic fertilizer treatments on Olsen-P concentrations.

5.1.3.2 Olsen-P associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: All OA + inorganic fertilizer treatments had significantly higher Olsen-P as compared with the CNF treatment (Figure 28). The PM1F treatment had the highest Olsen-P (160 mg kg^{-1}) which was 78%, 75%, 68.8%, 62.3% and 65.6% higher ($p < 0.05$) compared with the CNF, CF, PAS1F, AD_SW1F and MC1F treatments respectively.

30 t ha^{-1}: At 30 t ha^{-1}, the Olsen-P concentration level in the PM2F treatment was significantly higher as compared with the CNF, CF, PAS2F, AD_SW2F and MC2F treatments, respectively (Figure 28). Olsen-P concentration in the CF treatment was significantly lower as compared with all the OA + inorganic fertilizer treatments but was significantly higher compared with the CNF treatment, demonstrating the benefits of the combined use of organics and mineral inputs (Bedada *et al.*, 2014). Moharana *et al.* (2012) also found higher Olsen-P in soil amended with manure and inorganic fertilizer applied either alone or in combination over unfertilized control plots. The authors attributed the increase in Olsen-P to the release of organically bound P (solubilization) during decomposition of organic matter.

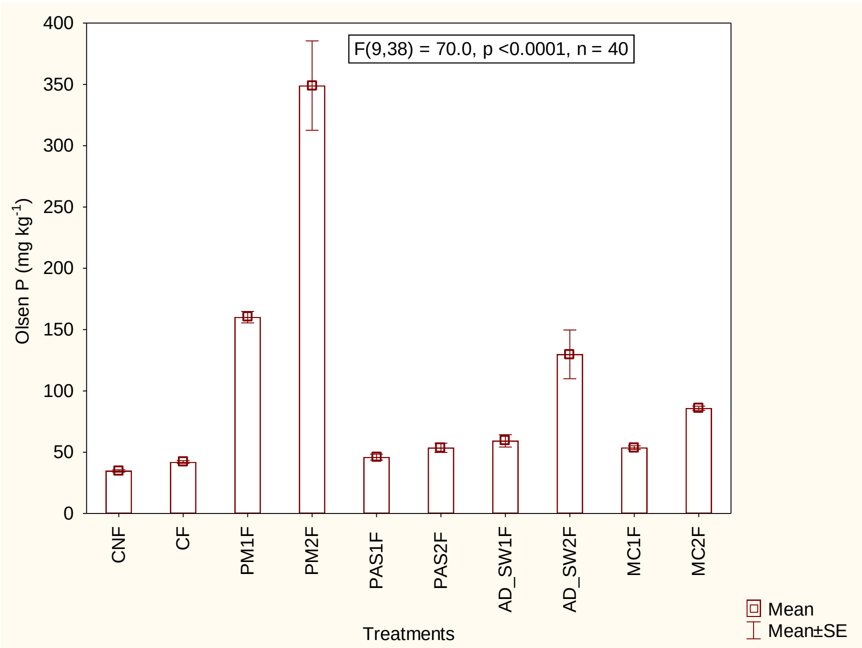


Figure 28 Effect of OA + inorganic fertilizer treatments on Olsen-P concentrations.

5.1.3.3 Application rates effect on Olsen-P:

With the exception of PAS1F and PAS2F treatments increasing OA application rate resulted in significant ($p < 0.05$) increases in Olsen-P. This is due to increased amount of Olsen-P added via the OAs. However, considering the relatively low Olsen-P associated with PAS amendment (Table 10, Section 3.3.1.2), it is possible that the high pH associated with the PAS1F and PAS2F treatments (Figure 25, Section 5.1.2.2) contributed to the non-significant effect on the Olsen-P due to P-fixation. In contrast, this was not the case for PM treatment. PM2F treatment had 54.3% higher ($p < 0.05$) Olsen-P as compared with PM1F treatment.

PM2F and PAS2F treatments had high ($p < 0.05$) pH levels (Figure 25, Section 5.1.2.2). Considering the high pH associated with these treatments, the effect of P-fixation to the carbonates for both treatments may not be of the same magnitude. This is due to the significantly high Olsen-P associated with the PM amendment (Table 10, Section 3.3.1.2) which increased with increasing OA application rates.

Having seen the OA treatments effects on the soil Olsen-P concentration, it is also crucial to know whether or not the OA treatments were supplying sufficient P to meet the P crop requirements based on RB209 recommendations (Table 9, Section 3.2.1). When the OAs are added to the soil, P enters the soil exchange complex and is likely sorbed by the carbonates since the test soil is associated with high pH (8.2) (Fontes and Weed, 1996; Fink *et al.*, 2016) and also due to P immobilization (Figure 5, Section 2.7.3).

The results indicate that at post-incubation, the PM1F, PM1NF, PM2F and PM2NF treatments, respectively, provide 7%, 5%, 45% and 37% of the recommended P rate early on for plant use (Figures 32 and 33 A1 and A2, Section 5.1.3). It is expected that this will have a significant effect on plant performance At higher OA application rates, the P supply from the PAS treatments was significantly lower than the PM, AD_SW and MC treatments. In contrast, the comparatively lower P supply associated with the OA treatments without inorganic fertilizer addition (Figure 33 A1) may suggest that P is limiting and could negetively affect plant performance (See Chapter 7 for more discussion). The results further show that the P supplies via CF treatment was not statistically different when compared with the CNF treatment. This is because the inorganic fertilizer applied to the CF treatment is designed to slowly release P for plant uptake throughout the plant growth period while the low P supply from the CNF treatment is due to the inherently low P concentration associated with the test soil (Table 6, Section 3.2). In contrast, the P associated with the NF treatments is organically bound and will be released over time via microbial activity.

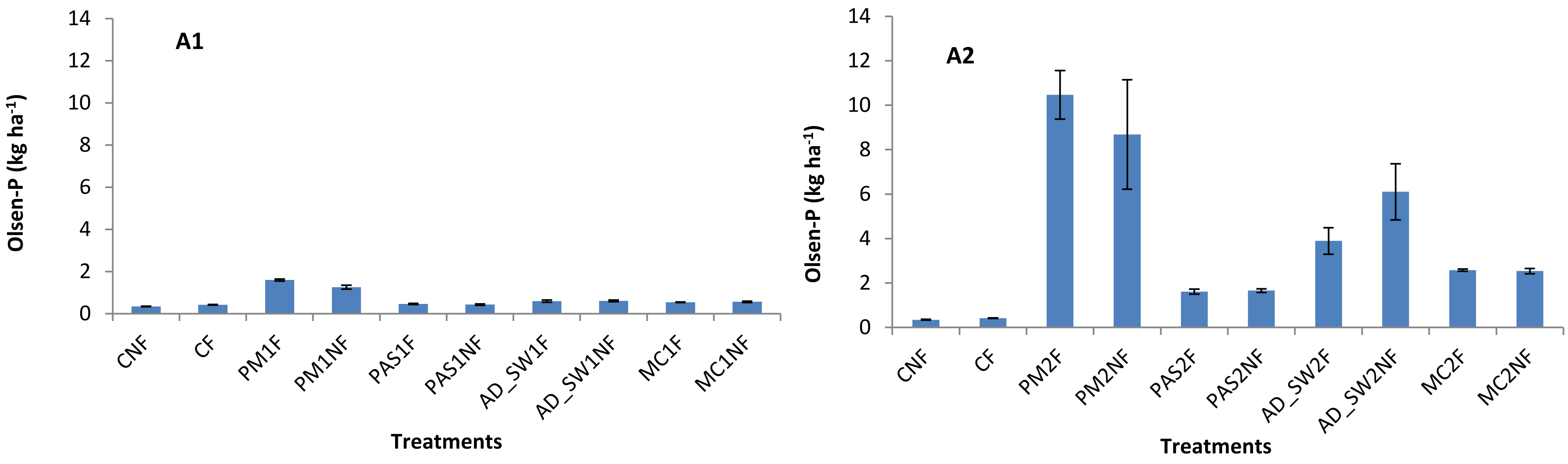


Figure 29 Amount of P as Olsen-P (A1 = 10 t ha^{-1}, A2 = 30 t ha^{-1}) supplied via OA treatments across both application rates as compared to the RB209 recommendation (24 kg P ha^{-1}), n = 72.

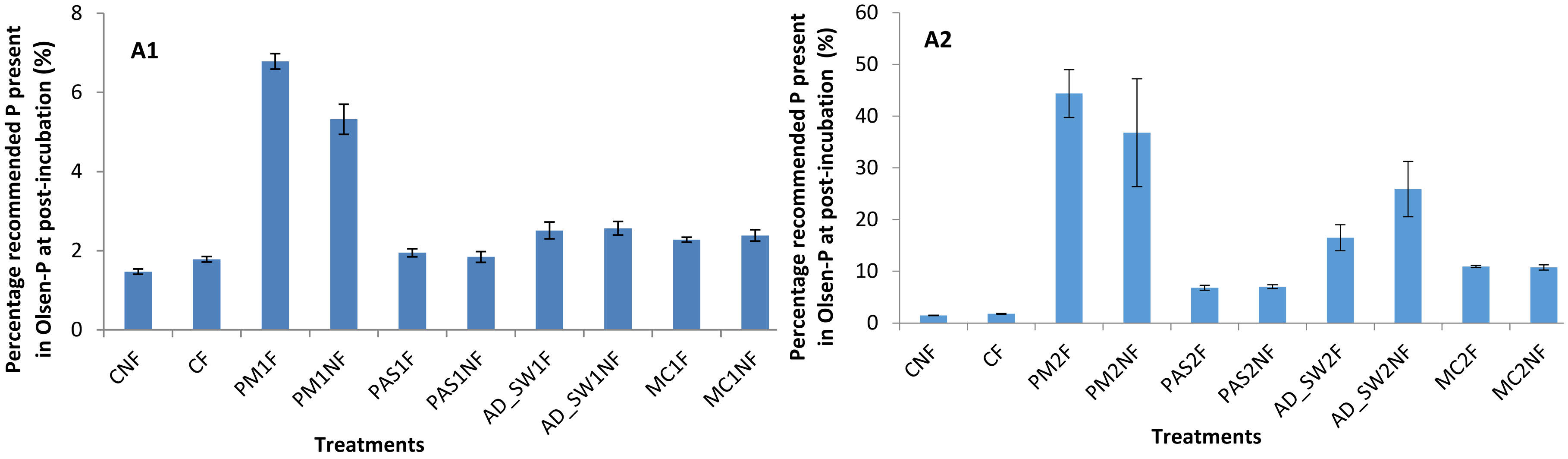


Figure 30 Percentage of RB209 recommended P as Olsen-P in OA treatments (with or without inorganic fertilizer) at post-incubation across both application rates, n = 72.

5.1.4 Effect of OA treatments on soil TON

5.1.4.1 Soil TON associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: The results indicate that the PM1NF, AD_SW1NF and MC1NF treatments had significantly (p <0.05) higher TON as compared with the CNF treatment (Figure 31). In contrast, the TON in PAS1NF and CNF did not differ statistically. The significantly higher TON in MC1NF as compared with PAS1NF is attributed to the significantly higher TON associated with the MC amendment (Table 10, Section 3.3.1.2). However, for PM1NF and AD_SW1NF treatments, it is postulated that the high TON associated with these treatments is due to the high NH_4-N that is associated with their OAs (Table 10), which by microbial actions/activities (mineralization) increased the soil TON content. This is evident by the highly significant (p <0.01) correlation (r = 0.58) between NH_4-N and MB_C (Table 17, Section 5.1.2.2).

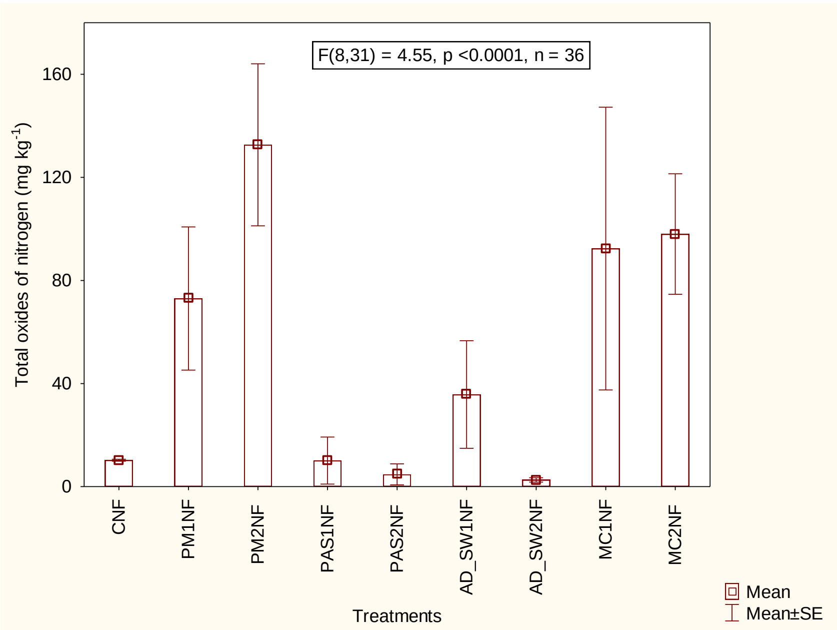


Figure 31 Effect of OA without inorganic fertilizer treatments on soil TON.

30 t ha^{-1}: The PM2NF treatment had 91%, 95%, 97%, and 30% higher (p <0.05) TON as compared with the CNF, PAS2NF, and AD_SW2NF treatments respectively (Figure 31). However, the TON in the PM2NF and MC2NF treatments was not significantly ($p < 0.05$) different. This is attributed to the significantly higher TON associated with MC amendment as compared with all other OAs (Table 10, Section 3.3.1.2). Unlike the MC amendment, the PM amendment was not associated with high TON, however, the high TON in the PM2NF treatment (Figure 31) can suggest N mineralization from NH_4-N, which is further enhanced by the comparatively lower C:N ratio associated with the PM relative to the other OAs (Table 10). The significant correlation ($r = 0.53$) that exists between the NH_4-N and TON confirms the mineralization actions of the soil microbes (Table 17, Section 5.1.2.2).

Contrary to expectation, the PAS2NF and AD_SW2NF treatments recorded significantly lower TON as compared with the CNF, PM2NF and MC2NF treatments. This is linked to the inherently low TON that is associated with the PAS and AD_SW amendments (Table 10, Section 3.3.1.2). Further, the significantly higher C:N ratio in the AD_SW amendment compared with the other OAs (Table 10) can also contribute to the significantly lower TON obtained due to N immobilization by the soil microbes (Table 17, Section 2.7.4). Gutser *et al.* (2005) demonstrated that the N availability of OAs is affected by the mineral-N content, Total-N content and the C:N ratio of the OAs with a low-N OA with a C:N ratio >15 associated with limited N availability due to N immobilization by the soil microbes. Further, McClellan *et al.* (2014) suggested that for OAs with a C:N ratio between 20 and 30 mineralization and immobilization can occur at equal rates. In another study, after two months OA (farmyard manure, vermicompost and spent compost) application, Cabilovski *et al.* (2014) found a significantly higher mineral N concentration in plots amended with the application of 170 kg N ha^{-1} via OAs as compared with the un-amended control.

5.1.4.2 Soil TON associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: With the exception of PAS1F, the OA + inorganic fertilizer treatments had significantly higher TON as compared with the CNF treatment (Figure 32). The AD_SW1F treatment recorded the highest TON level which was 95, 69, 75, 89, and 70% higher ($p < 0.05$) as compared with the CNF, CF, PM1F, AD_SW1F and MC1F treatments, respectively.

30 t ha^{-1}: At higher OA application rates, the OA + inorganic fertilizer treatments except for the PAS2F treatment had significantly higher TON as compared with the CNF treatment (Figure 32). Further, the TON in the PM2F, AD_SW2F and MC2F treatments were not significantly different. The high NH_4-N associated with PM and AD_SW amendments (Table 10, Section 3.3.1.2) contributed to the non-significant difference in the TON observed due in large part to microbial conversion of NH_4-N to TON. This is supported by the significant correlation (r = 0.58) between NH_4-N and MB_C (Table 17, Section 5.1.2.2).

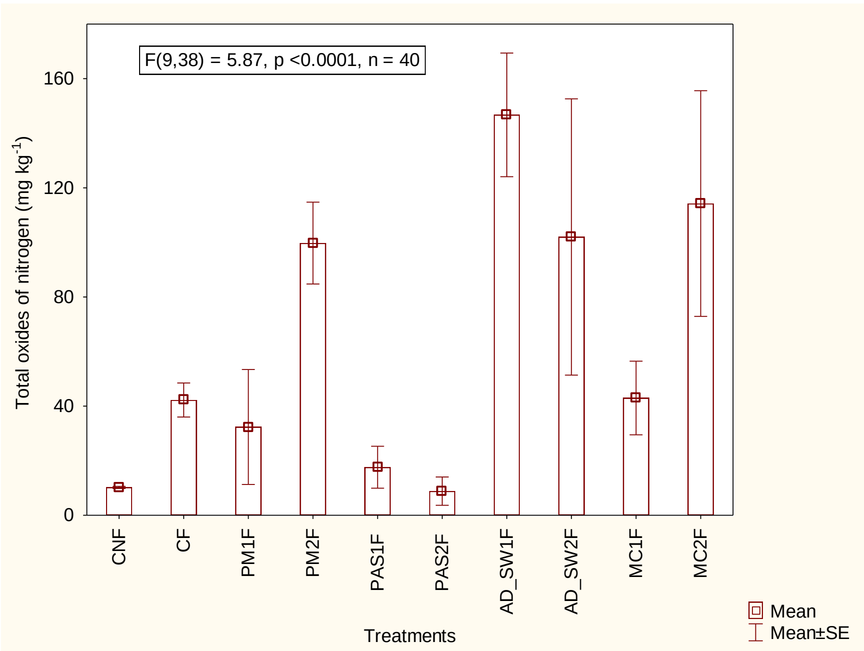


Figure 32 Effect of OA + inorganic fertilizer treatments on Total oxides of nitrogen.

5.1.4.3 Application rates effects on TON:

For the OA without fertilizer treatments, due to a high degree of variability within the treatment means, increasing OA treatment application rates had no significant effect on the TON for the PAS, PM and MC treatments (Figure 31). In contrast, the AD_SW2NF treatment had 85.7% lower ($p < 0.05$) TON as compared with the AD_SW1NF treatment. This is attributed to the high C:N ratio, associated with the AD_SW amendments (Table 10, Section 3.3.1.2). This result implies that at higher AD_SW treatment application rates, there is a greater tendency for N immobilization by soil microbes due to the effect of C:N ratio, thus resulting in the observed reduction in the TON with AD_SW2NF treatment [Table 10, Section 3.3.1.2] (Gutser *et al.*, 2005; McClellan *et al.*, 2014).

It is suggested here that the significant reduction in TON associated with the AD_SW2NF treatment may negatively affect maize plant growth and crop yield performance due to low or insufficient level of available N at the early growth stage (See Chapter 7 for more discussion on plant performance). However, since AD_SW2NF treatment is associated with high levels of NH_4-N, this can provide the maize plant the N nutrient it required. It is suggested that the low TON associated with the PAS treatments as compared with the other OA treatments may negatively affect plant performance (See Chapter 7 for more discussion). In contrast for the OA with inorganic fertilizer treatments, the TON in the PM2F and MC2F treatments was significantly higher by 66% and 61% compared with the PM1F and MC1F treatments, respectively. In contrast, PAS2F and AD_SW2F treatments did not vary significantly in their TON content as compared with the PAS1F and AD_SW1F treatments, respectively, due to high degree of variability within the treatment means (Figure 32).

5.1.5 Effect of OA treatments on Soil NH_4-N

5.1.5.1 Soil NH_4-N associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: The PM1NF and AD_SW1NF treatments had significantly higher NH_4-N as compared with the CNF treatment (Figure 33). This is due to the significantly high levels of NH_4-N that is associated with these OAs. With the exception of PAS1NF, the AD_SW1NF treatment had significantly higher NH_4-N as compared with the PM1NF and MC1NF treatment. The high NH_4-N in AD_SW1NF treatment as compared with the MC1NF is linked to the significant difference in NH_4-N that is associated with AD_SW and MC amendments (Table 10, Section 3.3.1.2). However, the significantly high levels of NH_4-N in the AD_SW1NF treatment as compared with the PM1NF treatment suggests lack of mineralization to TON due to the inherently high ($p < 0.05$) C:N that is associated with the AD_SW OA (Table 10). Further, the NH_4-N in PAS1NF and MC1NF treatments were not significantly different as compared with CNF treatment. This is linked to the low levels of NH_4-N in the PAS and MC OAs relative to PM and AD_SW (Table 10, Section 3.3.1.2).

30 t ha^{-1}: The results indicate that only the PM2NF and MC2NF treatments had significantly higher ($p < 0.05$) NH_4-N as compared with the CNF treatment. Further, the PM2NF treatment was associated with significantly higher NH_4-N (60 mg kg^{-1}) as compared with all other treatments. The high NH_4-N in the PM2NF treatment is due to high NH_4-N associated with PM OA (Table 10, Section 3.3.1.2) which manifested at higher application rates. Contrary to expectation, the AD_SW2NF treatment recorded the lowest treatment NH_4-N concentration though it was not significantly different ($p < 0.05$) compared with the PAS2NF treatment.

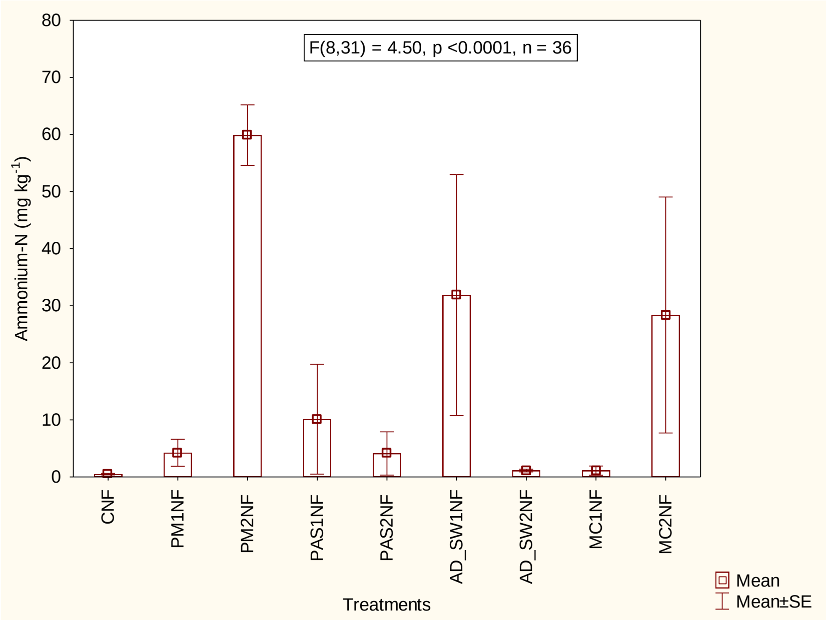


Figure 33 Effect of OA without inorganic fertilizer treatments on soil NH_4-N.

Considering the high NH_4-N associated with the AD_SW amendment (Table 10, Section 3.3.1.2), the low ($p < 0.05$) NH_4-N in the AD_SW2NF treatment can primarily be attributed to N immobilization by the soil microbes, due to the high C:N associated with the AD_SW amendment (Table 10). The high pH (10.3) associated with the AD_SW amendment (Table 10) can possibly provide a more conducive environment for nitrifying bacteria, thus resulting in the significant reduction in the NH_4-N (Sajuni *et al*. 2010).

5.1.5.2 Soil NH_4-N associated with organic amendment + fertilizer treatments

10 t ha^{-1}: The soil NH_4-N concentration associated with the low application rate treatments was in the order PM1F > AD_SW1NF ≥ CF > CNF = PAS1F = MC1NF treatment (Figure 34).

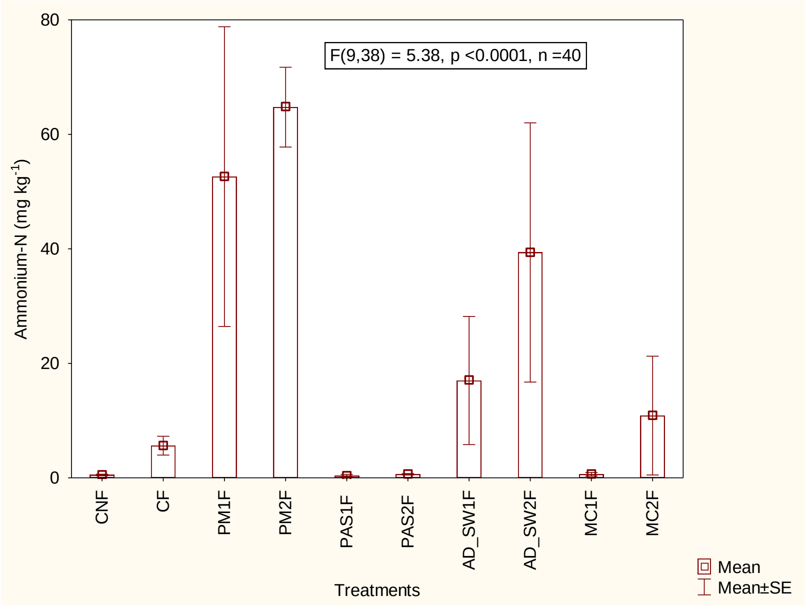


Figure 34 Effect of OA + inorganic fertilizer treatments on Ammonium-N

30 t ha^{-1}: At 30 t ha^{-1}, the PM2F treatment was associated with 98.4%, 92%, 98.4%, and 84.6% higher ($p < 0.05$) NH_4-N concentration than the CNF, CF, PAS2F, and MC2NF treatments, respectively. Further, significant differences in NH_4-N were observed between the PM2F and AD_SW2NF treatments (Figure 34). This is due to the non-significant difference in the NH_4-N content associated with the PM and AD_SW OAs (Table 10, Section 3.3.1.2).

5.1.5.3 Application rates effect on NH_4-N:

For the OA without inorganic fertilizer treatments, increasing application rate significantly ($p < 0.05$) influenced the NH4-N concentration. The NH_4-N in the PM2NF and MC2NF treatments were 91.6% and 93.3% higher ($p < 0.05$) than the PM1NF and MC1NF treatments respectively (Figure 33). In contrast, for the AD_SW treatment, increasing application rate resulted in a significant decrease in NH_4-N concentration; this is attributed to the effect of high C:N. The PAS1NF and PAS2NF treatments did not differ significantly in their NH_4-N concentration due to the significantly lower NH_4-N concentration associated with the PAS OA (Table 10). In contrast for the OA with inorganic fertilizer treatments, the PM, AD_SW and MC treatments showed a trend of increasing NH_4-N with application rate. However, the high degree of variability within treatment prevented the observed increases in NH_4-N concentrations from being significant (Figure 36).

5.1.6 Effect of OA treatments on Soil Organic Matter (SOM)

5.1.6.1 SOM associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: As hypothesized, all the OA treatments had significantly higher SOM as compared with the CNF treatment (Figure 35). This is due to the inherently high organic matter (OM) content associated with the OAs applied, which increased the SOM content as compared with the CNF (Table 10, Section 3.3.1.2). Further, the SOM in the PM1NF treatment was significantly higher as compared with the PAS1NF and MC1NF treatments, but was not significantly different as compared with the AD_SW1NF treatment. This is attributed to the significantly higher OM associated with the PM amendment relative to PAS and MC OAs (Table 10, Section 3.3.1.2). The non-significant effect in the SOM observed between the PM1NF and AD_SW1NF treatments was due to the non-significant difference in their OM content (Table 10, Section 3.3.1.2).

Contrary to expectation, the PAS1NF, AD_SW1NF and MC1NF treatments did not differ significantly in their SOM content, even though the OM content associated with the PAS, AD_SW and MC OAs varied significantly (Table 10, Section 3.3.1.2). This could be attributed to the effect of OM decomposition by the soil microbes, since the microbes, play key roles in the decomposition of organic residues (Nielsen and Winding, 2002) and cycling of nutrients (Figure 5, Sections 2.7.3-2.7.4), as evidenced by the significant positive correlation ($r = 0.59$) between SOM and MB_C (Table 17, Section 5.1.2.2).

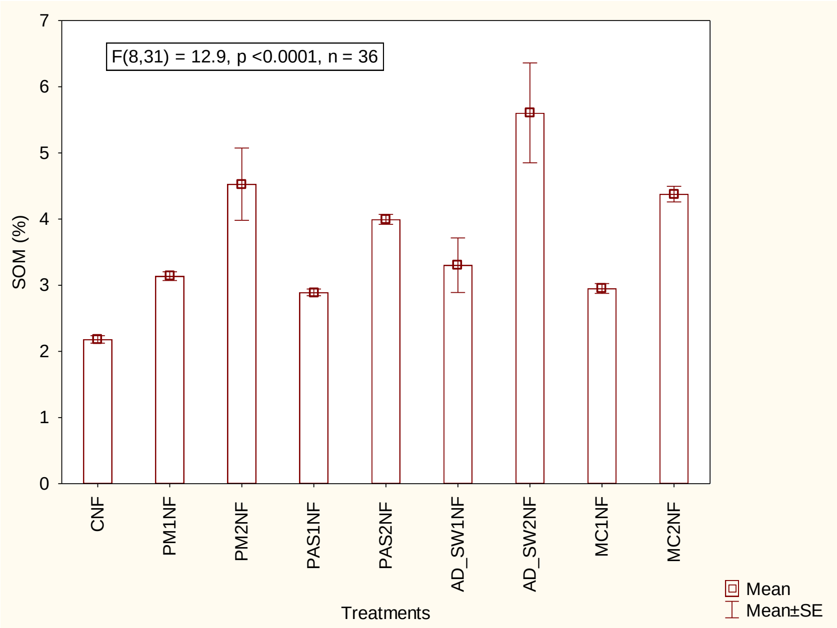


Figure 35 Effect of OA without inorganic fertilizer treatments on SOM

30 t ha^{-1}: Similarly, at the higher application rates, the PM2NF, PAS2NF, AD_SW2NF, and MC2NF treatments had higher ($p < 0.05$) SOM as compared with the CNF treatment. The AD_SW2NF treatment was 59%, 19.6%, 28.6%, and 21.4% higher ($p < 0.05$) as compared with the CNF, PAS2NF and MC2NF treatments, respectively, but was not significantly ($p < 0.05$) different as compared with the PM2NF treatment. This result is in agreement with previous studies which reported the significant positive effects on SOM following OA application as compared with control non-amended treatments (Cherif *et al.*, 2009; Celik *et al.,* 2010; Moharana *et al.*, 2012; Guo *et al.,* 2016).

5.1.6.2 SOM associated with OA + fertilizer treatments

10 t ha^{-1}: As postulated, PM1F, PAS1F, AD_SW1NF and MC1F treatments had significantly higher SOM than the CNF and CF treatments (Figure 36). The results indicate that the PM1F treatment recorded the highest SOM content (3.3%) as compared with CNF, CF, PAS1F, and AD_SW1NF but was not significantly different from the MC1F treatment. Celik *et al.* (2010) and Biau *et al.* (2012) reported increases in SOM with OA (manure) + inorganic fertilizer application.

30 t ha^{-1}: As expected, the PM2F, PAS2F, AD_SW2F and MC2F treatments had significantly higher SOM as compared with the CNF and CF treatments (Figure 36). The PM2F treatment recorded a significantly higher SOM content as compared with the CNF, CF, PAS2F, AD_SW2F and MC2F treatments by 59.3, 59, 48.1, 22.2 and 16.7%, respectively. No significant difference in SOM was observed for the AD_SW2F and PAS2F treatments. These results are similar to the findings of Biau *et al., (*2012) and Xun *et al.,* (2016).

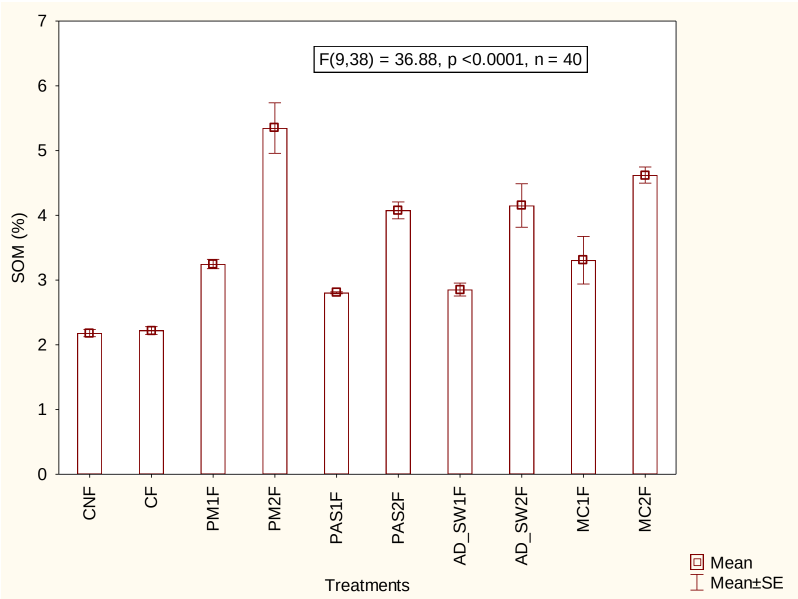


Figure 36 Effect of OA + inorganic fertilizer treatments on SOM.

5.1.6.3 Application rates effect on SOM:

Application rates effect on SOM: Across all OA treatments with and without inorganic fertilizer addition, increasing application rate significantly increased SOM by between 28.3–39%. Increasing SOM content mitigates soil degradation such as nutrient/SOM loss, erosion, compaction and poor crop yield (Muchena *et al.*, 2005; Montanarella, 2013; FAO, 2015a).

5.1.7 Effect of OA treatments on Available-K

5.1.7.1 Available-K associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: As expected, the PM1NF, PAS1NF, AD_SW1NF and MC1NF treatments had significantly higher Available-K as compared with the CNF treatment (Figure 37). The Available-K in the AD_SW1NF treatment (1000 mg kg^{-1}) was 70%, 30% and 50% higher ($p < 0.05$) as compared with the CNF, PM1NF and PAS1NF treatments, respectively, but was statistically the same as the MC1NF treatment. The significantly higher Available-K recorded in the OA treatments is due to the inherently high Available-K that is associated with the OAs (Table 10, Section 3.3.1.2). This is similar to the observations of Elhadi *et al.* (2016) Rautaray *et al* .(2003) and Cabilovski *et al.* (2014).

30 t ha^{-1}: Similarly, the PM2NF, PAS2NF, AD_SW2NF and MC2NF treatments recorded significantly higher Available-K as compared with the CNF treatment (Figure 37). Further, the Available-K associated with AD_SW2NF treatment was more than 30% higher as compared with the PM2NF, PAS2NF and MC2NF treatments, respectively.

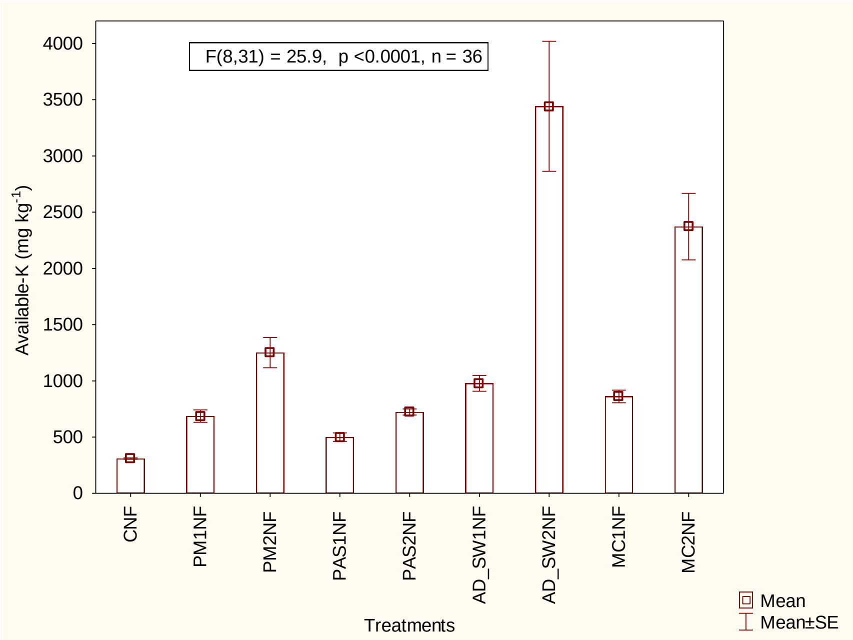


Figure 37 Effect of OA without inorganic fertilizer on Available-K.

5.1.7.2 Available-K associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: All the OA treatments (PM1F, PAS1F, AD_SW1F and MC1F) had significantly higher Available-K as compared with the CNF treatment (Figure 38). The AD_SW1F treatment recorded the highest Available-K (1500 mg kg^{-1}) and was significantly higher as compared with the PM1F, PAS1F and MC1F treatments. Contrary to expectation, the Available-K in the CF treatment was significantly higher as compared with the PAS1F treatment and was statistically at par with the PM1F treatment. This implies that the application of PM and PAS at 10 t ha^{-1} rates was insufficient to significantly affect the Available-K relative to the CF treatment.

30 t ha^{-1}: PM2F, PAS2F, AD_SW2F and MC2F treatments had significantly higher Available-K relative to the CNF treatment (Figure 38). Across the OA treatments, the Available-K in AD_SW2NF and MC2F treatments was more than 30% higher as compared with the PM2F and PAS2F treatments, respectively. This is due to the high ($p < 0.05$) Available-K contained in AD_SW and MC compared with PM and PAS amendments (Table 10, Section 3.3.1.2).

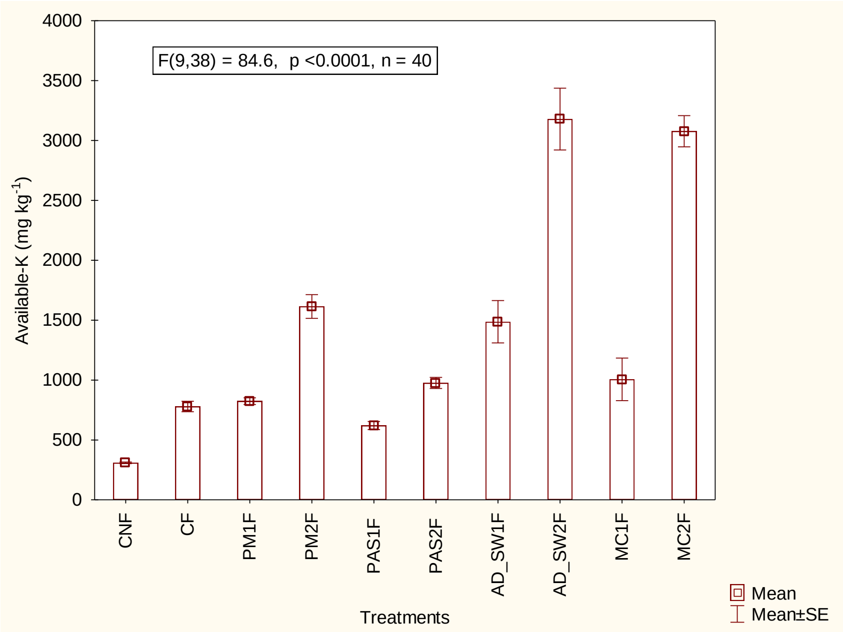
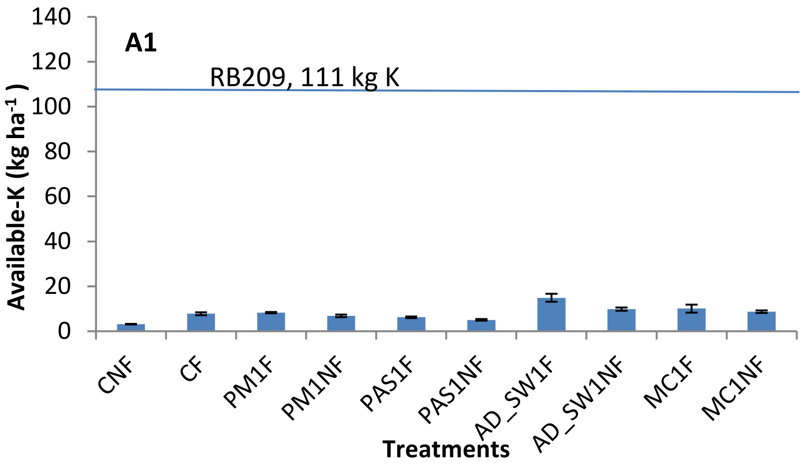


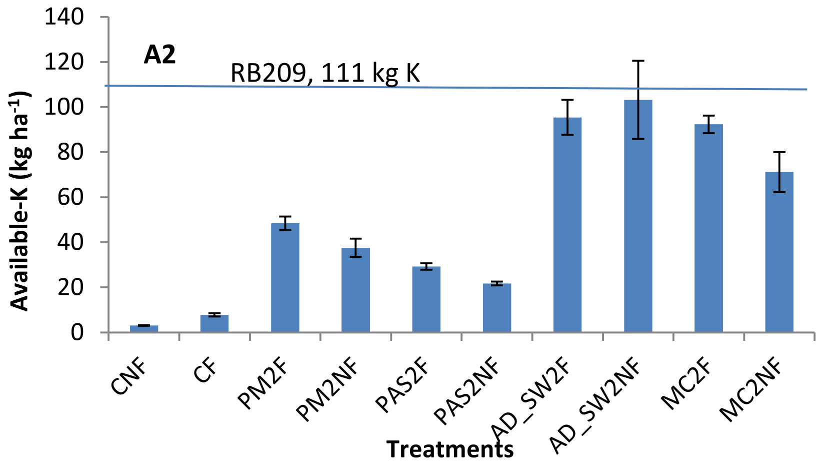
Figure 38 Effect of OA + inorganic fertilizer treatments on Available-K.

5.1.7.3 Application rates effect on Available-K:

For all OAs with or without inorganic fertilizer addition, increasing application rate resulted in a concomitant increase in Available-K concentration. Nevertheless, it is important to know whether the OA treatments were supplying adequate Available-K based on the RB209 K recommendation for maize.

At 10 t ha^{-1} the AD_SW1NF treatment had significantly higher K supply than all other treatments. At higher application rates, AD_SW2NF, AD_SW2F and MC2F treatments had significantly higher K supply as compared with all other treatments. The results indicate that the OA treatments applied at 10 t ha^{-1} and 30 t ha^{-1} rates respectively supplied 3-18% and 5-85% of the recommended K two weeks after incubation (Figure 42, Section 5.1.7). The K supply associated with the OA treatments is expected to have significant effects on plant performance (See Chapter 7).


A1
RB209, 111 kg K
Available-K (kg ha^{-1})
CNF
CF
PM1F
PM1NF
PAS1F
PAS1NF
AD_SW1F
AD_SW1NF
MC1F
MC1NF
Treatments


A2
RB209, 111 kg K
Available-K (kg ha^{-1})
CNF
CF
PM2F
PM2NF
PAS2F
PAS2NF
AD_SW2F
AD_SW2NF
MC2F
MC2NF
Treatments

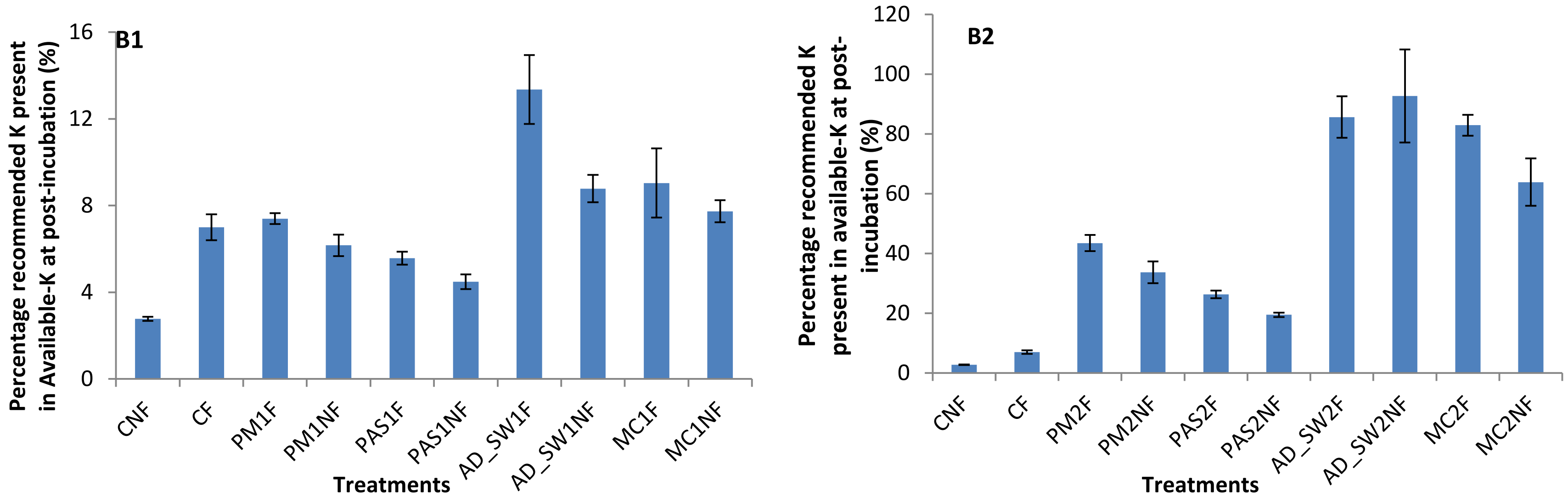


Figure 42 Actual amount of K in Available-K (A) as a percentage of RB209 recommended K in Available-K (B) present in the OA treatments at post-incubation across both application rates, n = 72.

5.1.8 Effect of OA treatments on Soil Available-Mg

5.1.8.1 Available-Mg associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: The PM1NF and AD_SW1NF treatments had significantly ($p < 0.05$) higher Available-Mg as compared with the CNF treatment (Figure 39). Further, the PM1NF treatment had the highest Available-Mg (420 mg kg^{-1}) which was >30% higher ($p < 0.05$) than CNF, PAS1NF, AD_SW1NF and MC1NF treatments respectively. The significantly higher Available-Mg in the PM1NF treatment is attributed to mineralization of Available-Mg from the SOM by the soil microbes. This is evidenced by the significant correlation (r = 0.59 and 0.53) that exists between MB_C and SOM; and that between MB_C and Available-Mg, respectively, (Table 17, Section 5.1.2.2).

The Available-Mg in the PAS1NF and MC1NF treatments were not statistically different as compared with the CNF treatment. This is contrary to expectation, considering the significantly higher Available-Mg associated with the MC amendment relative to the other OAs. It can suggest that the significantly high EC associated with the MC amendment in addition to the high Available-K inherent in the MC amendment can contribute to the non-significant effect in the Available-Mg observed between the MC1NF and CNF treatments due to Mg^{2+} displacement by the K^{+} (Metson, 1974; Gransee and Führs, 2013; McClellan *et al.*, 2014). The significant ($p < 0.01$) correlation (r = 0.51) between EC and Available-K suggests that the high Available-K associated with the MC2NF treatment might have caused the displacement of Mg cations from the soil solution thus resulting in the non-significant effect in Available-Mg as compared with the CNF treatment (Table 17, Section 5.1.2.2).

30 t ha^{-1}: The Available-Mg in the OA treatments was significantly higher as compared with the CNF treatment except for the MC2NF treatment. This is due to the above mentioned reason. The Available-Mg associated with the treatments is in the order: PM2NF ≥ AD_SW2NF > PAS2NF = MC2NF ≥ CNF.

Again, this result is contrary to expectation. This can be attributed to the above explained reasons. The high Available-Mg concentration associated with the OA treatments is expected to impact positively on plant growth and yield performance as compared with the CNF treatment (See Chapter 7).

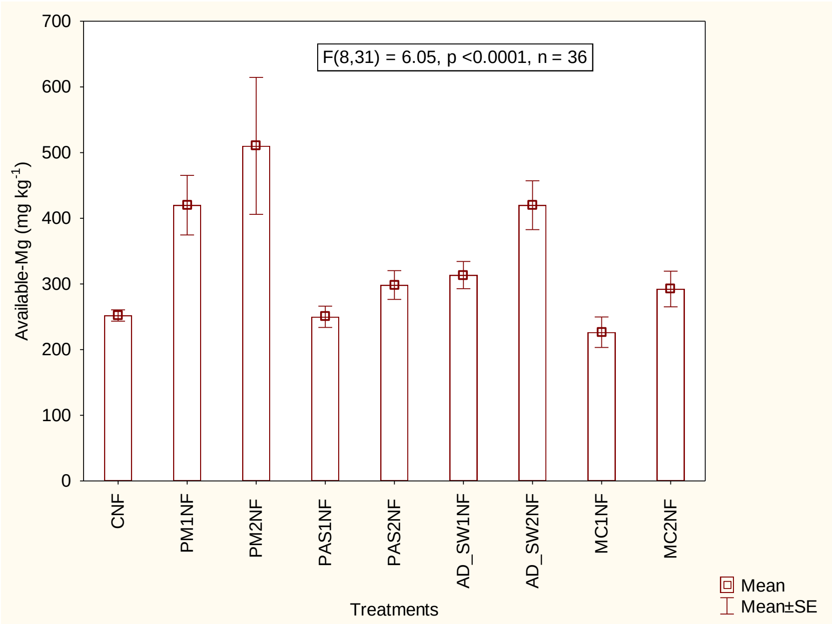


Figure 39 Effect of OA without inorganic fertilizer treatments on Available-Mg.

5.1.8.2 Available-Mg associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: Similar to the results obtained with OA treatment application without inorganic fertilizer, the PM1F recorded the highest Available-Mg (*circa* 430 mg kg^{-1}) and was significantly higher ($p < 0.05$) as compared with the CNF, CF, PAS1F, AD_SW1F and MC1F treatments (Figure 40). This is attributed to Available-Mg mineralization from the SOM by the soil microbes. The low Available-Mg in the CF treatment can be attributed to the K applied via the inorganic fertilizer which might have displaced the Mg cations on the exchange complex (Hull, 1998).

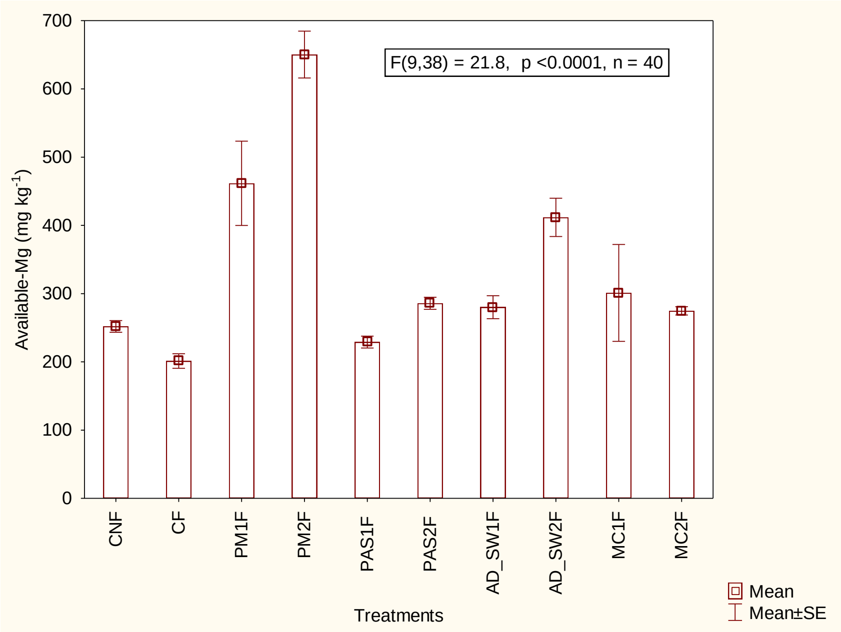


Figure 40 Effect of OA + inorganic fertilizer treatments on Available-Mg.

30 t ha^{-1}: With the exception of PAS2F and MC2F treatments, the OA treatments at 30 t ha^{-1} application rate had significantly higher Available-Mg as compared with the CNF treatment (Figure 40). The Available-Mg associated with the treatments is in the order: PM2F > AD_SW2F > PAS2F ≥ MC2F > CNF > CF. Again, this result is contrary to expectation considering the low Available-Mg associated with PM as compared with the AD_SW and MC OAs (Table 10, Section 3.3.1.2). This is attributed to microbial decomposition of SOM (Available-Mg mineralization from SOM) which is facilitated by the low C:N ratio associated with the PM OA (Table 10). Further, the significantly higher Available-K in the MC and AD_SW amendments can contribute to the low ($p < 0.05$) Available-Mg associated with the MC2F and AD_SW2F treatment as compared with the PM2F treatment due to Mg^{2+} displacement from the soil solution by the K^+ (Hull, 1998; McClellan *et al.*, 2014).

5.1.8.3 Application rates effect on Available-Mg:

For the OA without inorganic fertilizer treatments, increasing OA application rate resulted in a significant increase in Available-Mg with the exception of the

PM1NF and PM2NF treatments. This is attributed to the high variability within the treatment means.

Similarly, for the OA with inorganic fertilizer treatments**,** with the exception of MC, the results show that increase in OA application rates resulted in increase in the Available-Mg. Specifically, the PM2F, PAS2F and AD_SW2F treatments were 28.8%, 26.7% and 26.8% significantly higher ($p < 0.05$) as compared with PM1F, PAS1F and AD_SW1F treatments respectively. The high Available-Mg concentration associated with the OA treatments is expected to have significant effect on plant performance relative to the CNF treatment (See Chapter 7).

5.1.9 Effect of OA treatments on Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC) refers to the ability of the soil to retain and release soil nutrients. The application of OA is expected to significantly increase the soil CEC level as compared with the control treatments due to the presence of negative charges that are associated with SOM (Fact Sheet, 2007).

5.1.9.1 CEC associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1} and 30 t ha^{-1}: At both application rates the PM1NF, PAS1NF, AD_SW1NF and MC1NF treatments had no significant ($p < 0.05$) effect on the CEC as compared with the CNF treatment (Table 18, Section 5.1.10).

5.1.9.2 CEC associated with OA + inorganic fertilizer treatments

10 t ha^{-1} and 30 t ha^{-1} application rates: At both application rates, the CEC associated with the OA + inorganic fertilizer treatments were not significantly different ($p < 0.05$) as compared with the CNF treatment (Table 18, Section 5.1.10).

5.1.9.3 Application rates effect on CEC:

Contrary to expectation, increase in OA application rates had no significant effect on the CEC. The non-significant effect on the CEC at both rates may be attributed to low CEC associated with the OAs applied (though not measured) such that the rates at which the OA was applied were insufficient to affect the soil CEC. Maltas *et al.* (2013) reported a similar result after 12 years of OA application at 12 t ha^{-1} every year and 36 t ha^{-1} every three years. They found no significant effect on CEC with the OA treated plots as compared with the un-amended control plot. Cote and Ndayegamiye (1989) also found no significant effect on soil CEC with the application of 20 t ha^{-1} farm yard manure. However, at 40 t ha^{-1} and 60 t ha^{-1} application rates, significantly higher CEC as compared with the control was obtained. Soil pH is also an important factor affecting the soil CEC (Maltas *et al.*, 2013). This is because as pH decreases, the number of negative charges on the colloids increases; thereby decreasing soil CEC. Therefore, the non-significant effect on the soil CEC following OA application is due to the high pH levels (≥ 8.0) associated with the OA treatments.

5.1.10 Effect of OA treatments on Total-N

Most of the N in soil exists as organic-N which is not available for plant uptake (Figure 6Figure , Section 2.7.4). The Total-N indicates the amount of N (both the organic N and inorganic N) present in the soil. The availability of N contained in Total-N for plant uptake is generally affected by microbial activity (Lupwayi *et al.*, 2005). Therefore, since organic matter is a reservoir of nutrients (Morse, 2002), it is expected that OA application at both application rates with or without inorganic fertilizer addition will result in significantly higher ($p < 0.05$) Total-N as compared with the CNF treatment

5.1.10.1 Total-N associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: As anticipated, all OA treatments (PM1NF, PAS1NF, AD_SW1NF and MC1NF) were associated with significantly higher Total-N as compared with the CNF treatment (Table 18, Section 5.1.10). However, no significant difference in Total-N was observed between PM1NF, PAS1NF, AD_SW1NF and MC1NF.

Table 18 Treatment effect on chemical SQIs at Post-incubation

Treatments	CEC (cmol kg^{-1})	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	TOC (mg kg^{-1})	C:N	Bioavailable-TOC (%)	Total-P (mg kg^{-1})	Bioavailable-P (%)	C:P
Treatments without inorganic fertilizer									
CNF	19.6^{b}	190^{a}	560^{a}	0.480^{a}	3.06^{a}	0.07^{a}	1920^{a}	1.83^{a}	0.30^{a}
PM1NF	20.9^{b}	610^{cde}	4460^{b}	4400^{cd}	7.62^{b}	95.9^{c}	2320^{ab}	5.46^{gh}	2.01^{b}
PM2NF	19.3^{b}	1460^{gh}	13200^{cde}	12900^{cdef}	9.01^{bc}	95.2^{c}	3130^{cd}	9.31^{jk}	4.03^{de}
PAS1NF	19.5^{b}	520^{c}	4340^{b}	3970^{c}	9.28^{bc}	91.8^{c}	1970^{ab}	2.21^{abc}	2.23^{b}
PAS2NF	19.7^{b}	870^{f}	11200^{c}	11000^{cdef}	12.9^{e}	98.5^{c}	1973^{ab}	2.84^{cde}	5.67^{g}
AD_SW1NF	19.6^{b}	490^{c}	6060^{b}	5280^{cdef}	12.3^{e}	88.2^{c}	2010^{ab}	3.01^{de}	3.03^{bcd}
AD_SW2NF	17.0^{b}	1290^{gh}	19400^{f}	16900^{f}	15.1^{f}	88.1^{c}	2360^{abc}	8.48^{ij}	8.22^{h}
MC1NF	21.5^{b}	520^{cd}	5160^{b}	4570^{cde}	10.0^{cd}	88.4^{c}	1850^{a}	2.89^{cde}	2.62^{bc}
MC2NF	22.6^{b}	1320^{gh}	16400^{e}	14100^{def}	12.4^{e}	86.7^{c}	1960^{ab}	4.58^{fg}	8.80^{h}
Treatments with inorganic fertilizer									
CF	18.6^{b}	270^{b}	920^{a}	550^{b}	3.46^{a}	61.2^{b}	1950^{a}	2.16^{ab}	0.48^{a}
PM1F	22.1^{b}	770^{ef}	7300^{b}	6040^{cdef}	9.45^{c}	83.9^{c}	2180^{ab}	6.88^{hi}	3.63^{cde}
PM2F	18.6^{b}	1630^{h}	14200^{cde}	13300^{def}	8.76^{bc}	93.5^{c}	3210^{d}	10.8^{k}	4.44^{ef}
PAS1F	20.4^{b}	440^{c}	4250^{b}	3840^{c}	9.69^{c}	90.7^{c}	1900^{a}	2.46^{bcd}	2.27^{b}
PAS2F	14.6^{ab}	960^{fg}	12500^{cd}	10800^{cdef}	13.0^{e}	86.6^{c}	2010^{ab}	2.68^{bcd}	6.28^{g}
AD_SW1F	18.8^{b}	550^{cd}	5180^{b}	4060^{c}	9.61^{b}	78.8^{bc}	1890^{a}	3.21^{de}	2.76^{bc}
AD_SW2F	21.5^{b}	980^{fg}	12400^{cd}	11700^{cdef}	12.7^{e}	94.8^{c}	2230^{ab}	5.73^{gh}	5.57^{fg}
MC1F	18.9^{b}	840^{def}	7660^{b}	6960^{cdef}	9.37^{c}	91.2^{c}	2310^{ab}	2.46^{bcd}	3.10^{bcd}
MC2F	22.5^{b}	1320^{gh}	15200de	14400^{ef}	11.5^{de}	94.5^{c}	2550^{bc}	3.62^{ef}	6.33^{g}

For Tables 17-18; 20–21; 30-31: Means with the same letter(s) are not significantly different at 5% probability following a *post-hoc* Fisher LSD analysis.
CNF = control; CF = inorganic fertilizer only (applied at 50% recommended rate) ; PM1F = Poultry manure at 10 t ha^{-1} + Fertilizer; PM1NF = Poultry manure at 10 t ha^{-1} + No inorganic Fertilizer; PM2F = Poultry manure at 30 t ha^{-1} + Fertilizer; PM2NF = Poultry manure at 30 t ha^{-1} + No inorganic Fertilizer; PAS1F = PAS 100:2005 compliant compost at 10 t ha^{-1} + Fertilizer; PAS1NF = PAS 100:2005 compliant compost at 10 t ha^{-1} + No inorganic Fertilizer; PAS2F = PAS 100:2005 compliant compost at 30 t ha^{-1} + Fertilizer; PAS2NF = PAS 100:2005 compliant compost at 30 t ha^{-1} + No inorganic Fertilizer; AD_SW1F = Anaerobic digestate solid waste at 10 t ha^{-1} + Fertilizer; AD_SW1NF = Anaerobic digestate solid waste at 10 t ha^{-1} + No inorganic Fertilizer; AD_SW2F = Anaerobic digestate solid waste at 30 t ha^{-1} + Fertilizer; AD_SW2NF = Anaerobic digestate solid waste at 30 t ha^{-1} + No inorganic Fertilizer; MC1F = Mushroom compost at 10 t ha^{-1} + Fertilizer; MC1NF = Mushroom compost at 10 t ha^{-1} + No inorganic Fertilizer; MC2F = Mushroom compost at 30 t ha^{-1} + Fertilizer; MC2NF = Mushroom compost at 30 t ha^{-1} + No inorganic Fertilizer, n = 72.

30 t ha^{-1}: At the higher application rate, the Total-N in the PM2NF, PAS2NF, AD_SW2NF and MC2NF treatments was significantly (*circa* 300%) higher as compared with the CNF treatment. This corroborates the findings of Larney *et al*, 2011) and Moharana *et al.* (2012). Further, the results indicate that the PM2NF, AD_SW2NF and MC2NF treatments did not differ significantly in their Total-N but were significantly different ($p < 0.05$) from the PAS2NF treatment. This is due to the significantly higher Total-N associated with PM, AD_SW and MC OAs as compared with PAS (Table 10, Section 3.3.1.2).

5.1.10.2 Total-N associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: As anticipated, at 10 t ha^{-1} application rate, the PM1F, PAS1F, AD_SW1F and MC1F had 75.3, 56.8, 65.5 and 77.4% higher ($p < 0.05$) Total-N as compared with the CNF treatment, respectively. Further, the Total-N in the CF treatment was 30% higher ($p < 0.05$) as compared with the CNF treatment. This is due to the inorganic fertilizer addition. Further, the OA treatments had 38% higher Total-N compared with the CF treatment.

30 t ha^{-1}: Similarly, the PM2F, PAS2F, AD_SW2F and MC2F treatments gave significantly higher Total-N relative to CNF and CF treatments (Table 18, Section 5.1.10). These results corroborate the findings of other studies (Magdoff and Weil, 2004; Dijkstra *et al.*, 2013; Hewidy *et al.*, 2015).

5.1.10.3 Application rates effect on Total-N:

As anticipated, for all OA treatments tested, increasing OA application rate resulted in a concomitant increase in Total-N concentration.

5.1.11 Effect of OA treatments on Total-C and Total organic carbon (TOC)

Soil organic carbon (SOC) is the source of food and energy for soil microbes (Brady and Weil, 2010). As an index of SOM, SOC is also the major source of plant nutrients (Sparks, 2005). The SOC (measured in this study as TOC) is associated with different pools (such as: the labile, slow and inert pools) which have varying turnover rates, depending on the type of OAs and their stages of decomposition (Brady and Weil, 2010). The labile pool is classified as easily decomposed, organic C which are composed of freshly decomposing plant residues, animal remains and micro-organisms (Brady and Weil, 2010). According to Brady and Weil, (2010), the slow pool includes well decomposed OAs in the form of humus, while the inert pool is the organic fraction that is resistant to further breakdown, otherwise referred to as recalcitrant carbon. Hence, upon OA application, it is predicted that, the OA treatments will have significantly higher Total-C and TOC as compared with the CNF control treatment.

5.1.11.1 Total-C and TOC associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: As anticipated, the PM1NF, PAS1NF, AD_SW1NF and MC1NF treatments had a significantly higher Total-C and TOC as compared with CNF treatment (Table 18, Section 5.1.10). This is attributed to the effect of elevated Total-C and TOC in the OAs applied (Table 10, Section 3.3.1.2). However, no significant difference in the Total-C and TOC was observed between the OA treatments (PM1NF, PAS1NF, AD_SW1NF and MC1NF), even though the Total-C and TOC associated with the OAs applied (Table 10, Section 3.3.1.2) varied significantly. The non-significant effect observed is attributed to statistical 'noise' [within treatment variability] in the data generated (Table 18, Section 5.1.10). The results also indicate that the bioavailable-TOC (which is TOC expressed as percentage of Total-C) associated with the OA treatments did not differ significantly, but was significantly higher as compared with the CNF treatment (Table 18). This result confirms that the OA treatments were not significantly different in their TOC.

30 t ha^{-1}: The OA treatments had significantly ($p < 0.05$) higher Total-C and TOC as compared with the CF and CNF treatments. However, unlike with 10 t ha^{-1} application, these results show that the Total-C varied significantly across the OA treatments at higher (30 t ha^{-1}) application rates. For instance, the

AD_SW2NF treatment had the highest Total-C, which was significantly higher as compared with the PM2NF, PAS2NF and MC2NF treatments. This is due to the significantly higher OM content associated with the AD_SW amendment relative to all other OAs except for PM amendment (Table 10, Section 3.3.1.2). However, no significant difference in the TOC was observed between the PM2NF, PAS2NF, AD_SW2NF and MC2NF treatments. This is attributed to the high variability in the data which obscured PM2NF, PAS2NF, AD_SW2NF and MC2NF treatments from being statistically different (Table 18, Section 5.1.10). The bioavailable-TOC associated with these OA treatments did not differ significantly.

5.1.11.2 Total-C and TOC associated with OA + inorganic fertilizer treatments

The effect of OA treatments on the Total-C, TOC and bioavailable-TOC followed the same trend with the results obtained with OA without inorganic fertilizer treatments (Table 18). The CF treatment had significantly higher TOC compared with the CNF treatment. It is not mechanistically clear how the CF treatment is associated with higher ($p < 0.05$) TOC than the CNF treatment, since the CF treatment received no OA application. Study has shown that TOC associated with OAs (cattle manure, cattle manure-rice straw, cattle manure-wood shavings, and cattle manure-rice straw-wood shavings) incubated for two months was significantly higher as compared with the un-amended treatment, but did not vary significantly across the OAs (Mariaselvam *et al.*, 2014).

Long term (10 years) application of 10 t ha^{-1} cattle manure (5.5 g kg^{-1}) significantly increased the TOC as compared with the un-amended plots (3.4 g kg^{-1}) (Mando *et al.*, 2005). Sewage sludge municipal waste compost and vermicompost applied at 20 t ha^{-1} and 40 t ha^{-1} to silty clay soil significantly increased the TOC as compared with the control un-amended and inorganic fertilizer treatments. It was also reported that the TOC in the inorganic fertilizer treatment was significantly higher as compared with the control un-amended treatment (Gilani and Bahmanyar, 2008). According to the authors, increase in

TOC content with OA application was due to high organic C in this OAs and efficient metabolic activity of micro-organisms.

5.1.11.3 Application rates effect on Total-C and TOC:

The results show that increase in OA application rates significantly increased the Total-C but not the TOC. The non-significant difference in the TOC is attributed to the huge variance (statistical noise) between the 10 t ha^{-1} and 30 t ha^{-1} OA treatments (Table 18, Section 5.1.10).

These results further demonstrate the effectiveness of OAs in improving not only the Total-C content of a degraded soil but also the TOC and bioavailable-TOC content of soil, which are the key microbial energy sources required to drive SOM decomposition and recycling of nutrients (Figures 2, 5 and 6, Sections 2.3, 2.7.3 and 2.7.4) in the soil ecosystem (Gilani and Bahmanyar, 2008). This is supported by the significantly ($p < 0.01$) strong correlation ($r = 0.69$) between MB_C and TOC and $r = 0.56$ between MB_C and bioavailable-TOC measured for the OA treatments without inorganic fertilizer (Table 17, Section 5.1.2.2). The results suggest that increase in the soil C (Total-C, TOC and bioavailable-TOC) content with OAs application, will increase the MB_C (microbial population) (Table 17, Section 5.1.2.2) and will subsequently have a positive effect on plant performance (Table 17, Section 5.1.2.2).

5.1.12 **Effect of OA treatments on Total-P**

As an essential plant nutrient P is influenced by soil pH, soluble Al, Fe and Ca and SOM content (Mkhabela and Warman, 2005). Total-P is comprised of the organic and inorganic P. Inorganic P (Pi) according to Shen *et al.* (2011) accounts for 35% to 70% of Total-P in soil. However, the organic P fraction of Total-P can be released through mineralization processes (Figure 5, Section 2.7.3) mediated by soil organisms to increase soil Pi concentrations (Shen *et al.*, 2011). Following OA application, it is expected that the Total-P content of the OA treatments will be higher compared with the CNF treatment due to the inherently high Total-P associated with the OAs (Table 10, Section 3.3.1.2) and increased SOM content (Table 17, Section 5.1.2.2).

5.1.12.1 Total-P associated with OA (without inorganic fertilizer) treatments

10 t ha^{-1}: Contrary to expectation, no significant (p <0.05) difference in the Total-P content was observed between the OA treatments and CNF treatment (Table 18, Section 5.1.10). This suggests that the OAs applied at 10 t ha^{-1} was insufficient to have a marked effect on the Total-P. Although the Total-P was not significantly affected, the bioavailable-P (which is expressed as the percentage Olsen-P in Total-P) associated with the OA treatments differed significantly and were significantly higher than CNF treatment (Table 18, Section 5.1.10). This can suggest that the bioavailability of P is an important parameter relative to the Total-P concentration, since the bioavailable-P indicates the percentage Olsen-P in Total-P that is available for plant uptake. The result therefore suggests that OA treatments with higher bioavailable-P can have significant effect on plant growth and yield performance due to greater availability of P for plant uptake (See Chapter 7 for more discussion) and increased microbial biomass. This is evidenced by the significant (p <0.01) correlation (r =0.95, 0.68, 0.81, 0.81, 0.69, 0.80, and 0.63) that exist between bioavailable-P, P, K, Mg, Total-N, Total-P, SOM and MB_C, respectively (Table 17, Section 5.1.2).

30 t ha^{-1}: At 30 t ha^{-1} application rate, the Total-P associated with the PAS2NF, AD_SW2NF and MC2NF treatments did not differ significantly compared with the CNF treatment (Table 18, Section 5.1.10). In contrast, with the exception of AD_SW2NF, the PM2NF treatment had 63, 59, and 69% higher (p <0.05) Total-P compared with the CNF, PAS2NF, and MC2NF treatments, respectively. This is attributed to the high Total-P associated with the PM amendment, which increased with increase in OA application rates (Table 10, Section 3.3.1.2). The Total-P in the PM and AD_SW amendments did not differ significantly (Table 10, Section 3.3.1.2); this explains the non-significant effect on the Total-P observed between the PM2NF and AD_SW2NF treatments (Table 18, Section 5.1.10).

The results indicate that the bioavailable-P associated with the 30 t ha^{-1} OA treatments was significantly higher compared with the CNF treatment. The higher ($p < 0.05$) bioavailable-P in the OA treatments is attributed to the significantly higher C:P ratios associated with the OA treatments, which is evidenced by the significant correlation ($r = 0.53$) the C:P has with the bioavailable-P (Table 17, Section 5.1.2.2). Though a significant ($p < 0.05$) but weak correlation ($r = 0.38$) exists between the MB_C and Total-P, however, a significantly ($p < 0.01$) strong correlation ($r = 0.69$) was observed between the MB_C and bioavailable-P (Table 17, Section 5.1.2.2). This further suggests that the bioavailable-P is a more important indicator to consider than the Total-P content since the MB_C correlated ($r = 0.69$) strongly with the bioavailable-P than with Total-P ($r = 0.38$). This suggests that changes in the bioavailable-P following OA application can better reflect changes in the MB_C than the Total-P.

5.1.12.2 Application rates effect on Total-P:

OA treatment application rates had no significant ($p < 0.05$) effect on the Total-P across the treatments except for the PM2NF treatment which had a 35% higher ($p < 0.05$) Total-P concentration as compared with the PM1NF treatment.

5.1.12.3 Total-P associated with OA + inorganic fertilizer treatments

10 t ha^{-1}: The result also showed no significant difference in the Total-P between the OA + inorganic fertilizer treatments and the CNF treatment (Table 18, Section 5.1.10).

30 t ha^{-1}: However, at 30 t ha^{-1} application rate, the PM2F and the MC2F treatments had significantly higher Total-P as compared with the CF and CNF treatments. The Total-P content was in the order: PM2F > MC2F ≥ AD_SW2F ≥ PAS2F > CF = CNF. Similar to the results obtained with the 30 t ha^{-1} OA treatments without inorganic fertilizer, the PM2F treatment was associated with significantly higher Total-P as compared with all other OA treatments. This is due to the higher Total-P content in the PM amendment compared with the other amendments (Table 10, Section 3.3.1.2). Further, the OA treatments had significantly higher bioavailable-P compared with the CNF treatment. PM1F and

PM2F, respectively, were associated with significantly higher bioavailable-P compared with all other OA treatments.

As suggested earlier (Section 5.1.3), this present result is a testament that the PM amended treatments will be associated with significant positive effect on plant growth and development, since plants require sufficient P supply early on for adequate growth yield production by promoting plant root growth and hastening crop maturity (Mkhabela and Warman, 2005; Jin *et al.*, 2016) (See Chapter 7).

5.1.12.4 Application rates effect on Total-P:

With the exception of PM treatment, increase in OA treatment application rate was not associated with a significant increase in Total-P. This is due to earlier explained reasons.

As was with Olsen-P, having seen the OA treatments effects on the Total-P concentration, it is also important to know whether or not the OA treatments were supplying sufficient P to meet the P crop requirements based on RB209 recommendations (Table 9, Section 3.2.1). Total-P in the OA treatments applied at 10 t ha^{-1} did not vary significantly compared with CNF and CF treatments (Figure 41, Section 5.1.12.2). However, at 30 t ha^{-1} rate, the OA treatments were associated with significantly higher P supply than the CNF and CF treatments. The OA treatments supplied 56-76% more than the RB209 recommended P requirement via the Total-P concentration. The result also indicates that the PM2F treatment gave significantly higher P supply when compared with other treatments, except for PM2NF treatment. Therefore, depending on the soil microbes (types, population and microbial activities) associated with the OA treatments, this result suggests that more P will be available via microbial mineralization of the OAs (Figure 5, Section 2.7.3) and this will impact on plant P uptake and subsequently plant performance.

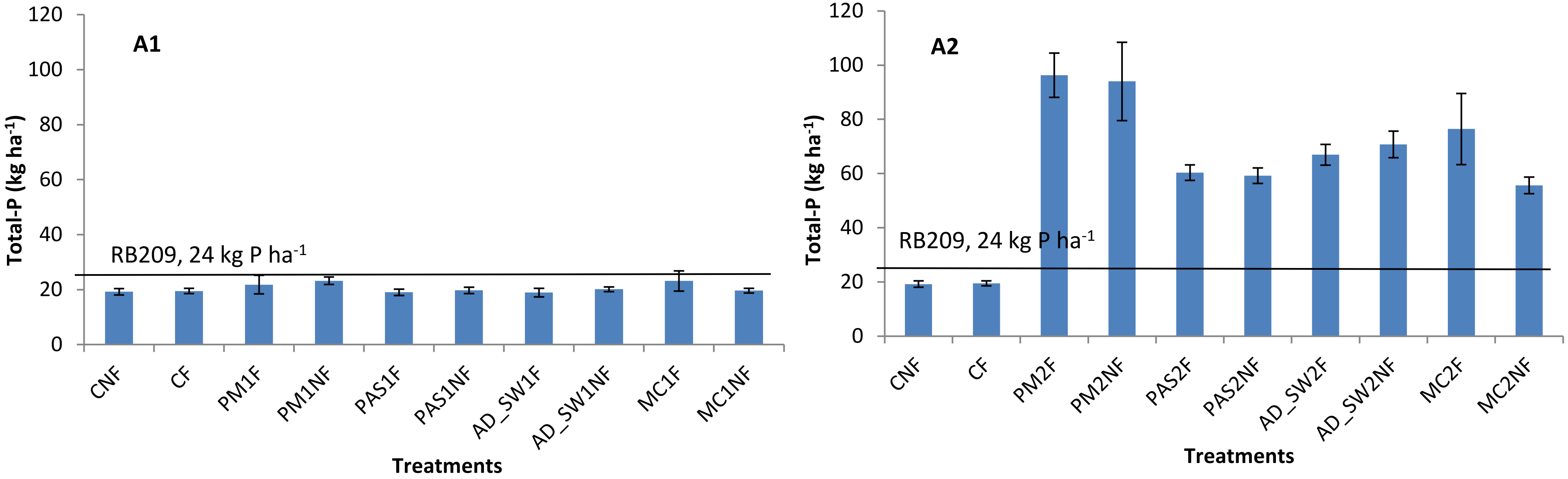


Figure 41 Amount of P as Total-P supplied via OA treatments across both application rates [A1 = 10 t ha^{-1}, A2 = 30 t ha^{-1}] as compared to the RB209 recommendation, n = 72.

5.1.13 Metal concentration associated with OA (without inorganic fertilizer)

Results of analysis indicated that Cr, Cd, Pb and Ni in the OAs were within the EC maximum permissible levels (Nicholson *et al.*, 2010), thus they are not discussed further. However, Cu and Zn are discussed because they are essential trace elements.

5.1.13.1 Organic amendment effects on Copper (Cu) concentration

There were significant differences in the Cu concentration across the treatments with or without inorganic fertilizer (Table 19, Section 5.1.13.2). The result shows that Cu concentrations in OAs with or without supplementary inorganic fertilizer were not significantly ($p < 0.05$) different compared with CNF treatment, except for PM2NF and PM2F which had higher ($p < 0.05$) Cu concentrations than CNF and all other OA treatments. The significantly higher Cu concentration in the PM2NF and PM2F treatments come from feed supplements that are often added to the poultry feedstock to improve poultry productivity (Rasnake, 2012).

5.1.13.2 Organic amendment effects on Zinc (Zn) concentration

The Zn concentration in OA treatments with or without inorganic fertilizer addition was not significantly ($p < 0.05$) different from the CNF treatment. Only PM1NF/2NF and PM1F/2F treatments had significantly ($p < 0.05$) higher Zn concentrations as compared with the CNF and all the other OA treatments. Like Cu, Zn is also poultry feed additives. Hence, the high Zn concentration associated with the PM amendment may probably be due to the poultry feedstocks which are fortified with micronutrients, especially Cu and Zn to boost the micronutrient levels of the poultry birds (Rasnake, 2012).

Table 19 Metal concentrations associated with the OA treatments (n = 72)

Treatments	Cu (mg kg^{-1})	Zn (mg kg^{-1})
OA treatments without inorganic fertilizer		
CNF	7.66^{bc}	90.3^{ab}
PM1NF	8.71^{c}	100^{c}
PM2NF	13.9^{d}	113^{d}
PAS1NF	8.11^{bc}	93.7^{abc}
PAS2NF	8.46^{bc}	87.2^{ab}
AD_SW1NF	7.41^{abc}	87.1^{ab}
AD_SW2NF	7.46^{abc}	90.2^{abc}
MC1NF	7.76^{abc}	86.8^{ab}
MC2NF	7.51^{abc}	90.1^{abc}
OA treatments with inorganic fertilizer		
CF	6.36^{a}	88.9^{ab}
PM1F	9.11^{c}	93.1^{abc}
PM2F	14.5^{d}	117^{d}
PAS1F	8.01^{bc}	93.3^{abc}
PAS2F	9.36^{c}	95.1^{bc}
AD_SW1F	6.76^{ab}	89.1^{ab}
AD_SW2F	7.51^{bc}	84.3^{a}
MC1F	7.81^{bc}	86.9^{ab}
MC2F	9.01^{c}	96.4^{bc}

Table 20 Summarized effects of OA treatment application on soil nutrients and SOM content at post-incubation (n = 72)

Treatments	TON	NH_4-N	Olsen-P	Available-K	Available-Mg (mg kg^{-1})	Zn	Cu	Total-N	Total-P	SOM (%)
OA treatments without inorganic fertilizer										
CNF	x	x	x	x	x	x	x	x	x	x
PM1NF	↗	↗	↗	↗	↗	↗	ns	↗	ns	↗
PM2NF	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
PAS1NF	ns	ns	↗	↗	ns	ns	ns	↗	ns	↗
PAS2NF	ns	ns	↗	↗	↗	ns	ns	↗	ns	↗
AD_SW1NF	↗	↗	↗	↗	↗	ns	ns	↗	ns	↗
AD_SW2NF	↘	ns	↗	↗	↗	ns	ns	↗	ns	↗
MC1NF	↗	ns	↗	↗	ns	ns	ns	↗	ns	↗
MC2NF	↗	↗	↗	↗	↗	ns	ns	↗	ns	↗
OA treatments with inorganic fertilizer										
CF	↗	↗	↗	↗	↘	ns	↘	↗	ns	↗
PM1F	↗	↗	↗	↗	↗	ns	ns	↗	ns	↗
PM2F	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
PAS1F	ns	ns	↗	↗	↘	ns	ns	↗	ns	↗
PAS2F	ns	ns	↗	↗	↗	ns	ns	↗	ns	↗
AD_SW1F	↗	↗	↗	↗	↗	ns	ns	↗	ns	↗
AD_SW2F	↗	↗	↗	↗	↗	ns	ns	↗	ns	↗
MC1F	↗	ns	↗	↗	↗	ns	ns	↗	↗	↗
MC2F	↗	↗	↗	↗	↗	ns	ns	↗	ns	↗

x = is the chemical SQIs values measured for CNF, ↗ = significantly higher relative to the CNF, ns = not significant relative to the CNF; ↘ = significantly lower relative to the CNF.

5.1.14 Summary:

EC

- With the exception of PAS treatments, all the other OA treatments with or without inorganic fertilizer addition had significantly higher EC than CNF treatment. This is due to the inherently high EC level that is associated with these OAs [PM, AD_SW and MC].
- Increasing OA treatment application rates with or without inorganic fertilizer addition significantly increased the EC level, particularly for PM and MC treatments.
- The MC treatments with or without inorganic fertilizer addition consistently had the highest EC level as compared with the other OAs, but the EC was within the permissible soil EC level (Ayers and Westcott, 1985; White, 2006).

pH

- Except for PAS1NF treatment, the AD_SW1NF, MC1NF and PM1NF treatments had a significantly lower ($p < 0.05$) soil pH compared with the CNF treatment.
- The MC2NF and MC2F treatments were associated with significantly lower pH as compared with all the other treatments. This is due to the significantly high EC associated with MC at higher (30 t ha^{-1}) application rate.
- Compared with the other OA treatments, the higher rates of MC amendment significantly lowered pH. This OA can be useful for alkaline soils in reducing P fixation by calcium carbonates (Figure 5, Section 2.7.3).
- With the low Olsen-P level in PAS amendment, the high pH associated with PAS1NF/2NF and PAS1F/2F treatments can further lower Olsen-P availability due to P fixation by calcium carbonate.

Olsen-P

- The OA treatments with or without supplementary inorganic fertilizer increased ($p < 0.05$) the Olsen-P concentration as compared with the CNF treatment.
- Increase in the Olsen-P concentration was more pronounced in the PM treatments at both application rates relative to the other OA treatments. The result indicates that addition of OA affected the soil P-pool.
- Higher rates [30 t ha^{-1}] of OA application had significantly higher Olsen-P levels than OA applied at lower [10 t ha^{-1}] rates.
- It is postulated that the Olsen-P associated with the OA treatments will have greater effect on maize crop growth and yield performance compared with CNF due to higher P availability for plant uptake (See Chapter 7).

TON

- The OA treatments with the exception of PAS significantly increased ($p < 0.05$) TON concentration as compared with the CNF treatment, especially for the PM and MC amended treatments at both application rates with or without inorganic fertilizer addition.
- The PAS treatments with or without inorganic fertilizers were associated with significantly low TON compared with all other OA treatments, with the exception of AD_SW2NF treatment.
- The AD_SW2NF treatment had significantly lower TON than all other treatments. As explained earlier, this was due to N immobilization (Figure 6, Section 2.7.4) due to the significantly high C:N ratio associated with AD_SW amendment (Table 10, Section 3.3.1.1).

NH_4-N

- OA application significantly increased the NH_4-N concentration as compared with the CNF treatment, especially the PM treatments at both application rates with or without inorganic fertilizer addition.

- NH_4-N concentration in MC treatment was significantly higher compared with the CNF treatment only at higher OA application rate.
- NH_4-N in PAS treatment at both application rates with or without inorganic fertilizer addition was not significantly different from CNF treatment. This is due to the inherently low NH_4-N associated with the PAS OA (Table 10, Section 3.3.1.2).
- The inherently low NH_4-N in the PAS treatments relative to all the other OA treatments can have a significant effect on N availability and can affect maize plant performance (See Chapter 7 for more discussion).

SOM

- OA treatments had significantly higher SOM than the CNF treatment.
- Across the OA treatments, increasing OA application rate significantly increased the SOM compared with the CNF and CF treatments.
- Higher (30 t ha^{-1}) OA treatment application rates had over 35% significantly higher SOM as compared with lower OA treatment rates [10 t ha^{-1}].

Available-K

- OAs at either application rates with or without inorganic fertilizer addition increased the soil Available-K content as compared with the CNF treatment.
- Except for MC2F, AD_SW2F treatment had higher ($p < 0.05$) Available-K than the other OAs treatments due to the inherently high Available-K associated with the AD_SW amendment.
- Across the treatments with or without inorganic fertilizer addition, increasing OA treatment application rates from 10 t ha^{-1} to 30 t ha^{-1} increased the Available-K by 27-55%.
- It is postulated that maize grown in the OA treatment will outperform (i.e. will have higher biomass and cob yield) that grown in the CNF treatment, due to greater nutrient provisioning (See Chapter 7).

Available-Mg

- At both application rates with or without inorganic fertilizer addition, the OA treatments had significantly higher Available-Mg than the CNF treatment (except for PAS1NF/1F and MC1NF).
- With the exception of PAS1F treatments, following inorganic fertilizer addition, all the OA treatments had higher ($p < 0.05$) Available-Mg relative to CF and CNF treatments.
- Available-Mg in MC2F was not significantly different compared with MC1F treatment.

Total-N

- OAs applied at both rates with or without inorganic fertilizer significantly increased the Total-N by more than 38 and 50% compared with the CF and CNF and treatments, respectively.
- CF treatment had 30% higher ($p < 0.05$) Total-N than the CNF treatment.
- It is suggested that increase in Total-N with OA application will have a positive effect on N availability for plant uptake since soil microbes are responsible for OA mineralization (decomposition) to release organically bound N contained in the Total-N (Figure 6, Section 2.7.4).
- It is hypothesized here that the OA treatments will have a significant impact on biological SQIs and plant performance compared with the CNF treatment due to increased Total-N concentration [Figure 4, Section 2.10] (See Chapters 6 and 7).

Total-C and TOC

- Application of OAs significantly increased the Total-C, TOC, and bioavailable-TOC compared with the CNF and CF treatments. This is attributed to high Total-C and TOC inherent in the OAs applied.
- OA treatment at 30 t ha^{-1} application rates had significantly higher Total-C than the 10 t ha^{-1} OA treatment.
- For the TOC, increasing OA treatment application rates did not significantly increase the TOC.

Total-P

- At 10 t ha^{-1}, with or without inorganic fertilizer addition, the Total-P concentration in the OA treatments was not significantly higher compared with the CNF treatment.
- A similar trend was observed for the OA treatments applied at 30 t ha^{-1} rates, except for the PM2NF and PM2F treatments which had significantly higher Total-P as compared with all other treatments.
- The Total-P did not differ significantly across the OA treatments, except for the PM treatments.
- The bioavailable-P associated with the OA treatments varied significantly across the OA treatment; with the PM treatments having the highest ($p < 0.05$) bioavailable-P compared with all other OA treatments.
- Except for AD_SW2NF, with the high ($p < 0.05$) Total-P and bioavailable-P associated with the PM2NF/2F treatments, it is postulated that the PM treatments will be associated with significantly greater positive effects on the plant permanence (growth, biomass, cob yield) compared with other OA treatments, as explained earlier.
- With the high Total-P associated with the OA treatments, it is suggested that the soil microbes will mineralize it, making P (Olsen-P) available for plant uptake.

Metals

- With the exception of 30 t ha^{-1} PM treatments, all other OA treatments application at both application rates with or without inorganic fertilizer addition had no effect on the Cu concentration compared with the CNF treatment.
- Only the PM treatments had significantly higher Zn concentrations compared with the CNF treatment.
- All metal concentrations associated with the OA treatments at both application rate with or without inorganic fertilizer were below the EU

Maximum Permissible levels. This suggests that the rates of OAs applied are not potential metal pollution hazards (Nkoa, 2014).

Overall, the results demonstrate that potency of OAs in improving the chemical SQIs of a degraded soil.

5.1.15 Conclusions:

Across the types and rates of OAs applied, the results indicate that, in general, the OA treatments had significant positive effects on the SQIs measured. Increasing application rate in general resulted in a concomitant increase in the SQI measured. This demonstrates the potency of OAs in improving the soil nutrients and SOM content of a degraded soil, as summarized in Table 20. Based on the results obtained, at either application rates and with or without inorganic fertilizer addition, the OA treatments, particularly the PM treatment, are expected to have greater positive effects on the crop performance as compared with the CNF treatment.

6 RESULTS AND DISCUSSION – Effect of OAs on Biological SQIs

The soil microbial biomass is essential for nutrient cycling in the agro-ecosystems (Figures 5 and 6, Sections 2.7.3 and 2.7.4) (Lupwayi *et al.*, 2005; Hu *et al.*, 2011; Cao *et al.*, 2016). Soil management practices strongly affect the size and diversity of the microbial biomass pool (Masto *et al.*, 2006). Soil microbial biomass and microbial activity have been regarded as useful indicators of soil health, because these indicators are sensitive to changes in soil management practices (Zhen *et al.*, 2014). Despite the important functions soil microbes play in the soil, it has been reported that some of the soil micro-organisms can be functionally redundant; that is to say, such soil microbes only add to the microbial population, but are unable to carry out their microbial functions or activities (Cao *et al.*, 2016).

Adequate microbial populations, abundant bio-diversity, and high activity of micro-organisms are important factors needed to maintain a sustainable ecosystem (Hu *et al.*, 2011). Microbial biomass carbon (MB_C) and microbial respiration (MResp) are fundamental microbial properties and are affected by many factors present in the soil environment, such as pH, SOM, TOC, temperature, moisture status and presence/absence of soil nutrients (Godley, 2007). The addition of animal manure and NPK fertilizer considered as a source of SOM enrichment, increases soil biological activity (Naveed *et al.*, 2014). Therefore, in this study, the OA treatments are expected to have a significantly more active (as measured by microbial respiration, microbial and metabolic quotients) and larger microbial community (as measured by MB_C) relative to the control treatment due to increased SOM, TOC content and soil nutrients [specially NPK] (Table 17, Section 5.1.2.2).

6.1.1 Effect of OA (without inorganic fertilizer) treatments on soil microbial biomass carbon (MB_C)

10 t ha^{-1}: As expected, the OA treatments (PM1NF, PAS1NF, AD_SW1NF and MC1NF) had significantly higher MB_C as compared with CNF (Figure 42).

PM1NF and AD_SW1NF recorded the highest MB_C being >94%, >70% and >77% higher as compared with CNF, PAS1NF and MC1NF, respectively.

30 t ha^{-1}: Similar to the 10 t ha^{-1} results, the MB_C in PM2NF, PAS2NF, AD_SW2NF and MC2NF were significantly higher when compared with the CNF treatment. This is due to the increased SOM, TOC and nutrients [N (Total-N, TON and NH_4-N), P (Olsen-P and Total-P), K and Mg] supplied via the OAs which provided the microbiology with nutrient and energy requirements. This is evidenced by the highly significant correlations (r = 0.59 and 0.69) between MB_C and SOM, and TOC respectively; and between MB_C and Total-N, TON, NH_4-N, Olsen-P, Total-P, and K (r = 0.70, 0.38, 0.58, 0.57, 0.38 and 0.49), respectively (Table 17, Section 5.1.2.2).

This result corroborates the findings of Vinhal-Freitas *et al.* (2010). Further, the MB_C level was in the order: PM2NF > AD_SW2NF = MC2NF > PAS2NF > CNF. Relative to the OA treatments, the PAS2NF was associated with the lowest MB_C. This is attributed to in insufficient nutrients (N (TON, NH_4-N and Total-N), P (Olsen-P and Total-P), K and Mg) and significantly lower SOM and TOC contents that is associated with the PAS amendment (Table 10, Section 3.3.1.2).

As shown in Table 10 (Section 3.3.1.2), the OAs were associated with not only a variable C content but also a high N content in the forms of TON, NH_4-N and Total-N. The C and N content of the OAs can be used as an energy and nutrient sources for soil micro-organisms and can contribute to the significant increases in MB_C (Figure 42). These results are in the agreement with results obtained by Lee *et al.* (2004), who reported that the addition of OAs (food waste compost) increased MB_C.

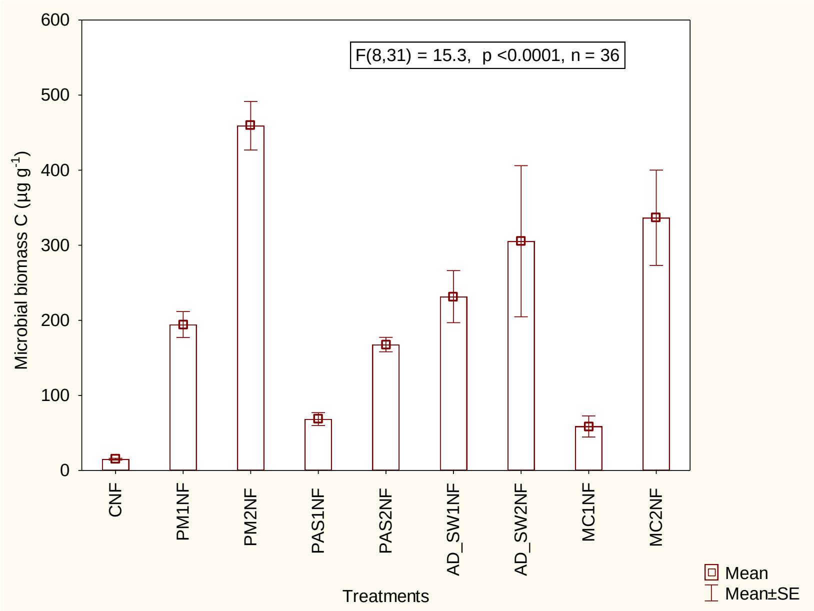


Figure 42 Effect of OA without inorganic fertilizer treatments on soil MB_C.

The significantly lower MB_C recorded for the CNF treatment confirms that the CNF treatment is 'microbially' compromised. The inherently low NPK content of the test soil (Table 6, Section 3.2) suggests that the NPK are not adequate to support biological activity without OA addition. The influx of microbial loads inherent in the added OAs (Table 10, Section 3.3.1.2) contributed to an increase in the MB_C associated with the OA treatments. Blagodatsky *et al.* (2000) attributed increases in soil MB_C to the incorporation of easily degradable materials (which stimulate the autochthonous microbial activity) and the incorporation of exogenous micro-organisms.

The higher MB_C reflects higher microbial activities (Tejada *et al.*, 2006). According to Ramesh *et al.* (2009) an increase in MB_C upon OA (organic manures) application was linked to increased substrate carbon availability which stimulated microbial growth. The authors also linked the increase in MB_C to the direct effect of the micro-organisms added via the application of compost.

6.1.2 Effect OA + inorganic fertilizer treatment on soil MB_C

10 t ha^{-1}: The MB_C associated with the OAs + inorganic fertilizer followed a similar trend as was observed for the OA without inorganic fertilizer treatments (Section 6.1.2). All the amended treatments showed significantly higher MB_C when compared with the CNF and CF treatments (Figure 43). This is due to the effect of added OAs with enriched the soil with carbon (SOM, Total-C, and TOC) and nutrients [N (Total-N, TON and NH_4-N), P (Olsen-P and Total-P), K and Mg] supplied via the OAs (Table 10, Section 3.3.1.2).

The AD_SW1F treatment recorded a relatively higher (320 mg kg^{-1}) MB_C and was 93.8, 92.2, 84.8, and 88% significantly ($p < 0.05$) higher as compared with the CNF, CF, PAS1F, and MC1F treatments, respectively. However, although the AD_SW1F treatment had 42.4% higher MB_C than the PM1F both treatments were statistically the same. This is due to the high degree of variance within and between the AD_SW1F and PM1F treatments.

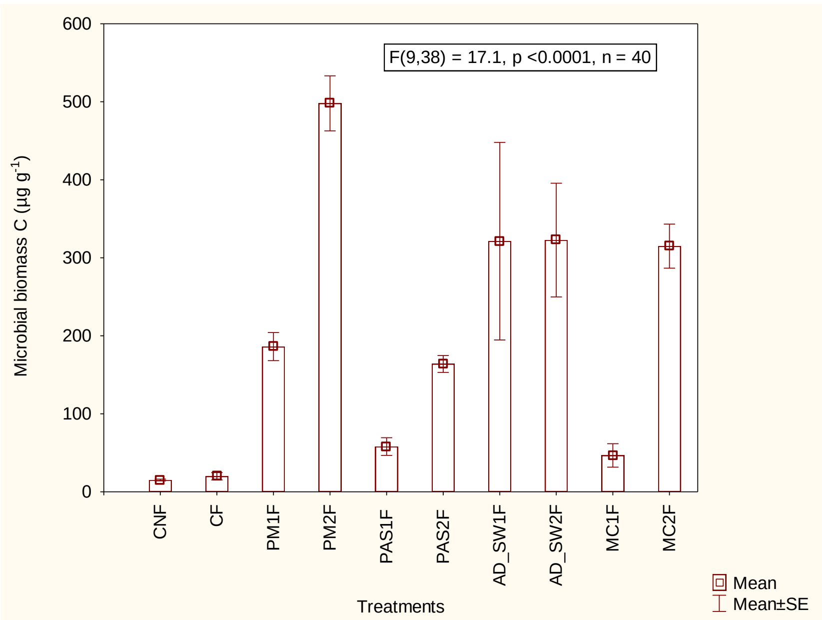


Figure 43 Effect of OA + inorganic fertilizer treatments on soil MB_C.

30 t ha^{-1}: The results show that MB_C in the PM2F, PAS2F, AD_SW2F and MC2F treatments were significantly higher as compared with the CNF and CF treatments. The MB_C level was in the order PM2F > AD_SW2F ≥ MC2F > PAS2F > CF = CNF treatments.

6.1.3 Application rates effect on MB_C:

For both with and without inorganic fertilizer OA treatments, MB_C increased with increased OA application rate. The MB_C in the PM2NF/F, PAS2NF/F and MC2NF/F treatments was 56-62%, 67-72% and 85-87% higher ($p < 0.05$) than that in the PM1NF/F, PAS1NF/F and MC1NF/F treatments, respectively. However, the MB_C associated with the AD_SW2NF/F and AD_SW1NF/F treatments did not differ significantly. This is due to the high degree of variance within and between the treatments (Figure 43). Further, the high C:N ratio associated with the AD_SW amendment (Table 10, Section 3.3.1.2) can contribute to the non-significant difference in the MB_C observed between AD_SW2NF/F and AD_SW1NF/F treatments, due to nutrient immobilization and competition for available nutrients by the soil microbes (Spohn, 2014).

6.2 Effect OA treatments on soil microbial biomass quotient (C_{mic}:C_{org})

The soil microbial biomass quotient (C_{mic}:C_{org}) as an indicator of microbial stress (Godley, 2007) has also been associated with the effectiveness of the soil microbes in utilizing C resources (Wardle and Ghani, 1995). Thus, it is expected that application of OA will reduce microbial stress (increase C_{mic}:C_{org}) and enhance microbial growth.

6.2.1 Soil C_{mic}:C_{org} associated with OA without inorganic fertilizer treatments

10 t ha^{-1} and 30 t ha^{-1}: As anticipated, the OA treatments at either application rates had more than 65% higher ($p < 0.05$) C_{mic}:C_{org} as compared with the CNF treatment (Table 21). This is due to the high supply of C and nutrients (N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg) via the OAs applied.

Although PAS was associated with low nutrient content for adequate crop production (Table 10, Section 3.3.1.2.), however these nutrients were sufficient to boost the microbial growth and activities (Table 17, Section 5.1.2.2). The significantly lower C_{mic}:C_{org} in the CNF confirms that the test soil is nutrient (N [TON, NH_4-N], P [Olsen-P], K and Mg) depleted and can further explain the lower MB_C associated with the CNF treatment (Figure 42 and 43). Further, with the exception of MC1NF/2NF treatments, higher OA treatments application rates was not associated with increase in the C_{mic}:C_{org} as compared with lower OA treatment rates C_{mic}:C_{org}. This suggests that application of OA at either rate provided sufficient nutrients (N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg) for soil microbes. (Table 17, Section 5.1.2.2).

6.2.2 Soil C_{mic}:C_{org} associated with OA + inorganic fertilizer treatments

10 t ha^{-1} and 30 t ha^{-1} rate

Similar to OA treatments alone, the C_{mic}:C_{org} associated with the OA treatments with inorganic fertilizer addition were >30% higher ($p < 0.05$) as compared with CNF and CF. This is due to above explained reasons. This suggests that stress due to insufficient nutrient supply contributed to the lower MB_C obtained (Table 16, Section 5.1.2.2).

Table 21 Effect OA treatments on the microbial biomass quotient (n = 72)

Treatments	C_{mic}:C_{org} (%)
OA treatments without inorganic fertilizer	
CNF	0.07^{a}
PM1NF	0.62^{def}
PM2NF	1.08^{f}
PAS1NF	0.24^{bc}
PAS2NF	0.42^{cd}
AD_SW1NF	0.70^{def}
AD_SW2NF	0.63^{de}
MC1NF	0.20^{b}
MC2NF	0.77^{def}
OA treatments with inorganic fertilizer	
CF	0.09^{a}
PM1F	0.57^{def}
PM2F	0.95^{ef}
PAS1F	0.21^{b}
PAS2F	0.40^{cd}
AD_SW1F	0.77^{ef}
AD_SW2F	0.84^{def}
MC1F	0.13^{b}
MC2F	0.68^{def}

6.2.3 Summary

As an important and active component of the soil, the MB_C regulates the transformation and storage of nutrients in the soil [Figures 5 and 6, Sections 2.7.3–2.7.4] (Moharana *et al.*, 2012). The results of this study indicate that:

- Two weeks after OA application, the soil MB_C was for all OA treatments >50% higher as compared with CNF.
- With the exception of AD_SW treatments, increasing OA application rates with or without inorganic fertilizer addition significantly increased the MB_C.
- OA treatment application increased the C_{mic}:C_{org} (reduced microbial stress) due to increased supply of C (SOM, TOC, and Total-C) and nutrients (N[TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg) (Table 17, Section 5.1.2.2).

- The C_{mic}:C_{org} increased with increase in OA application rates (Table 21).

6.2.4 Conclusions

This demonstrates the potentials of OAs in improving the biological health of a degraded soil with or without inorganic fertilizer addition. The increase in the MB_C will influence the nutrient and P cycling processes (Figures 5 and 6) via OA decomposition, which will affect the release of nutrients N (Total-N, TON and NH_4-N), P (Olsen-P and Total-P), K and Mg) for plant uptake (Table 16, Section 5.1.2.2) which invariably will affect plant performance (See Chapter 7).

7 RESULTS AND DISCUSSION – Effect of OAs on Plant Performance

7.1 OA treatment effects on plant growth performance

Inorganic fertilizers and/or OAs provide essential nutrients required to improve plant growth and higher crop yield. OAs can have significant effects on plant height (Srivas and Singh, 2004; Carpici and Celik, 2010; Ahmadi *et al.* 2014), leaf numbers (Srivas and Singh, 2004), girth [stem diameter] (Carpici and Celik, 2010), biomass (Maltas *et al.*, 2013; Yang, Sun and Zhang, 2014), and cob yields (Leroy *et al.*, 2007; Maltas *et al.*, 2013). Thus, following the observed positive effects of OAs (with and without inorganic fertilizer on the physical, chemical and biological SQIs (Chapters 4, 5 and 6), it is expected that crop performance (plant height, number of leaves, stem diameter; biomass [above ground (AG_{DB}), below ground (BG_{DB}) and cob yields [DW]) on OA amended soil will outperform those grown in the un-amended control (CNF) treatment.

7.1.1 Effect of OAs (without inorganic fertilizer) treatments on number of plant leaves at 2-7 weeks after planting

The mean number of leaves per plant did not vary significantly across the treatments at 2 weeks after planting (2 WAP) (Figure 44). This suggests that the maize plants relied on the food reserves in the maize seed and external nutrient supply (i.e. from the OAs) had little or no effect on plant leaf number (Grant *et al.*, 2001). At 2WAP the undeveloped root system is not capable of taking up plant nutrients.

Beyond 2 WAP, the OA treatments (PM1NF, PM2NF, AD_SW1NF, AD_SW2NF, MC1NF, and MC2NF) had significantly higher numbers of plant leaves as compared with the CNF treatment. As predicted in Chapter 5, this is due to the higher soil nutrient content (NPK, Mg) (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8), and increased SOM content (Figure 31, Section 5.1.6) and bioavailable-P (Table 18, Section 5.1.9.2) associated with the OA treatments (except for PAS treatments). This is shown by the significant correlation between soil nutrients and number of plant leaves (Table 22, Section 7.1.1). Further, the significant effects on the physical and biological SQIs [Chapters 4 and 6] (such as lower BD, increased porosity, higher WC_{FC}, AWC, higher MB_C, C_{mic}:C_{org}) associated with OA application can contribute to the significantly higher number of plant leaves obtained. This is because a lower soil BD will allow the plant roots to develop and exploit available nutrients released by the soil microbes through mineralization (Figures 5 and 6, Section 2.7.3-2.7.4) resulting in increased number of plant leaves (Table 22, Section 7.1.1).

In contrast to *a priori* expectations, the PAS1NF and PAS2NF treatments had a significantly lower number of plant leaves as compared with all other OA treatments (but this was not significantly different from the CNF treatment, Figure 44). This is attributed to the inherently low nutrient (NPK and Mg) availability and SOM associated with the PAS treatments (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8). This is also due to the lower P and K nutrient supply associated with PAS treatments as compared with the other OA treatments (Figures 28 and 38, Sections 5.1.3 and 5.1.7). Five WAP and beyond is a critical period in maize plant growth, as the crop has high nutrient (especially N) and water requirements. Therefore, nutrient deficiency during this period can adversely affect plant performance (Baligar *et al.*, 2001; Roberts, 2008). It is evident that with the exception of the PAS treatments, the OAs consistently maintained significantly higher numbers of plant leaves (Figure 44) as compared with the CNF treatment. As explained above, this indicates that the PAS1NF and PAS2NF treatments are associated with low nutrient levels, especially NPK and Mg (Tables 10 and 22, Sections 3.3.1.1 and 7.2.1; Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8).

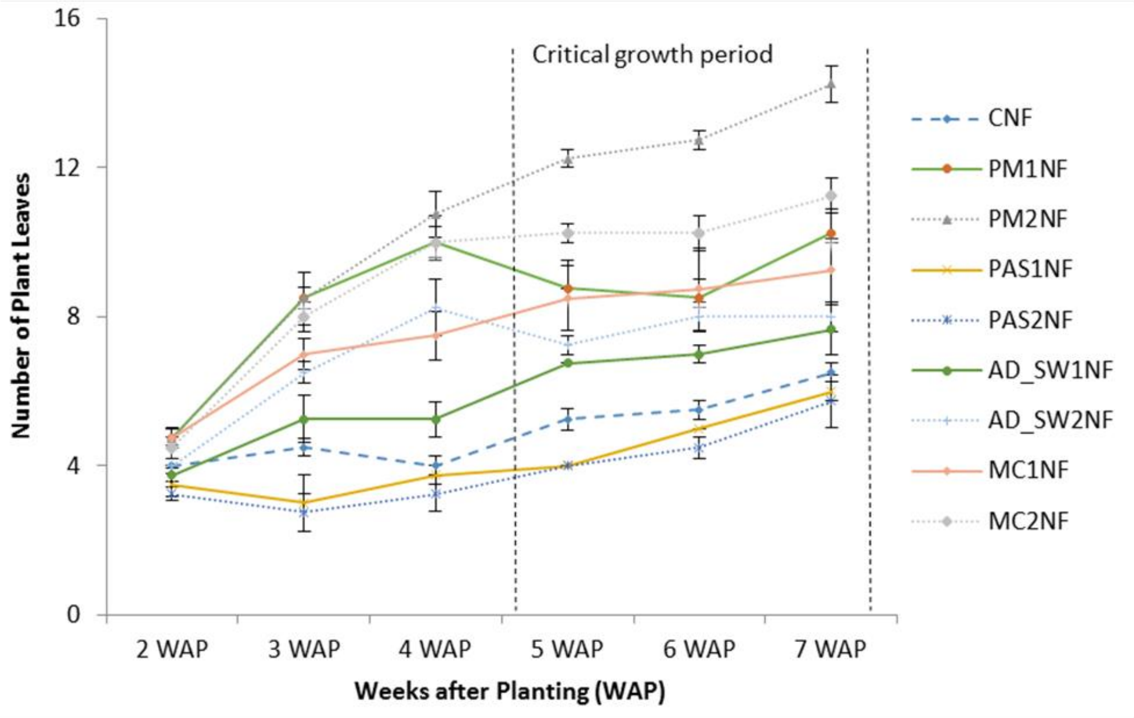


Figure 44 Effect of OA (without inorganic fertilizer) treatments on the number of plant leaves at 2-7 WAP

Vertical (error) bars denote +/-1 standard error of the mean at 5% probability following a *post-hoc* Fisher LSD analysis, n = 72.

Table 22 Correlation coefficients between SQIs, stem diameter, number of plant leaves, and plant height at 2-7 WAP

	Stem diameter (mm)					Number of plant leaves					Plant height (cm)				
	3 WAP	4 WAP	5 WAP	6 WAP)	7 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
	OA treatments without inorganic fertilizer														
Olsen-P (mg kg^{-1})	0.42*	0.58*	0.58*	0.62*	0.64*	0.51*	0.58*	0.57*	0.59*	0.63*	0.33*	0.54*	0.54*	0.57*	0.54*
TON (mg kg^{-1})	0.58*	0.59*	0.52*	0.58*	0.62*	0.66*	0.60*	0.68*	0.58*	0.62*	0.50*	0.57*	0.57*	0.59*	0.55*
NH4-N (mg kg^{-1})	0.18^{ns}	0.26^{ns}	0.34*	0.31^{ns}	0.37*	0.29^{ns}	0.34*	0.45*	0.42*	0.50*	0.08^{ns}	0.16^{ns}	0.24^{ns}	0.28^{ns}	0.25^{ns}
Available-K (mg kg^{-1})	0.32*	0.50*	0.56*	0.50*	0.48*	0.41*	0.53*	0.39*	0.41*	0.28^{ns}	0.49*	0.49*	0.51*	0.51*	0.49*
Available-Mg (mg kg^{-1})	0.36*	0.48*	0.51*	0.51*	0.49*	0.46*	0.43*	0.42*	0.41*	0.49*	0.24^{ns}	0.49*	0.45*	0.49*	0.46*
SOM (%)	0.24^{ns}	0.44*	0.48*	0.47*	0.46*	0.34*	0.50*	0.39*	0.42*	0.36*	0.27^{ns}	0.38*	0.41*	0.45*	0.43*
Total-N (mg kg^{-1})	0.38*	0.55*	0.56*	0.55*	0.57*	0.45*	0.60*	0.56*	0.58*	0.56*	0.36*	0.49*	0.49*	0.53*	0.52*
TOC (mg kg^{-1})	0.27^{ns}	0.44*	0.48*	0.43*	0.45*	0.34*	0.49*	0.42*	0.45*	0.41*	0.30^{ns}	0.38*	0.40*	0.42*	0.43*
Total-P (mg kg^{-1})	0.35*	0.46*	0.43*	0.46*	0.51*	0.43*	0.45*	0.47*	0.44*	0.49*	0.21^{ns}	0.43*	0.41*	0.44*	0.40*
MB_C (µg g^{-1})	0.44*	0.56*	0.61*	0.56*	0.60*	0.53*	0.60*	0.64*	0.67*	0.67*	0.33*	0.47*	0.51*	0.53*	0.54*
Bioavailable-P (mg kg^{-1})	0.46*	0.63*	0.65*	0.66*	0.67*	0.55*	0.63*	0.58*	0.61*	0.62*	0.41*	0.58*	0.60*	0.62*	0.60*
C_{min}:C_{org}	-0.25^{ns}	-0.37*	-0.34*	-0.31^{ns}	-0.32*	-0.31^{ns}	-0.45*	-0.38*	-0.37*	-0.36*	-0.21^{ns}	-0.26^{ns}	-0.30^{ns}	-0.34*	-0.37*
WC_{FC} (g g^{-1})	0.15^{ns}	0.33*	0.38*	0.34*	0.31^{ns}	0.24^{ns}	0.37*	0.30^{ns}	0.35*	0.28^{ns}	0.22^{ns}	0.29^{ns}	0.32^{ns}	0.31^{ns}	0.31^{ns}
AWC (g g^{-1})	0.28^{ns}	0.49*	0.53*	0.53*	0.53*	0.43*	0.55*	0.54*	0.58*	0.47*	0.34*	0.41*	0.47*	0.45*	0.44*
BD (g cm^{-3})	-0.31^{ns}	-0.45*	-0.53*	-0.40*	-0.42*	-0.36*	-0.51*	-0.37*	-0.41*	-0.37*	-0.32*	-0.40*	-0.41*	-0.42*	-0.43*

	3 WAP	4 WAP	5 WAP	6 WAP)	7 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
	Stem diameter (mm)					Number of plant leaves					Plant height (cm)				
	OA treatments with inorganic fertilizer														
Olsen-P (mg kg^{-1})	0.55*	0.45*	0.45*	0.37*	0.39*	0.46*	0.51*	0.51*	0.36*	0.41*	0.42*	0.40*	0.44*	0.50*	0.39*
TON (mg kg^{-1})	0.45*	0.31*	0.45*	0.49*	0.35*	0.41*	0.41*	0.39*	0.45*	0.48*	0.43*	0.38*	0.44*	0.41*	0.38*
NH4-N (mg kg^{-1})	0.53*	0.47*	0.48*	0.37*	0.31*	0.42*	0.45*	0.42*	0.39*	0.38*	0.45*	0.42*	0.44*	0.43*	0.35*
Available-K (mg kg^{-1})	0.35*	0.37*	0.51*	0.53*	0.43*	0.50*	0.56*	0.33*	0.32*	0.42*	0.44*	0.38*	0.52*	0.50*	0.46*
Available-Mg (mg kg^{-1})	0.49*	0.48*	0.45*	0.33*	0.34*	0.45*	0.51*	0.42*	0.22^{ns}	0.21^{ns}	0.36*	0.44*	0.46*	0.47*	0.34*
SOM (%)	0.46*	0.45*	0.53*	0.52*	0.52*	0.55*	0.60*	0.49*	0.40*	0.42*	0.45*	0.43*	0.51*	0.57*	0.45*
Total-N (mg kg^{-1})	0.52*	0.45*	0.53*	0.52*	0.53*	0.58*	0.61*	0.55*	0.46*	0.48*	0.46*	0.43*	0.54*	0.59*	0.48*
TOC (mg kg^{-1})	0.53*	0.48*	0.58*	0.57	0.53*	0.61*	0.62*	0.48*	0.37*	0.41*	0.47*	0.48*	0.57*	0.60*	0.48*
Total-P (mg kg^{-1})	0.35*	0.23^{ns}	0.26^{ns}	0.24^{ns}	0.28^{ns}	0.33*	0.31*	0.39*	0.36*	0.34*	0.30*	0.19^{ns}	0.27^{ns}	0.29*	0.21^{ns}
MB_C (µg g^{-1})	0.60*	0.50*	0.58*	0.52*	0.42*	0.58*	0.63*	0.45*	0.39*	0.50*	0.56*	0.53*	0.53*	0.57*	0.50*
Bioavailable-P (mg kg^{-1})	0.51*	0.54*	0.55*	0.45*	0.48*	0.49*	0.59*	0.50*	0.32*	0.38*	0.43*	0.46*	0.50*	0.55*	0.46*
C_{min}:C_{org}	-0.49*	-0.73*	-0.78*	-0.77*	-0.73*	-0.74*	-0.75*	-0.75*	-0.69*	-0.62*	-0.74*	-0.66*	-0.80*	-0.82*	-0.81*
WC_{FC} (g g^{-1})	0.38*	0.46*	0.52*	0.43*	0.29*	0.51*	0.55*	0.33*	0.20^{ns}	0.20^{ns}	0.45*	0.42*	0.42*	0.49*	0.46*
AWC (g g^{-1})	0.32*	0.39*	0.52*	0.47*	0.36*	0.50*	0.57*	0.37*	0.33*	0.40*	0.48*	0.39*	0.47*	0.52*	0.53*
BD (g cm^{-3})	-0.52*	-0.56*	-0.34*	-0.21^{ns}	-0.24^{ns}	-0.57*	-0.52*	-0.56*	-0.46*	-0.34*	-0.52*	-0.54*	-0.52*	-0.49*	-0.40*

ns = not Significant, TON = Total oxides of Nitrogen, NH4-N = Ammonium-Nitrogen, SOM = Soil organic matter, TOC = Total organic C, MB_C = Microbial biomass C, C_{min}:C_{org} Microbial biomass quotient WC_{FC} = Water content at field capacity, BD = Bulk density, AWC = Available water capacity, n = 72, * = $p < 0.05$, ns = not significant at $p < 0.05$.

7.1.2 Effect of OAs + inorganic fertilizer treatments on number of plant leaves at 2-7 weeks after planting

It was expected that OA + inorganic fertilizer would have significant effects ($p < 0.05$) on the number of plant leaves (Figure 45). However, 2 WAP no significant effect on the number of plant leaves was observed between the OA treatments and the CNF treatments. This is explained in Section 7.1.1. Beyond 2 WAP, all the OA treatments and the CF treatment recorded significantly higher numbers of leaves as compared with the CNF treatment. This is explained by the greater nutrient provisioning from the OA treatments (Table 22, Section 7.1.1). These results imply that inorganic fertilizer addition (NPK applied at 50% RB209 recommended rates) had marked effects on the number of plant leaves, particularly for the PAS treatments. In Figure 44, there is a greater 'spread' in number of plant leaves across the treatments, indicating high level of variability in the nutrients associated with the OAs applied.

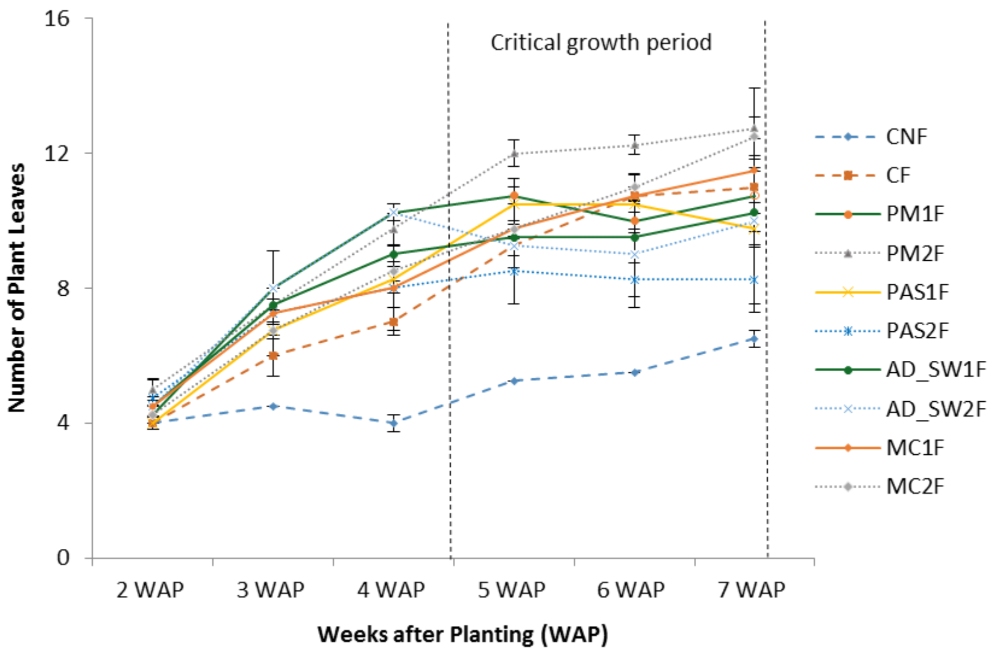


Figure 45 Effects of OA + inorganic fertilizer treatments on number of plant leaves 2-7 WAP, n = 72.

Vertical (error) bars denote +/-1 standard error of the mean at 5% probability following a *post-hoc* Fisher LSD analysis.

With inorganic fertilizer addition (Figure 45), the variability between treatments is narrowed. Thus, adding inorganic fertilizer to the PAS OA is critical to enhance plant performance (Ahmad *et al.*, 2006; Shisanya *et al.*, 2009).

7.1.3 Summary

The results indicate that application of OA increased the number of plant leaves due to higher overall nutrient supply and/or availability (Table 22, Section 7.1.1). Where no additional fertilizer was added, unlike the other OAs, the PAS treatments at both application rates did not increase the number of plant leaves as compared with the CNF treatment. This is due to an inadequate nutrient NPK supply. However, with inorganic fertilizer addition, the PAS treatments had significantly higher numbers of plant leaves as compared with the CNF treatment. This demonstrates that the NPK and Mg nutrient levels associated with the PAS amendment alone OAs were insufficient to support plant growth.

The significant differences in the number of plant leaves following OA application is expected to have a significant impact on plant biomass due to increased C synthesis (photosynthates) from the plant leaves. This is shown by the significant positive relationship between the number of plant leaves and total plant biomass (Table 23).

Table 23 Correlations between number of plant leaves at various WAP and plant performance indicators at harvest

	AG_{DB} (g)	BG_{DB} (g)	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
			Number of plant leaves					
			OA treatments without inorganic fertilizer					
Cob_{DW} (g)	0.68**	0.59**	0.65**	0.78**	0.77**	0.76**	0.73**	0.78**
AG_{DB} (g)		0.88**	0.62**	0.90**	0.94**	0.89**	0.87**	0.85**
BG_{DB} (g)			0.55**	0.74**	0.86**	0.73**	0.72**	0.70**
2 WAP				0.78**	0.68**	0.72**	0.69**	0.69**
3 WAP					0.91**	0.88**	0.83**	0.82**
4 WAP						0.91**	0.89**	0.85**
5 WAP							0.97**	0.94**
6 WAP								0.95**
			OA treatments with inorganic fertilizer					
Cob_{DW} (g)	0.71**	0.50*	0.36*	0.55**	0.65**	0.79**	0.81**	0.72**
AG_{DB}		0.72**	0.27^{ns}	0.80**	0.81**	0.79**	0.79**	0.70**
BG_{DB}			0.36*	0.56**	0.63**	0.56**	0.62**	0.61**
2 WAP				0.47*	0.40*	0.36*	0.34*	0.27^{ns}
3 WAP					0.91**	0.76**	0.56**	0.57**
4 WAP						0.85**	0.66**	0.66**
5 WAP							0.84**	0.78**
6 WAP								0.88**

WAP = Weeks after Planting, * = $p < 0.05$, ** = $p < 0.01$, ns = not Significant, n = 72.

7.1.4 Effect of OAs (without inorganic fertilizer) treatments on stem diameter (mm) at 2-7 WAP

Mean plant stem diameter varied significantly across the treatments during the growth period, except at 2 WAP at which point the stem diameters associated with the OA treatments were not statistically different from the CNF (Figure 46). This is explained in Section 7.2.1. As anticipated, based on the soil NPK Mg content and bioavailable-P associated with the OA treatments at 3 WAP and beyond; the PM1NF, PM2NF, AD_SW1NF, AD_SW2NF, MC1NF, and MC2NF treatments consistently had significantly higher stem diameter as compared with CNF (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8; Table 18, Section 5.1.9.2).

In contrast, the PAS1NF and PAS2NF treatments recorded a significantly lower stem diameter as compared with all the other treatments throughout the growth periods, except at 2WAP. As explained in Section 7.1.1, the thinner stem diameter associated with the PAS treatment is attributed to low nutrient (NPK, Mg) availability for plant uptake (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8), low number of plant leaves (Figure 44) and consequently low photosynthates.

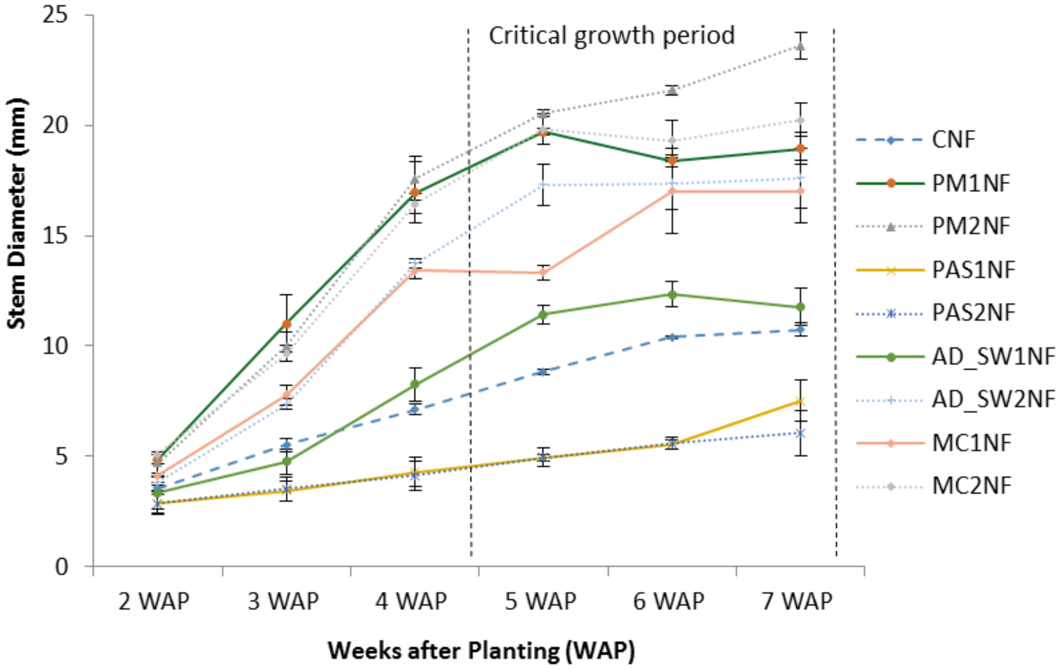


Figure 46 Effect of OAs (without inorganic fertilizer) treatments on stem diameter 2-7 WAP, n = 72.

7.1.5 Effect of OAs + inorganic fertilizer treatments on stem diameter (mm) 2-7 WAP

All the OA treatments + inorganic fertilizer were associated with significantly higher stem diameter as compared with CNF (Figure 47). Throughout the growing period, the PM1F, PM2F, AD_SW1F, AD_SW2F treatments, maintained a significantly higher stem diameter as compared with the CF treatment. Unlike the PAS1NF and PAS2NF treatments, the PAS1F and PAS2F treatments had significantly thicker stem diameters than the CNF treatment. As explained in the previous sections, this is due to the effect of the inorganic fertilizer which provided higher levels of available NPK, Mg and bioavailable-P.

This is supported by the significant correlation between soil nutrients [NPK and Mg], bioavailable-P and stem diameter (Table 22, Section 7.1.1).

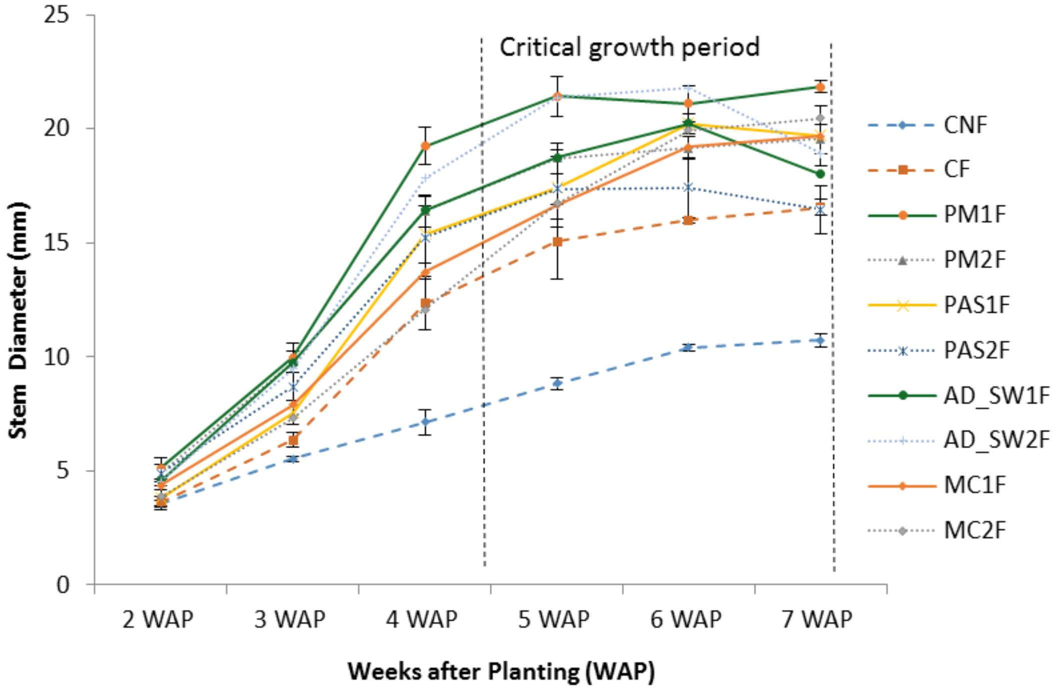


Figure 47 Effect OA + inorganic fertilizer treatments on stem diameter 2-7 WAP, (n = 72).

7.1.6 Effect of OAs (without inorganic fertilizer) treatments on plant height (cm) at 2-6 WAP

Plant height is influenced by many factors such as photosynthesis, soil moisture content (WC_{FC}, AWC, EAW), nutrient availability (NPK and Mg), and rooting depth (as affected by the soil BD) (O'Keeffe, 2009). Plant height is an important plant performance indicator (Yin *et al.*, 2011) and it is linked to NPK Mg nutrient uptake (especially N) during maize vegetative development (Tables 22 and 23, Section 7.1.1). With the exception of MC2NF which was taller than CNF, at 2 WAP, the plant heights in the OA treatments were not significantly different to the CNF treatment (Figure 48). As explained in Sections 7.1.1–7.1.5, the non-significant difference in the plant height at 2 WAP suggests that the maize plant still depends on the food reserves in the maize seed, such that any external nutrient supply had little or no effect on plant height (Grant *et al.*, 2001).

Beyond 2 WAP, the OA treatments maintained a significantly higher ($p < 0.05$) plant height compared with the CNF treatment, with the exception of PAS1NF and PAS2NF which consistently had significantly lower plant height than all other treatments. This is because of low available NPK and Mg nutrients, inadequate to support plant growth (Table 22, Section 7.1.1). This is also evidenced by the low MB_C and low C_{mic}:C_{org} associated with the PAS OA (Figure 42**,** Section 6.1.1; Table 21; Section 6.2.2), which suggests that the microbes in the PAS treatments showed a high level of stress due to insufficient nutrient availability (NPK, and Mg) compared with the other OAs. Lupwayi *et al.* (2014) found a positive correlation between MB_C and soil nutrients (NPK and Mg.

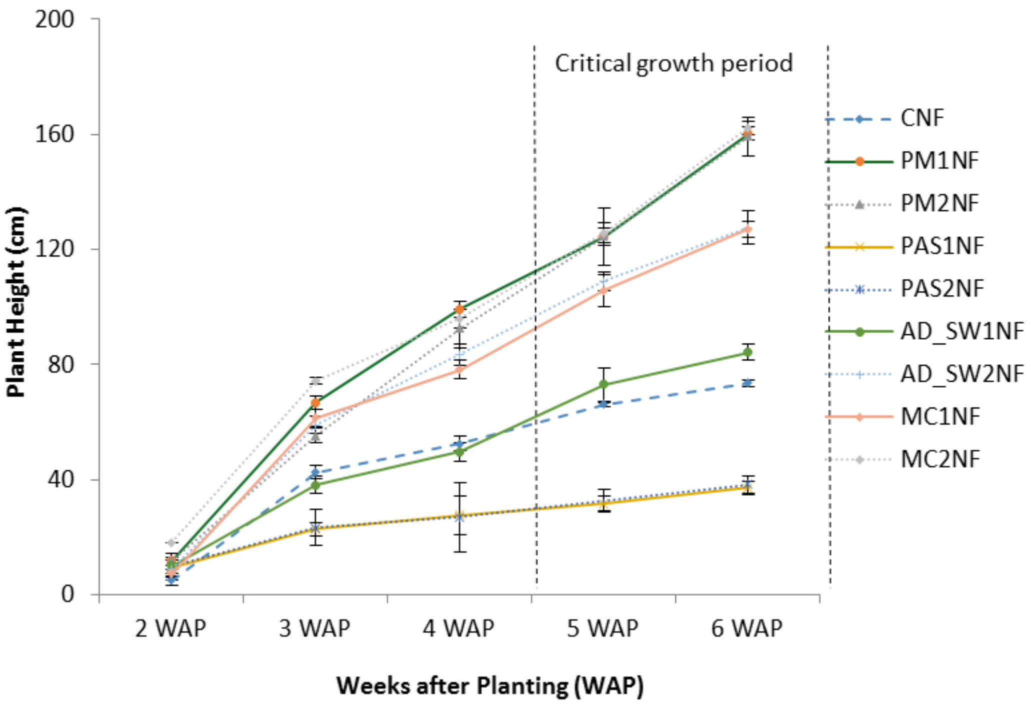


Figure 48 Effect of OAs (without inorganic fertilizer) treatments on plant height 2-6 WAP, n = 72.

7.1.7 Effect OAs + inorganic fertilizer treatments on plant height at 2-6 WAP

As compared with OA without inorganic fertilizer treatments, a different trend in the plant height was observed for the OA treatments where the inorganic fertilizer was added (Figure 49).

As expected, all the OA + inorganic fertilizer treatments had significantly higher plant height as compared with the CNF treatment. As suggested earlier (Sections 7.1.1–7.1.6); the significantly higher plant height in the PAS1F and PAS2F treatments as compared with the CNF treatment is attributed to the NPK and Mg supplied via inorganic fertilizer addition, which resulted in the observed increase in plant height (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8). The increase in plant height following OA + inorganic fertilizer application is due to the increase in available NPK, Mg nutrients and higher plant nutrients uptake (Table 22, Section 7.1.1; See Section 7.4 for more discussion on nutrient uptake).

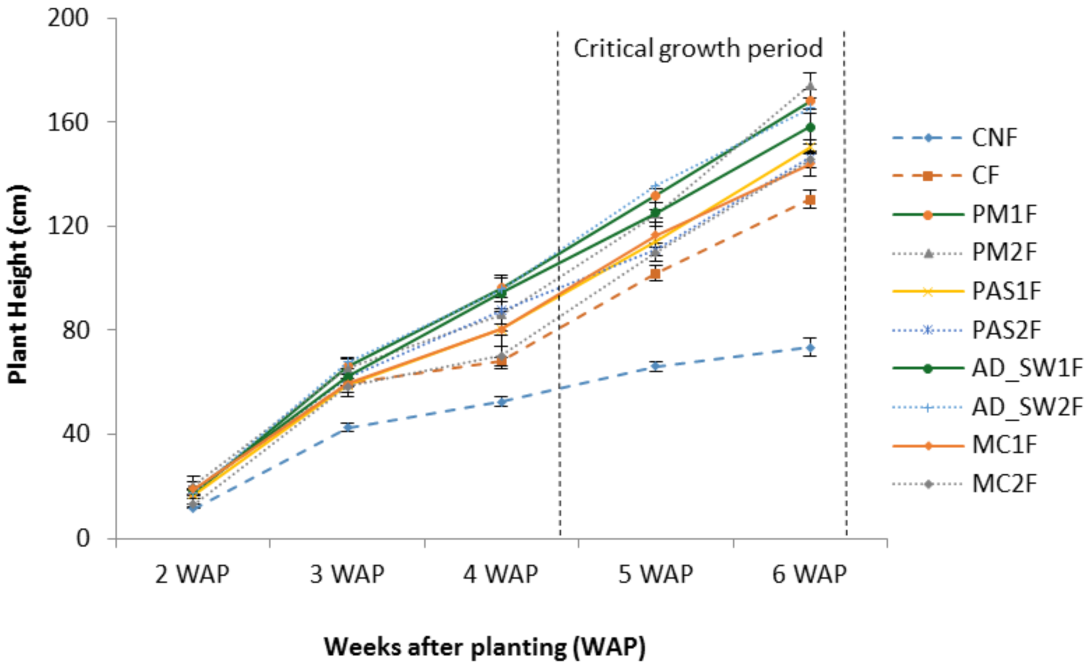


Figure 49 Effect of OA + inorganic fertilizer treatments on plant height 2-6 WAP, n = 72.

7.1.8 Summary

- With the exception of PAS1NF and PAS2NF, application of OAs at both rates with or without inorganic fertilizer significantly improved maize growth (as expressed by plant height and stem diameter), due to increased NPK and Mg nutrient supply, increased MB_C and reduced soil BD (Table 21, Section 6.2.2).
- The present study suggests that PAS alone does not enhance plant growth.
- PM1NF and PM2NF had higher ($p < 0.05$) stem diameter and plant heights as compared with the other OA treatments applied at 10 t ha^{-1} and 30 t ha^{-1}, respectively. As anticipated in Sections 5.1.3 and 5.1.7, based on RB209 P and K requirement for maize, the PM treatments had significantly higher Available-P for plant uptake as compared with other OA treatments. This accounts for the significant higher number of plant leaves, stem diameter and plant height associated with the PM treatments as compared with the other treatments.
- The PM1NF and PM2NF showed no significant difference in plant heights. This is due to the high nutrients supplied by this amendment (Table 10, Section 3.3.1). Further, the non-significant difference between the PM 10 and 30 t ha^{-1} treatments suggests that adequate nutrients were supplied at 10 t ha^{-1} and that 30 t ha^{-1} supplied excess (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8).

7.1.9 Vegetative growth stages

The vegetative growth of maize is a period of high nutrient uptake (O'Keeffe, 2009) at which the plant accumulates the nutrients it requires for its life cycle. A strong correlation between plant height measured at V10 and V12 vegetative growth stage and maize yield has been reported (Yin *et al.*, 2011).

Plant vegetative growth (Figure 50 A) indicates that the maize plant in the PAS treatments at both application rates consistently had lower vegetative growth rate [delayed plant growth] throughout the growing period as compared with all other treatments. This result strongly suggests that the maize plants grown in the PAS treatment were not receiving adequate supply of NPK, Mg nutrients when compared with the maize plants in all other OA treatments (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8). This is because limited available nutrients especially P at the early growth stage can restrict crop growth and development (Grant *et al.* 2001; Table 22 and 23 Sections 7.1.1 and 7.1.3).

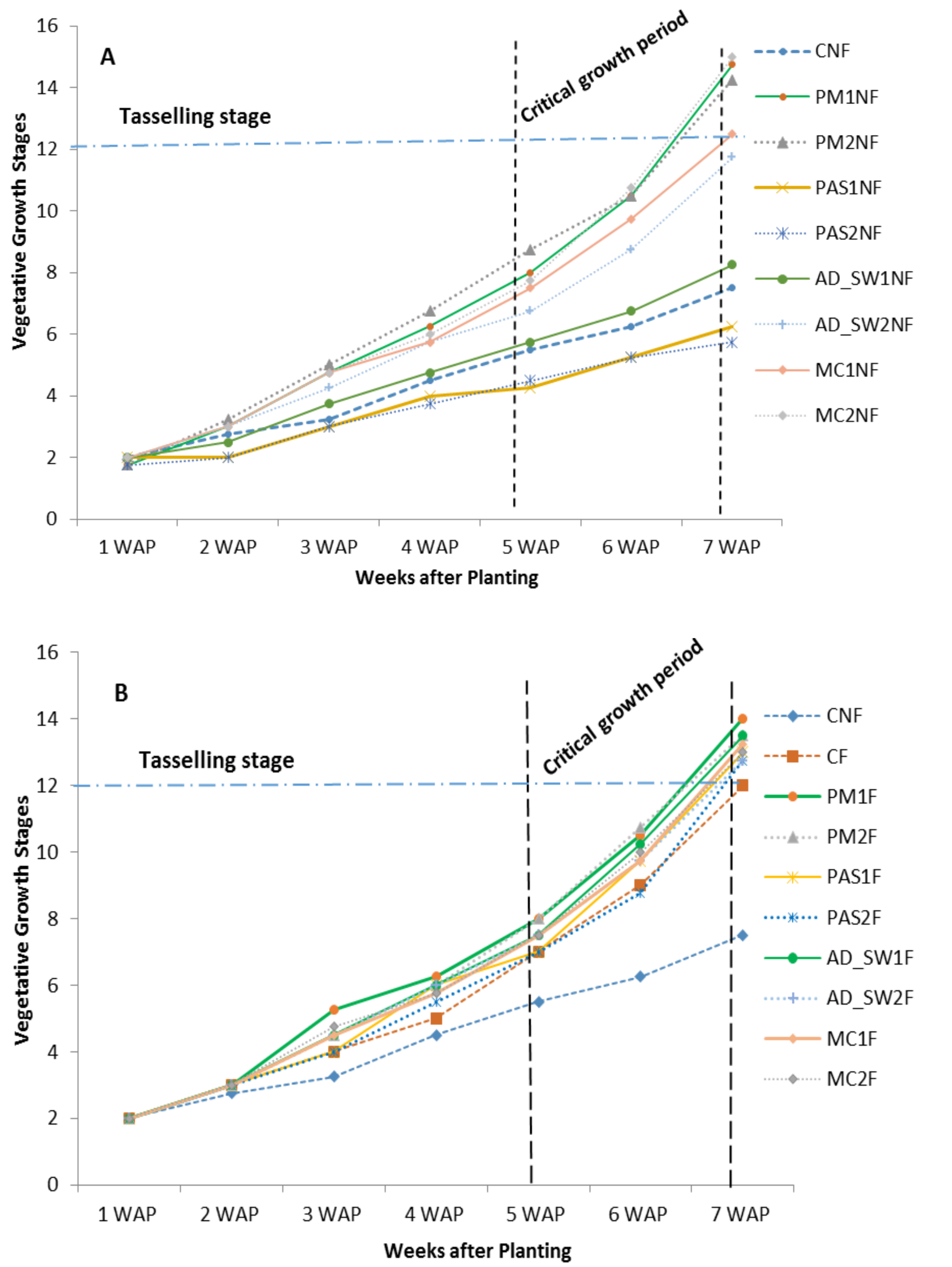


Figure 50 Effect of OA treatments on maize vegetative growth stage 1-7 WAP: A) without inorganic fertilizer addition B) with inorganic fertilizer addition.

WAP = Weeks after Planting. See Figure 15, Section 3.5.4 for pictorial presentation of vegetative growth stages, n = 72.

Table 24 Correlations between stem diameter, numbers of plant leaves and plant height at different weeks after planting

	4 WAP-SD (mm)	5 WAP-SD (mm)	6 WAP-SD (mm)	7 WAP-SD (mm)	3 WAP-NL	4 WAP-NL	5 WAP-NL	6 WAP-NL	7 WAP-NL	3 WAP-H_T (cm)	4 WAP-H_T (cm)	5 WAP-H_T (cm)	6 WAP-H_T (cm)	7 WAP-H_T (cm)
OA treatments without inorganic fertilizer														
3 WAP-SD	0.93**	0.87**	0.81**	0.81**	0.91**	0.85**	0.80**	0.74**	0.75**	0.89**	0.92**	0.89**	0.88**	0.88**
4 WAP-SD		0.95**	0.95**	0.94**	0.96**	0.95**	0.91**	0.87**	0.83**	0.90**	0.96**	0.97**	0.97**	0.97**
5 WAP-SD			0.90**	0.89**	0.94**	0.92**	0.84**	0.80**	0.78**	0.86**	0.94**	0.95**	0.94**	0.93**
6 WAP-SD				0.98**	0.92**	0.92**	0.92**	0.89**	0.85**	0.82**	0.90**	0.94**	0.95**	0.93**
7 WAP-SD					0.92**	0.93**	0.94**	0.92**	0.88**	0.79**	0.88**	0.92**	0.93**	0.92**
3 WAP-NL						0.91**	0.88**	0.83**	0.82**	0.88**	0.96**	0.97**	0.96**	0.95**
4 WAP-NL							0.91**	0.89**	0.85**	0.81**	0.88**	0.92**	0.93**	0.94**
5 WAP-NL								0.97**	0.94**	0.75**	0.81**	0.87**	0.87**	0.86**
6 WAP-NL									0.95**	0.67**	0.75**	0.82**	0.83**	0.83**
7 WAP-NL										0.64**	0.74**	0.79**	0.80**	0.81**
3 WAP-H_T											0.93**	0.93**	0.90**	0.90**
4 WAP-H_T												0.98**	0.96**	0.95**
5 WAP-H_T													0.98**	0.97**
6 WAP-H_T														0.98**

	4 WAP-SD (mm)	5 WAP-SD (mm)	6 WAP-SD (mm)	7 WAP-SD (mm)	3 WAP-NL	4 WAP-NL	5 WAP-NL	6 WAP-NL	7 WAP-NL	3 WAP-H_T (cm)	4 WAP-H_T (cm)	5 WAP-H_T (cm)	6 WAP-H_T (cm)	7 WAP-H_T (cm)
								OA treatments with inorganic fertilizer						
3 WAP-SD	0.77**	0.73**	0.62**	0.45*	0.77**	0.65**	0.52**	0.28^{ns}	0.34*	0.75**	0.83**	0.71**	0.65**	0.58**
4 WAP-SD		0.95**	0.82**	0.72**	0.87**	0.86**	0.71**	0.52**	0.42*	0.84**	0.91**	0.91**	0.88**	0.82**
5 WAP-SD			0.92**	0.83**	0.88**	0.91**	0.77**	0.60**	0.55**	0.85**	0.86**	0.91**	0.89**	0.85**
6 WAP-SD				0.92**	0.84**	0.85**	0.76**	0.63**	0.58**	0.71**	0.77**	0.86**	0.84**	0.80**
7 WAP-SD					0.73**	0.78**	0.76**	0.68**	0.60**	0.62**	0.62**	0.76**	0.77**	0.75**
3 WAP-NL						0.91**	0.76**	0.56**	0.57**	0.75**	0.85**	0.91**	0.89**	0.85**
4 WAP-NL							0.85**	0.66**	0.66**	0.78**	0.74**	0.90**	0.94**	0.92**
5 WAP-NL								0.84**	0.78**	0.66**	0.54**	0.78**	0.85**	0.86**
6 WAP-NL									0.88**	0.61**	0.36*	0.58**	0.67**	0.70**
7 WAP-NL										0.58**	0.30*	0.52**	0.62**	0.68**
3 WAP-H_T											0.78**	0.77**	0.77**	0.76**
4 WAP-H_T												0.87**	0.80**	0.71**
5 WAP-H_T													0.96**	0.90**
6 WAP-H_T														0.96**

WAP = Weeks after Planting SD = Stem diameter, NL = Number of plant leaves, H_T = plant height, n = 72, * = p <0.05, ** = p <0.01.

Beyond 2 WAP, obvious differences in the plant growth stages were observed across the OA treatments. This is due to significant differences in the nutrient supplied via the OA treatments and its corresponding uptake by the plants (Figures 27, 31, 37, and 39, Sections 5.1.3–5.1.4, 5.1.6–5.1.8; Table 22, Section 7.1.1). This result explains the obvious differences in the plant performance indicators observed across the treatments. The nutrient uptake levels for PAS1NF, PAS2NF and AD_SW1NF, especially N and P, were low as compared with all other OA treatments (Figures 59 and 61, Sections 7.4.1 and 7.4.3 for more discussion). This confirms that inadequate nutrient availability (especially NPK) (Figures 27, 31, 37, and 39, Sections 5.1.3-5.1.5) and its corresponding uptake hindered the development of the plants grown in PAS1NF and PAS2NF (Moore *et al.*, 2014).

It is important to note that the OA treatments without inorganic fertilizer addition had varied and wide spread effect (variability between treatments) on plant vegetative growth. Thus, not all the plants particularly those in PAS1NF/2NF and AD_SW1NF treatments achieved tasselling (Figure 50 A) which is critical to cob formation and important for plant yield performance. As suggested earlier, this is due to inadequate supply of available nutrients (N [TON, NH4-N] P K, Mg).

With supplementary inorganic fertilizer, the OA treatments had higher V-stages as compared with the CNF treatment (Figure 50 B). Hence, all the plants grown in OA treatment + inorganic fertilizer treatment achieved tasselling. This will significantly affect cob formation and plant yield performance (See Chapter 7.3). Inorganic fertilizer addition narrows the variability between treatments. This result demonstrates the effect inorganic fertilizers (readily available nutrient) had on plant vegetative growth, particularly for the PAS treatments which is associated with low nutrients (Table 10, Section 3.3.1.2). It also suggests that combined application of OAs and inorganic fertilizer has greater effect in achieving high crop performance than sole application of OAs [except for PM which is rich in plant nutrients] (Figures 8 and 10, Section 3.3.2).

7.1.10 Effect of OAs (without inorganic fertilizer) on plant height at tasselling (male flowering) (PH_T)

Tasselling (male flowering) is an important and a critical developmental growth stage in maize, since tasselling indicates the physiological transformation from the vegetative growth stage to the reproductive growth stage. At this stage, the maize plant neither increases in height nor produces new plant leaves but only produces the tassel head. Thus, plants with lower height at tasselling may suffer from shading effects (low light interception by the plant leaves) from the neighbouring tall plants ('board effect') which can affect crop yield performance. Plant height at tasselling can affect plant height at first ear which influences the number of cobs produced per plant (Srivas and Singh 2004; Carpici and Celik, 2010).

As anticipated, the present study indicated that the OA application had significant effects on maize PH_T at 7 WAP (Figure 51). The results showed that with the exception of PAS1NF and PAS2NF, all OA treatments had significantly higher PH_T than the CNF treatment. Furthermore, it was observed that increasing OA application rates from 10 t ha^{-1} to 30 t ha^{-1} significantly increase ($p < 0.05$) the PH_T for AD_SW1NF AD_SW2NF, MC1NF and MC2NF, but not for PM1NF, PM2NF, PAS1NF and PAS2NF. There are two possible explanations for this. First, it is possible that the nutrient content in the PM1NF treatment was adequate for maize plant growth such that increasing OA application rate did not significantly affect the PH_T. This suggests that the nutrient supplied by the PM2NF treatment was in excess and was not taken up by the maize plant. This is clearly evident from the plant nutrient concentration and uptake analysis (Table 25, See Section 7.2.1 for more discussion). Similarly, the N uptake for PM2NF was approximately 50% higher ($p < 0.05$) compared with PM1NF (Figure 59, See Section 7.4.1 for more discussion). This supports the suggestions that maize plants in the PM2NF treatments had excessive availability of NPK.

The non-significant difference in PH_T observed between PAS1NF and PAS2NF is due to inadequate nutrient provisioning associated with the PAS amendment, (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.18). This is evidenced by the significant correlation between soil nutrients and plant height (Table 22, Section 7.1.1). Hence, the results explain why the increase in PAS application rate (PAS2NF) made no difference to the PH_T since the PAS treatment was associated with low NPK and Mg nutrient content and low MB_C as compared with other OA treatments.

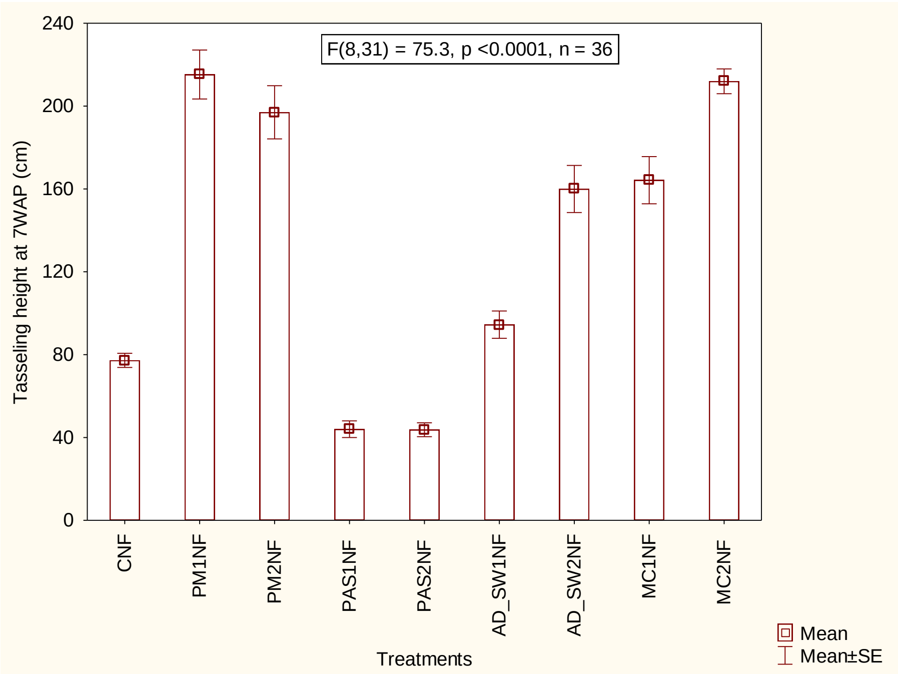


Figure 51 Effect of OA (without inorganic fertilizer) treatments on plant height at Tasselling (male flowering) at 7 WAP.

7.1.11 Effect of OAs + inorganic fertilizer treatments on Plant height at Tasselling (flowering) (PH_T)

With inorganic fertilizer addition, all the OA treatments had significantly higher PH_T than the CNF treatment (Figure 52). However, unlike with PAS treatments without inorganic fertilizer, the PH_T in PAS1F and PAS2F treatments was over 60% higher than CNF. This result further indicates that OA + inorganic fertilizer addition had a greater effect on PH_T than sole application of PAS amendment, due to increased levels of plant available NPK and Mg nutrients (Figures 27, 31, 33, 37, and 39, Sections 5.1.3 - 5.1.5, 5.1.7 and 5.1.8). However, the effect of inorganic fertilizer addition was not observed in the PM treatments at either application rate. This is attributed to the adequate nutrient supply (NPK and Mg) associated with the PM amendment (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8). This is manifest by greater N and P NUE associated with the PM1F as compared with PM2F treatment (Figure 63; See Section 7.5 for more discussion).

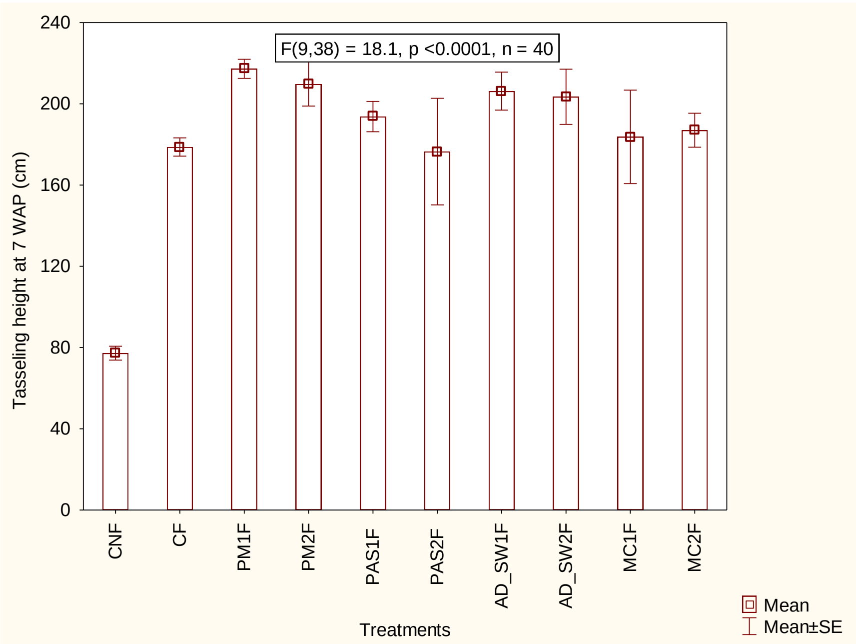


Figure 52 Effect of OA + inorganic fertilizer treatments on plant height at tasselling at 7 WAP.

7.1.12 Summary

- All the OA treatments had significantly higher PH_T as compared with the CNF treatment, except PAS1NF and PAS2NF treatments which had the lowest PH_T.
- With inorganic fertilizer addition, the PAS1F and PAS2F treatments had 58% and 54% higher ($p < 0.05$) PH_T than the CNF treatment, respectively.
- With the exception of PAS, the results show that OA application can support adequate plant growth due to sufficient nutrient supply.

7.2 OA treatment effects on maize plant biomass (component parts) at harvest

This section discusses the effects of the OA treatments on above ground biomass [AG_{DB}], and below ground biomass [BG_{DB}] and cob yield [Cob_{DW}]. on a dry weight (DW) basis It was expected that the OA treatments with or without inorganic fertilizer would produce significantly more plant biomass as compared with the control treatment due to the effects of OA treatments on soil productivity as represented by the SQIs tested (Cherif *et al.*, 2009).

7.2.1 Effect of OA (without inorganic fertilizer) treatments on AG_{DB}

Significant effects on AG_{DB} were observed for the OA treatments (Figure 53). With the exception of PAS1NF treatment, the PM1NF, AD_SW1NF and MC1NF treatments had significantly higher AG_{DB} as compared with the CNF treatment by 60, 24, and 45.7%, respectively. In contrast, the PAS1NF treatment was associated with a significantly lower AG_{DB} than the CNF treatment. This is attributed to reasons explained above.

PM1NF had AG_{DB} values that were 66, 42 and 21% higher ($p < 0.05$) than the PAS1NF, AD_SW1NF and MC1NF treatments, respectively. At the higher OA application rate (30 t ha^{-1}), all the OA treatments with the exception of PAS2NF treatment had significantly more AG_{DB} as compared with the CNF treatment. The AG_{DB} at 30 t ha^{-1} application rate was in the order: PM2NF > MC2NF > AD_SW1NF > PAS1NF. This is due to the reasons outlined above and is further supported by the significant correlation between the chemical SQIs and AG_{DB} (Table 25, Section 7.3.1). Further, the higher AG_{DB} in PM2NF as compared with all other treatments is attributed to high NPK and Mg nutrient availability (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8), higher P supply (Figure 31 Sections 5.1.3) and greater MB_C (Figure 42, Section 6.1.1) and biological activities (Table 21, Section 6.2.2) associated with the PM treatment. This resulted in significantly higher N and P uptake in the PM treatment as compared with all other OA treatments (Figure 59, See sections 7.4 for further discussion) and consequently resulted in the higher AG_{DB}

obtained (Figure 53, Section 7.3.1). This is evidenced by the significant correlation between the SQIs and AG_{DB} (Table 25, Section 7.2.1).

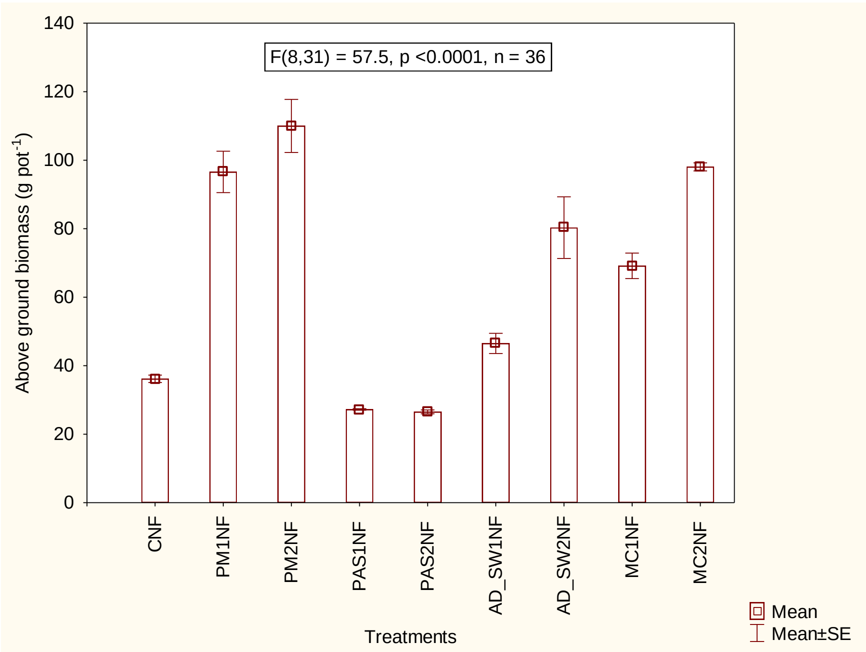


Figure 53 Effect of OA (without inorganic fertilizer) treatments on AG_{DB} at harvest.

The significant positive ($p < 0.05$) correlation between the soil nutrient (NPK and Mg) contents, AG_{DB} and plant nutrient uptake supports the fact that higher plant performance is due to higher nutrient availability, increased SOM, bioavailable-P and the positive effects the OA had on the physical SQIs, such as reduced BD, increased WC_{FC} and AWC (Table 25, Section 7.2.1).

The result shows that the increase in OA application rate from 10 t ha^{-1} to 30 t ha^{-1} increased the AG_{DB} with the exception of PASN1NF and PAS2NF treatments which did not differ significantly due to low NPK and Mg nutrient availability for plant uptake as explained in subsequent sections (Figures 59 and 61, Sections 7.4.1 and 7.4.3). In addition, the result on the soil biological activities indicates that the soil microbes associated with the PAS amended treatment showed significantly higher stress levels as compared with the other OA treatments, as evidenced by low C_{mic}:C_{org} (Table 21 Sections 6.2.2). The significant negative correlation between C_{mic}:C_{org} and AG_{DB} (Table 25, Section

7.2.1) suggests that there was competition for the available nutrients between the soil microbes and the maize plant. This can further explain the significantly lower AG_{DB} in the PAS treatment, since the PAS amendment is associated with inadequate N, P and K (Table 10, Section 3.3.1.2; Figures 8, and 10, Section 3.3.2).

No significant difference in AG_{DB} was observed between the PM1NF and PM2NF treatments. However, unlike the PAS treatment, the non-significant difference on the AG_{DB} observed between the PM1NF and PM2NF treatments suggest that the PM1NF treatment provided adequate nutrients for plant uptake such that increasing the OA application rates to 30 t ha^{-1} had no significant effect on the AG_{DB}. This implies that the PM2NF treatment provided more nutrients than the plant required which resulted in the excess nutrient [NP] uptake (Figures 59 and 61 Sections 7.4.1 and 7.4.3) with no corresponding effect on the AG_{DB} (Figure 54). In contrast, the AG_{DB} in the MC2NF and AD_SW2NF treatments was 33% and 41% higher ($p < 0.05$) than in the MC1NF and AD_SW1NF treatments, respectively. The significantly positive ($p < 0.05$) correlation between AG_{DB} and soil nutrient content confirms that the increase in the AG_{DB} at higher treatment application rates is due to greater NPK and Mg nutrient supply (Table 25).

Table 25 Correlation between selected SQIs, plant performance indicators, plant nutrient uptake and nutrient use efficiency (n = 72)

Treatments	Cob_{DW} (g)	AG_{DB} (g)	BG_{DB} (g)	7 WAP PH_T (cm)	N-uptake ($g\ g^{-1}$)	NUE ($g\ g^{-1}$)	P-uptake ($mg\ g^{-1}$)	PUE ($g\ g^{-1}$)	K-uptake ($mg\ g^{-1}$)	Cu-uptake ($\mu g\ g^{-1}$)	Zn-uptake ($\mu g\ g^{-1}$)
OA treatments without inorganic fertilizer											
Olsen-P ($mg\ kg^{-1}$)	0.40*	0.67**	0.61**	0.54*	0.74**	0.28^{ns}	0.74**	0.26^{ns}	0.67**	0.80**	0.63**
EC	0.63*	0.57*	0.48*	0.64**	0.42*	0.68**	0.43*	0.73**	0.66**	0.18^{ns}	0.55*
pH	-0.53*	-0.31^{ns}	-0.18^{ns}	-0.48*	-0.15^{ns}	-0.59*	-0.16^{ns}	-0.62**	-0.35*	-0.03^{ns}	-0.34*
TON ($mg\ kg^{-1}$)	0.63**	0.56*	0.38*	0.55*	0.50*	0.50*	0.42*	0.56*	0.51*	0.48*	0.58*
NH4-N ($mg\ kg^{-1}$)	0.30^{ns}	0.38*	0.19^{ns}	0.25^{ns}	0.50*	0.14^{ns}	0.29^{ns}	0.25^{ns}	0.39*	0.42*	0.40*
Available-K ($mg\ kg^{-1}$)	0.30^{ns}	0.53*	0.56*	0.49*	0.40*	0.30^{ns}	0.62**	0.30^{ns}	0.62**	0.19^{ns}	0.43*
Available-Mg ($mg\ kg^{-1}$)	0.35*	0.53*	0.39*	0.46*	0.61**	0.29^{ns}	0.67**	0.20^{ns}	0.56*	0.78**	0.51*
SOM (%)	0.32*	0.53*	0.52*	0.43*	0.51*	0.26^{ns}	0.62**	0.26^{ns}	0.60**	0.40*	0.47*
Total-N ($mg\ kg^{-1}$)	0.49*	0.64**	0.55*	0.52*	0.68**	0.39*	0.69**	0.41*	0.73**	0.57*	0.64**
TOC ($mg\ kg^{-1}$)	0.36*	0.53*	0.49*	0.44	0.52*	0.31^{ns}	0.63**	0.32*	0.65**	0.35*	0.50*
Total-P ($mg\ kg^{-1}$)	0.37*	0.54*	0.52*	0.43*	0.54*	0.31^{ns}	0.64**	0.32*	0.64**	0.40*	0.51*
MB_C ($\mu g\ g^{-1}$)	0.31^{ns}	0.48*	0.37*	0.40*	0.59*	0.14^{ns}	0.55*	0.14^{ns}	0.47*	0.77**	0.49*
Bioavailable-P ($mg\ kg^{-1}$)	0.56*	0.64**	0.51*	0.54*	0.73**	0.45*	0.72**	0.49*	0.72**	0.58*	0.67**
Bioavailable-TOC ($mg\ kg^{-1}$)	0.40*	0.73**	0.72**	0.60**	0.75**	0.35*	0.81**	0.30^{ns}	0.74**	0.74**	0.66**
C_{min}:C_{org}	-0.30^{ns}	-0.40*	-0.36*	-0.37*	-0.36*	-0.31^{ns}	-0.45*	-0.31^{ns}	-0.44*	-0.30^{ns}	-0.39*
WC_{FC} ($g\ g^{-1}$)	0.24^{ns}	0.40*	0.30^{ns}	0.31^{ns}	0.43*	0.19^{ns}	0.48*	0.22^{ns}	0.48*	0.26^{ns}	0.37*
AWC ($g\ g^{-1}$)	0.32*	0.56*	0.46*	0.44*	0.60**	0.21^{ns}	0.58*	0.32*	0.63**	0.31^{ns}	0.5
BD ($g\ cm^{-3}$)	-0.40*	-0.51*	-0.47*	-0.43*	-0.50*	-0.35*	-0.64**	-0.35*	-0.60**	-0.36*	-0.50*

Treatments	Cob_{DW} (g)	AG_{DB} (g)	BG_{DB} (g)	7 WAP PH_T (cm)	N-uptake ($g\ g^{-1}$)	NUE ($g\ g^{-1}$)	P-uptake ($mg\ g^{-1}$)	PUE ($g\ g^{-1}$)	K-uptake ($mg\ g^{-1}$)	Cu-uptake ($\mu g\ g^{-1}$)	Zn-uptake ($\mu g\ g^{-1}$)
OA treatments with inorganic fertilizer											
Olsen-P ($mg\ kg^{-1}$)	0.40*	0.27^{ns}	0.18^{ns}	0.39*	0.57*	0.06^{ns}	0.71**	-0.07^{ns}	0.43*	0.76**	0.58*
EC	0.28^{ns}	0.37*	0.24^{ns}	0.25^{ns}	0.61**	0.01^{ns}	0.37*	0.07^{ns}	0.57*	0.19^{ns}	0.52*
pH	-0.04^{ns}	-0.21^{ns}	-0.31*	-0.10^{ns}	-0.28^{ns}	0.00^{ns}	-0.07^{ns}	-0.10^{ns}	-0.27^{ns}	0.29*	-0.19^{ns}
TON ($mg\ kg^{-1}$)	0.25^{ns}	0.47*	0.51*	0.38*	0.60**	0.06^{ns}	0.53*	0.03^{ns}	0.62**	0.15^{ns}	0.56*
NH4-N ($mg\ kg^{-1}$)	0.34*	0.32*	0.19^{ns}	0.35*	0.48*	0.11^{ns}	0.57*	0.00^{ns}	0.42*	0.59*	0.50*
Available-K ($mg\ kg^{-1}$)	0.21^{ns}	0.44*	0.44*	0.46*	0.60**	-0.01^{ns}	0.53*	-0.01^{ns}	0.64**	0.26^{ns}	0.52*
Available-Mg ($mg\ kg^{-1}$)	0.31*	0.20^{ns}	0.13^{ns}	0.34*	0.44*	0.01^{ns}	0.67**	-0.18^{ns}	0.36*	0.67**	0.48*
SOM (%)	0.35*	0.45*	0.36*	0.45*	0.65**	0.01^{ns}	0.68**	-0.05^{ns}	0.63**	0.63**	0.65**
Total-N ($mg\ kg^{-1}$)	0.42*	0.49*	0.37*	0.48*	0.71**	0.06^{ns}	0.70**	0.00^{ns}	0.67**	0.63**	0.69**
TOC ($mg\ kg^{-1}$)	0.32*	0.49*	0.36*	0.49*	0.64**	0.02^{ns}	0.63**	-0.06^{ns}	0.67**	0.53*	0.60**
Total-P ($mg\ kg^{-1}$)	0.31*	0.51*	0.37*	0.48*	0.67**	0.00^{ns}	0.65**	-0.05^{ns}	0.70**	0.53*	0.62**
MB_C ($\mu g\ g^{-1}$)	0.27^{ns}	0.21^{ns}	0.25^{ns}	0.21^{ns}	0.45*	-0.02^{ns}	0.41*	0.00^{ns}	0.35*	0.51*	0.49*
Bioavailable-P ($mg\ kg^{-1}$)	0.36*	0.43*	0.51*	0.50*	0.63**	0.05^{ns}	0.76**	-0.11^{ns}	0.63**	0.49*	0.66**
Bioavailable-TOC ($mg\ kg^{-1}$)	0.40*	0.33*	0.22^{ns}	0.46*	0.56*	0.10^{ns}	0.76**	-0.08^{ns}	0.47*	0.73**	0.56*
C_{min}:C_{org}	-0.64**	-0.84**	-0.62**	-0.81**	-0.62**	-0.61**	-0.60**	-0.52*	-0.73**	-0.36*	-0.52*
WC_{FC} ($g\ g^{-1}$)	0.09^{ns}	0.36*	0.29*	0.46*	0.31*	0.07^{ns}	0.36*	0.06^{ns}	0.37*	0.12^{ns}	0.23^{ns}
AWC ($g\ g^{-1}$)	0.23^{ns}	0.47*	0.38*	0.53*	0.47*	0.15^{ns}	0.42*	0.23^{ns}	0.51*	0.10^{ns}	0.35*
BD ($g\ cm^{-3}$)	-0.19^{ns}	-0.29*	-0.33*	-0.40*	-0.43*	-0.01^{ns}	-0.60**	0.21^{ns}	-0.46*	-0.36*	-0.44*

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

7.2.2 Effect of OA+ inorganic fertilizer treatments on AG_{DB}

As hypothesized, all the OA with inorganic fertilizer treatments had significantly higher AG_{DB} as compared to the CNF treatment (Figure 54). This is due to reasons previously explained (Tables 22 and 25, Section 7.1.1 and 7.2.1). Further, with the exception of the PAS2F and AD_SW2F treatments (which were statistically the same as the CF treatment) all other OA treatments showed significantly higher AG_{DB} as compared with the CF treatment. The result further shows that with inorganic fertilizer addition, OA application rates had no significant effect on the AG_{DB}. This result demonstrates that the treatments at both application rates + inorganic fertilizer provided adequate supply nutrient to the plant (Figures 8, and 10, Section 3.3.2).

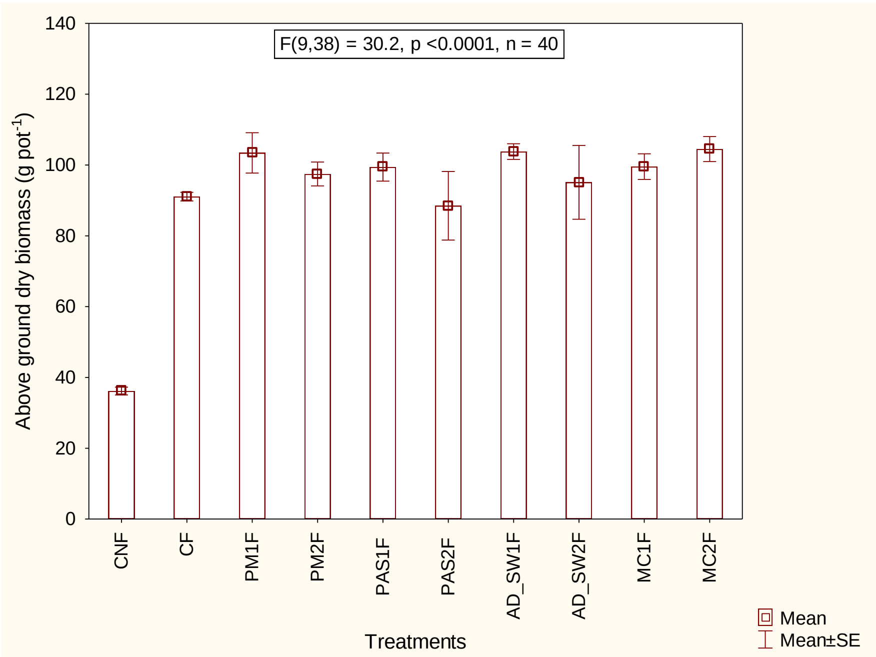


Figure 54 Effect of OA + inorganic fertilizer treatments on AG_{DB} at harvest.

Unlike the PAS1NF and PAS2NF treatments (Figure 53), the significantly higher AG_{DB} recorded for PAS1F and PAS2F treatments is due to the addition of inorganic fertilizer. This is because the NPK in inorganic fertilizers are in a more readily available form than OAs. This result again confirms that the nutrient level in the PAS NF treatments was inadequate and thus cannot support higher biomass production unless it is supplemented by inorganic fertilizer. This is evidenced by the significant correlation that exist between available N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg PK, bioavailable-P and AG_{DB} (Table 25, Section 7.2.1).

7.2.3 Effect of OA (without inorganic fertilizer) treatments on below ground dry biomass (BG_{DB})

Similar to the AG_{DB} result, all the OA treatments gave significantly higher BG_{DB} than the CNF, except for the PAS1NF treatment (Figure 55). This is attributed to NPK and Mg availability (Figure 27, 31 37, 39, Sections 5.1.3–5.1.4, 5.1.7-5.1.8) and their corresponding uptake by the plant (Table 25, Section 7.2.1). At 10 t ha^{-1}, the PM1NF treatment had the highest ($p < 0.05$) BG_{DB}, while the PAS1NF treatment recorded a significantly lower BG_{DB} as compared with all the other treatments, with exception of the CNF treatment. The PM1NF treatment had 87.5%, 90%, 81% and 50% higher BG_{DB} than the CNF, PAS1NF, AD_SW1NF, and MC1NF treatments, respectively. This result confirms that plants require adequate P supply early for root growth and development [Figure 27, Sections 5.1.3] (Mkhabela and Warman, 2005; Jin *et al.*, 2016).

At the higher OA application rate (30 t ha^{-1}), the BG_{DB} was not significantly ($p<0.05$) different between the PM2NF, AD_SW2NF and MC2NF treatments, but these treatments had significantly higher BG_{DB} as compared with the PAS2NF and CNF treatments. This is attributed to the low available N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg associated with the PAS amendment (Table 10, Section 3.3.1; Figure 27, 31 37, 39, Sections 5.1.3, 5.1.4, 5.1.7, 5.1.8). The significantly lower BG_{DB} recorded for PAS2NF compared with all other OA treatments can also be due to nutrient competitions between the plant roots and the soil microbes since the PAS treatments showed significantly higher microbial stress levels as compared with the other OA treatments as evidenced by low C_{mic}:C_{org} (Table 21, Section 6.2.2)

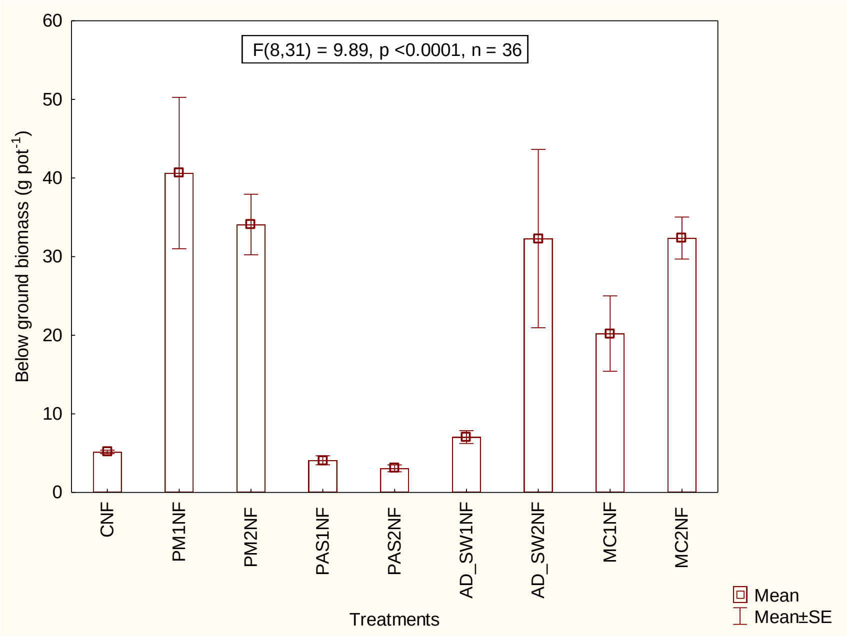


Figure 55 Effect of OA (without inorganic fertilizer) treatments on BG_{DB} at harvest.

Increasing OA application rates from 10 t ha^{-1} to 30 t ha^{-1} significantly increased the $BG_{DB,}$ except for the PM1NF/2NF and PAS1NF/2NF treatments which showed no significant difference (Figure 61). These trends reflect those for the AG_{DB}. In contrast, the BG_{DB} associated with AD_SW2NF and MC2NF treatments were 75% and 39% higher ($p < 0.05$) than the AD_SW1NF and MC1NF treatment, respectively.

OA applications micronutrients as well as major nutrients which enhance nutrient absorption capacity of plants resulting in more root biomass (Manna *et al.*, 2005). Application of OAs to soil has been reported to improve, soil WHC and nutrient availability to plants (Celik *et al.*, 2004), thus improving plant root growth and development (Ahmad *et al.*, 2014). Thus, the observed significant correlations between BD, increased available N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg nutrient levels, AWC and BG_{DB} supports the existing literature (Table 25, Section 7.2.1).

7.2.4 Effect of OA + inorganic fertilizer treatments on below ground dry biomass (BG_{DB})

All OA + inorganic fertilizer treatments at both application rates were associated with significantly higher ($p < 0.05$) BG_{DB} as compared with the CNF treatment (Figure 56). As explained in Section 7.1.7, this is attributable to increased SOM, higher available nutrients (N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K, Mg, increased MB_C, soil AWC; reduced microbial stress and decreased BD [r = 0.38, 0.61, 0.56, 0.39, 0.52, 0.37, -0.36, 0.46 and -0.47, respectively] (Table 25, Section 7.2.1).

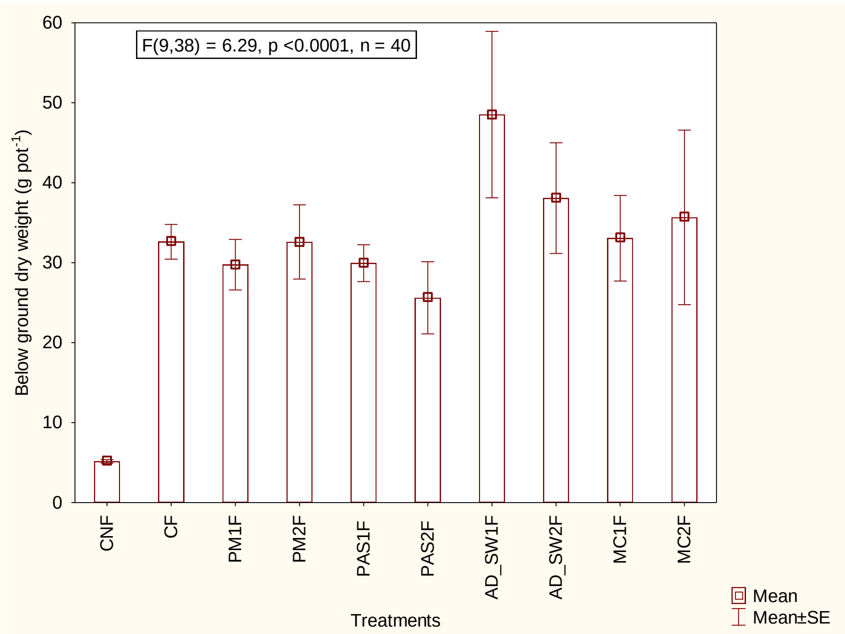


Figure 56 Effect of OA + inorganic fertilizer treatments on BG_{DB} at harvest.

Increasing OA application rates from 10 t ha^{-1} to 30 t ha^{-1} did not significantly increase the BG_{DB} for PM1F/2F, PAS1F/2F, AD_SW1F/2F and MC1F/2F treatments. The non-significant difference in BG_{DB} observed across OA treatment application rates is related to the non-significant difference in the plant root NPK, Mg, Zn and Cu nutrient uptake associated with these OA treatments (Table 26, see Section 7.3.2 for more discussion). The non-significant difference in BG_{DB} can also be attributed to the root exudates. This is because it is reported that the rhizosphere (the soil micro-environment around plant roots) is characterized by high levels of microbial activity that influence SOM decomposition and nutrient cycling (Dijkstra *et al.*, 2013; Bhaduri *et al.*, 2015). Exudates from plant roots are another source of carbon and energy (food) for the soil microbes. Root exudation releases organic compounds such as water soluble sugars, organic sugars, amino acids, vitamins, hormones, amino compounds, phenolics and sugar phosphate esters into the surrounding soil (Bhaduri *et al.*, 2015). Thus, these exudates provide additional nutrients for the soil microbes which through microbial action (mineralization) (Figures 5 and 6, Sections 2.7.3–2.7.4) release available nutrients for plant uptake.

Moharana *et al.* (2012) reported that the combined application of inorganic fertilizer and OAs enhanced soil nutrient supply and improved soil physical properties (Hati *et al.*, 2006), which resulted in higher nutrient uptake and greater BG_{DB}. This is evident by the significant ($p < 0.05$) positive correlation between BG_{DB} and the physical (AWC, r = 46, and BD, r = -47), chemical (Olsen P, r = 0.61, TON = 0.38, Available-K, r = 0.56, Available-Mg, r = 0.39 and SOM, r = 0.52) and biological SQIs [MB_C, r = 0.37 and C_{min}:C_{org}, r =-0. 37] (Table 25, Section 7.2.1).

7.2.5 Summary

- Except for the PAS treatments without inorganic fertilizer, all other OA treatments with or without inorganic fertilizer had significantly higher AG_{DB}, and BG_{DB} than the CNF treatment.
- Overall, the PM treatment applied at 30 t ha^{-1} outperformed the other OA treatments for: number of plant leaves, stem diameter, plant height, V-stages and AG_{DB}.
- Inorganic fertilizer addition had a marked effect on the OA treatments particularly on PAS OAs. This suggests that the PAS amendment alone cannot be used effectively for soil nutrient enrichment for short duration (season), crops such as maize unless it is supplemented with inorganic fertilizer.

- Increasing PM treatment application rates from 10 t ha^{-1} to 30 t ha^{-1} had no significant effects on AG_{DB}, and BG_{DB}. This suggests that higher rates of PM application with or without inorganic fertilizer were providing nutrients (N, P and K) in excess of maize plant requirements (Figures 59-62, Sections 7.4.1–7.4.4).
- It is therefore postulated that frequent application of PM at higher rates can over time result in the accumulation of nutrients (especially P), which may cause environmental hazards/pollution through runoff and leaching.
- The MC and AD_SW amendments gave high K concentrations. Thus, frequent application of both amendments at higher rates can lead to K accumulation, which can induce nutrient imbalances in the soil and consequently affect crop growth and yield performance.

7.3 OA treatment effects on maize cob yield (Cob_{DW})

Following the trends in the maize component plant parts (i.e. number of plant leaves, stem diameter, plant height, AG_{DB} and BG_{DB}) observed across the treatments, it is expected that the PM, AD_SW and MC amended treatments at both application rates will be associated with significantly higher Cob_{DW} than the control (CNF) treatment. This is due to higher nutrient [NPK and Mg] provisioning and availability (Rezig *et al.*, 2013) (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8), increased SOM (Shen *et al.*, 2011) [Figure 31 Section 5.1.6], higher MB_C and biological activities, [Figure 42, Section 6.1; Table 21, Section 6.2], reduced BD, higher porosity, and increased WHC and AWC (Cherif *et al.*, 2009; Moharana *et al.*, 2012; Guo *et al.,* 2016) [Table 15, Section 4.1.1] associated with these OA treatments.

7.3.1 Effect of OA (without inorganic fertilizer) on Cob_{DW}

As anticipated, at the 10 t ha^{-1} application rate, the PM1NF and MC1NF treatments had significantly ($p < 0.05$) higher Cob_{DW} (Figure 57, Section 7.3.1) as compared with the CNF treatment. Gudugi *et al.* (2012), Muyayabantu *et al.* (2012) and Bedada *et al.* (2014) reported higher maize yield following OA application as compared with the un-amended control treatment. The Cob_{DW} in the PM1NF treatment was 100% higher than that in the CNF, PAS1NF, AD_SW1NF treatments, respectively. This is so because the plants grown in CNF and PAS1NF treatments failed to produce cobs at harvest, since they did not achieve tasselling during the reproductive stage (Figure 50 A, Section 7.1.9) due to in adequate nutrient supply. This indicates that nutrients provided by these treatments were insufficient to support cob formation (Table 22, Section 7.1.1).

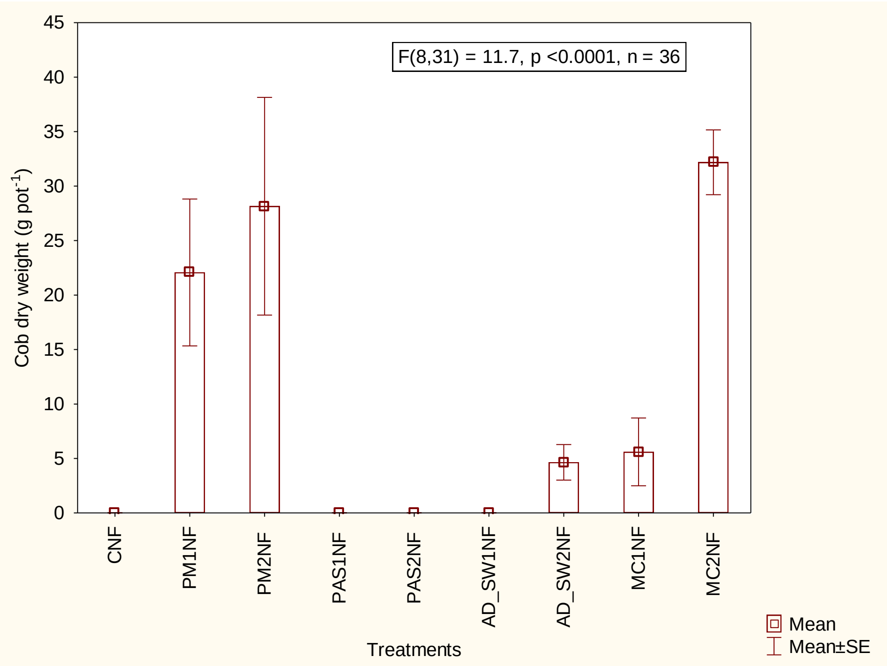


Figure 57 Effect of OA (without inorganic fertilizer) treatments on cob yield dry weight.

The lack of Cob_{DW} for the AD_SW1NF treatment can in large part be attributed to the delay in maize tasselling (the reproductive stage) initiation and the production of fewer silk (the female flowers) observed during the reproductive growth stage (V12) at 7 WAP (Figure 50 A, Section 7.1.9). Again, this is due to the low N-uptake and NUE associated with the AD_SW1NF treatment which inhibited these treatments from tasselling (Figures 59 and 63, See Sections 7.4.1 and 7.5.1 for more discussion). However, the significant correlation (Table 25, Section 7.2.1) between Cob_{DW}, NUE and plant height at tasselling (as proxy measurement of plant tasselling initiation) strongly suggest that delayed tasselling initiation, low N-uptake and NUE associated with the AD_SW1NF treatment explain why the AD_SW1NF treatment produced no Cob_{DW}. At the higher OA treatment application rate (30 ha^{-1}), the PM2NF, AD_SW2NF and MC2NF treatments had significantly higher Cob_{DW} than the CNF treatment. The results indicate that the PM2NF and MC2NF treatments did not significantly differ in their Cob_{DW}, but had significantly higher Cob_{DW} compared with the AD_SW2NF treatment. This is explained above, and is also due to the significantly lower NUE and PUE of the AD_SW2NF treatments as compared with the PM2NF and MC2NF treatments (Figures 63 and 65 Sections 7.5.1 and 7.5.3). This is supported by the significant correlation between the available NP, Total-N, and Cob_{DW} [r = 0.63, 0.40, 0.49] (Table 25, Section 7.2.1) and that between Cob_{DW}, N-uptake, P-uptake, K-uptake, NUE and PUE [r = 0.65, 0.65, 0.74, 0.93 and 0.96, respectively] (Table 28). Increasing the application rate of the OA treatments from 10 t ha^{-1} to 30 t ha^{-1} significantly increased the Cob_{DW} only for the AD_SW2NF and MC2NF treatments. Both treatments had 100% and 79% more ($p < 0.05$) Cob_{DW} than the AD_SW1NF and MC1NF treatments, respectively.

The significantly higher NUE associated with PM1NF as compared with the PM2NF treatment (Figure 63, Section 7.5.1), the non-significant difference in the PUE observed between PM1NF and PM2NF treatments (Figure 65, Section 7.5.3), and the non-significant difference in the N and P concentrations in plant tissues associated the PM1NF and PM2NF treatments (Table 26, see Section 7.3.2 for more discussion) contributed to the similarities in Cob_{DW}. This confirms that the PM treatment applied at 10 t ha^{-1} provided adequate NPK and Mg; even though the P and K supplied via the PM1NF and PM2NF at post-incubation were less than the recommended rates (Figures 32 and 42, Sections 5.13 and 5.17). Therefore, the extra nutrient supply is from microbial mineralization of the OM contained in the OAs (Figures 5 and 6 and Sections 2.73–2.7.4).

In contrast, the significant increase in Cob_{DW} associated with AD_SW2NF and MC2NF treatments suggests that the nutrients provided by the AD_SW1NF and MC1NF treatments are inadequate to support maize cob production. Increasing the OA treatment application provided more nutrient and consequently in creased Cob_{DW}. This is evidenced by the significantly positive correlations between Cob_{DW} and N-uptake, P-uptake and soil nutrients (NPK and Mg) (Table 25, Section 7.2.1). These results suggest 30 t ha^{-1} application rates are required for the AD_SWNF and MCNF treatments to achieve higher Cob_{DW} production.

A multiple regression analysis ($p < 0.05$, $r^2 = 0.78$) revealed that across all treatments and application rates, Cob_{DW} is predicted by the equation:

$$Y = -12 + 0.06(EC) - 8.94(SOM) + 0.07(\text{Available-Mg}) - 2.54(TON) - 0.02(\text{Available-K}) + 0.24(\text{Olsen-P}) \qquad (7)$$

The multiple regression result confirms that adequate nutrients particularly NPK and Mg in addition to SOM and the soil EC content are critical for Cob_{DW} production. This result confirms the findings of Ayers and Westcott (1985) who suggested that a soil EC of ≤1.7 dS m^{-1} is ideal for optimum (100%) maize yield, while a soil EC level of 2.5 dS m^{-1} and 3.8 dS m^{-1} will result in 10% and 25% reduction in maize yield. Biau *et al.* (2012) observed higher nutrient uptake at higher application of N for pig slurry soil amendments applied at 45 m^3 ha^{-1}, equivalent to 315 kg N ha^{-1} $year^{-1}$) and fertilizer applied at 300 kg N ha^{-1} but found no significant differences in the biomass produced, which the authors suggest to be due to some degree of 'luxury consumption'. Cherif *et al.* (2009) observed that municipal solid waste compost (MSWC) and farm yard manure (FYM) application significantly enhanced wheat grain yields. They found that the control treatment had the lowest yield (17.6 t ha^{-1}) while the highest yields (60.2 t ha^{-1}) were obtained following the application of MSWC at 80 t ha^{-1}. The present study found that inadequate nutrient supply delayed maize tasselling particularly the PAS treatments [without inorganic fertilizer addition] and consequently produced no cob formation [low yield performance]. However, this defect was overcome when PAS was supplemented with inorganic fertilizer.

7.3.2 Effect of OA + inorganic fertilizer treatments on Cob Yield DW (Cob_{DW})

In the present study, the results show that inorganic fertilizer addition had a marked effect on Cob_{DW}, particularly in the PAS and AD_SW treatments, due to the higher readily available NPK associated with the inorganic fertilizer (Figures 28, 32, 34, 38, and 40, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8; Table 25, Section 7.2.1). Thus, as predicted, all the OA + inorganic fertilizer treatments had significantly higher ($p < 0.05$) Cob_{DW} as compared with CNF (Figure 58). At 10 t ha^{-1} application rate, the PM1F treatment had the highest Cob_{DW} which was 100%, 18.1%, and 21.2%, higher ($p < 0.05$) than that of the CNF, CF, and PASIF treatments, respectively.

The PM1F treatment Cob_{DW} did not statistically differ from that of the AD_SW1F and MC1F treatments. The maize Cob_{DW} performance was in the order PM1F ≥ MC1F ≥ CF ≥ AD_SW1F ≥ PAS1F > CNF. The higher Cob_{DW} recorded for PAS1F and PAS2F as compared with the CNF treatment is due to the effect of inorganic fertilizer addition which, as anticipated, provided additional available nutrients [NPK], resulting in greater N and P uptake, NUE and PUE [Figures 59-66 Sections 7.4 and 7.5). As explained earlier, the higher Cob_{DW} associated with the OA + inorganic fertilizer treatments as compared to the CNF treatment is due to the positive effects the OAs had on the physical (e.g. increased AWC, reduced BD [Table 15, Section 4.1.1]), chemical (increased N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg nutrient availability, SOM and TOC content (Figures 27, 31, 33, 37, and 39, Sections 5.1.3 - 5.1.5, 5.1.7 and 5.1.8, Table 18, Section 5.1.9.2). and biological (increased MB_C [Figure 42, Section 6.1.1] and microbial activity; reduced microbial stress (due to availability of TOC) [Table 21, Section 6.2.2]) SQIs, which cumulatively resulted in improved crop yield performance. This result is evidenced by the significant correlations that exist between the SQIs (AWC, r = 0.32; BD, r = -0.40; TON, r = 0.63; Total-N, r = 0.49; Olsen-P, r = 0.40; SOM, r = 0.36) and Cob_{DW} (Table 25, Section 7.2.1).

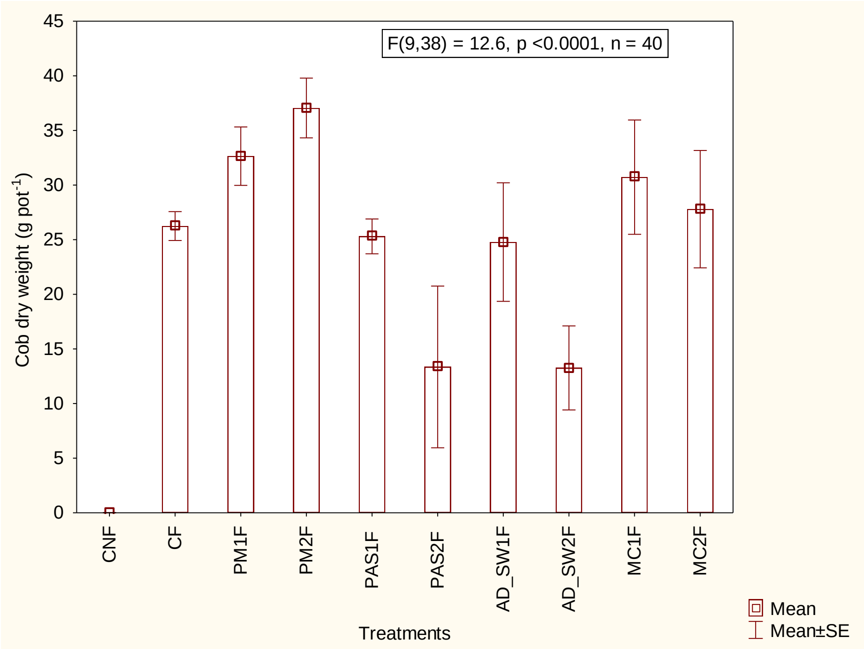


Figure 58 Effect of OA + inorganic fertilizer treatments on cob yield dry weight

Other studies have reported similar results. Grain yield of wheat following the application of FYM varied from 1.67 t ha^{-1} in the unfertilized control treatment, 3.7 t ha^{-1} (in the FYM applied at 20 t ha^{-1}) to 5.33 t ha^{-1} in integrated use of FYM + NPK (applied at 10 t ha^{-1} FYM + 2.5 t ha^{-1} NPK) (Moharana *et al.*, 2012). Application of OAs in combination with the inorganic fertilizer increased soil nutrient supply (Mittra *et al.*, 2005). Cherif *et al.* (2009) found significantly higher wheat grain yields (61.9 t ha^{-1}) with the application of MSWC at 80 t ha^{-1} + NPK fertilizer treatments as compared with the control treatment.

At the 30 t ha^{-1} application rate, all the OA + inorganic fertilizer treatments had higher ($p < 0.05$) Cob_{DW} than the CNF treatment. The PM2F treatment had the highest ($p < 0.05$) Cob_{DW} which was 13.2, 63.2, 63.2 and 21.1% higher ($p < 0.05$) as compared with the CF, PAS2F, AD_SW2F and MC2F treatments respectively. The CF and MC2F treatments did not differ significantly in their Cob_{DW}. However, the PAS2F and AD_SW2F treatments recorded significantly lower Cob_{DW} as compared with the CF treatment. This is in large part attributed to nutrient immobilization by the soil microbes due to the high C:N ratio associated with these OAs (Table 10, Section 3.3.1.2; Table 18, Section

5.1.9.3) which affected the NUE and PUE associated with PAS2F and AD_SW2F treatment (Figure 59, Section 7.5.2 and 7.5.4). This resulted in significantly lower Cob_{DW} (Figure 58).

For PM and MC, increasing OA application rates from 10 t ha^{-1} to 30 t ha^{-1} had no significant effect on the Cob_{DW}. This is attributed to excess nutrient uptake as evidenced by the higher N and P uptake (Figure 60, Section 7.4.2–7.4.4), and reduced NUE and PUE (Figure 64, Section 7.5.2–7.5.4). According to Smith and Loneragan (1997) nutrients absorbed in excess of a plant's immediate requirement are held at different plant parts or lost from plant shoot by guttation [the excretion of droplets of liquid-like sap from plant leaves or tips] or by excretion via the plant roots. For the PM and MC + inorganic fertilizer treatments, PM2F and MC2F treatments were associated with significantly lower NUE and PUE as compared with the PM1F and MC1F treatments (Figure 64, Section 7.5.2–7.5.4). This indicates that the nutrient provided by the PM1F and MC1F treatments were more efficiently utilized than that from the PM2F and MC2F treatments. This can also explain the observed non-significant difference in the Cob_{DW}.

This result suggests that OAs (PM and MC) applied at 10 t ha^{-1} + inorganic fertilizer or at 30 t ha^{-1} alone may be economical to farmers, since no significant effect on the Cob_{DW} was observed. However, applying OA + inorganic fertilizer treatments at 10 t ha^{-1} rates can compromise other benefits (residual effects) associated with OA treatments applied at higher rates [30 t ha^{-1}], such as reduced BD, increased WC_{FC}, AWC, SOM, NPK, Total-N, Total-P, TOC and MB_C (See Chapter 8 for more discussion). Application of 30 t ha^{-1} OAs is strongly recommended. This is because of the anticipated long term soil health (ecosystem) benefits and high yields for subsequent crops.

In contrast, the PAS2F and AD_SW2F treatments had 46.2% and 44% significantly lower Cob_{DW} as compared with the PAS1F and AD_SW1F treatments, respectively. This is attributed to nutrient immobilization by the soil microbes (Figures 5 and 6, Sections 2.7.3-2.7.4) since PAS and AD_SW amendments are associated with high C:N (Table 10, Section 3.3.1.2) which consequently affected nutrient availability for plant uptake [Figure 59, Section 7.4.2–7.4.4]. For instance, the PAS2F treatment was associated with 25% and 4.8% reductions ($p < 0.05$) in N and P-uptake as compared with the PAS1F treatment, respectively (Figure 59, Section 7.4.2–7.4.4).

The NUE and PUE in PAS2F were 42% and 37% lower ($p < 0.05$) as compared with PAS1F treatment. Therefore, the significant reductions in N and P uptake and in NUE and PUE associated with PAS2F contributed to the significant reduction in Cob_{DW} observed between PAS1F and PAS2F treatments (Figure 57). Furthermore, as with the PM1F, PAS1F and MC1F treatments, the NUE and PUE associated with AD_SW1F treatment was significantly higher as compared with the AD_SW2F treatments (Figure 59; Section 7.4.2). This result can further explain the lower ($p < 0.05$) Cob_{DW} associated with the AD_SW2F treatment. Therefore, the highly significant ($p < 0.01$) positive correlations (r = 0.65 and 0.65) that exist between Cob_{DW} and N-uptake and P-uptake and the positive correlations between Cob_{DW} and NUE (r = 0.93) and PUE (0.96) (Table 22, Section 7.4.2) confirms that insufficient nutrient uptake contributed to the significant reduction in the Cob_{DW} associated with the PAS2F and AD_SW2F treatments as compared PAS1F and AD_SW1F treatments, respectively.

Moharana *et al.* (2012) reported significantly higher grain yield of wheat with integrated use of FYM and NPK fertilizers (1.67 t ha^{-1}) as compared with the unfertilized control (5.33 t ha^{-1}). They observed that the significantly higher yield following FYM + NPK application as compared to FYM alone indicated the superiority of integrated nutrient management over the application of either NPK fertilizer or OA alone. This is due to the synergistic effect of the immediate release and availability of nutrients associated with NPK fertilizer and the slow release of nutrients associated with OAs.

The plant nutrient (macro- and micro-nutrients) analysis showed that the nutrient (NPK, Mg, Cu, and Zn) concentrations varied significantly across the OA treatments (Table 26 Section 7.3.2). This is due to the differences in the nutrient content (NPK, and Mg (Figures 27, 31, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8), Cu and Zn (Table 19, Section 5.1.10), SOM content (Figure 36, Section 5.1.6) and the varied pH levels [Figure 24, Section 5.1.2.1] of the OA treatments, which affect the mobility and bioavailability of micro-nutrients in the soil (Zeng *et al.*, 2011).

With the exception of AD_SW1NF and PAS1NF/2NF, the maize grain-NPK, Mg, Zn and Cu concentrations in all other OA treatments with or without inorganic fertilizer were significantly higher as compared with the CNF treatment (Table 26). This is attributed to the effects of the macro- and micro- nutrients supplied via the OAs (Table 11, Sections 3.1.2 and 5.1.10).

The non-significant difference in the grain NPK, Mg, Zn and Cu concentrations observed for AD_SW1NF, PAS1NF/2NF as compared with the CNF treatments is because these OA treatments failed to produce any cob yields due to insufficient nutrient supply via the OAs applied (Figure 57, Section 7.6.1, Table 25, Section 7.2.1).

Table 26 Effect of OA treatments on plant macro-nutrient concentration on dry matter basis (n = 72)

Treatment	Grain-N (g kg^{-1})	Grain-P (mg kg^{-1})	Grain-K (mg kg^{-1})	Grain-Mg (mg kg^{-1})	Shoot-N (g kg^{-1})	Shoot-P (mg kg^{-1})	Shoot-K (mg kg^{-1})	Shoot-Mg (mg kg^{-1})	Root-N (g kg^{-1})	Root-P (mg kg^{-1})	Root-K (mg kg^{-1})	Root-Mg (mg kg^{-1})
OA treatments without inorganic fertilizer												
CNF	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	11.4^{a}	1568^{cde}	20.7^{bcd}	1.73^{a}	5.00^{abc}	776^{bcd}	4.44^{abcd}	1.04^{bc}
PM1NF	14.2^{cde}	2449de	4.14^{bcde}	0.61^{c}	15.0^{abcde}	2293^{fgh}	19.6^{ab}	2.08^{def}	6.80^{cdef}	2159^{i}	3.92^{abd}	1.32^{defg}
PM2NF	18.6^{de}	1436^{bcd}	2.21^{bcde}	0.37^{bc}	33.0^{g}	2881^{hi}	24.6^{efgh}	2.15^{efg}	14.1^{j}	2162^{hi}	5.8^{ce}	1.48^{fg}
PAS1NF	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	14 5^{abc}	2467^{gh}	24.8^{efgh}	2.42^{abcd}	5.20^{abcd}	557^{ab}	4.02^{abd}	0.89^{ab}
PAS2NF	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	13 2^{abcde}	2627^{ghi}	25.6^{h}	2.52^{ab}	5.50^{abcde}	1116^{defg}	3.39^{a}	1.01^{abcd}
AD_SW1NF	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	12.8^{abcde}	3641^{ij}	26.7^{fgh}	2.6^{abc}	9.60^{ghi}	1695^{fghi}	3.87^{ab}	0.84^{a}
AD_SW2NF	11.2^{bc}	1678^{cde}	4.24^{bcde}	0.43^{bc}	14.5^{abce}	4760^{j}	26.5^{h}	2.79^{abcd}	9.90^{hi}	2216^{i}	3.56^{ef}	1.36^{efg}
MC1NF	10.6^{bc}	552^{b}	2.26^{bcde}	0.33^{bc}	11.7^{ab}	1406^{abc}	23.8^{efgh}	3.12^{abcd}	6.30^{bcdef}	1241^{efg}	3.72^{ab}	1.19^{cdef}
MC2NF	12.7^{bcd}	2330de	3.60^{bcde}	0.63^{c}	16.7^{cdef}	2450^{gh}	26^{fgh}	4.24^{cde}	7.50^{efg}	1105^{def}	6.47^{ab}	1.09^{bcde}
OA treatments with inorganic fertilizer												
CF	16.0^{cde}	1406^{bcd}	3.10^{bcd}	0.40^{bc}	17.4^{df}	1043^{a}	17.5^{a}	1.76^{cde}	4.20^{a}	405^{a}	5.28^{ce}	0.97^{abc}
PM1F	15.2^{bc}	2195de	3.92^{bcde}	0.52^{bc}	20.2^{ef}	1984^{defg}	23.1^{defg}	2.03^{fg}	7.00^{def}	1408^{fgh}	5.5^{ce}	1.18^{cdef}
PM2F	20.0^{cde}	2721^{e}	4.50^{cde}	0.27^{c}	39.5^{h}	3625^{ij}	26.1^{gh}	2.1^{g}	13.6^{j}	2263^{i}	8.64^{f}	1.67^{g}
PAS1F	14.2^{cde}	1756^{cde}	3.85^{bcde}	0.48^{bc}	14.6^{abcde}	1113^{ab}	20^{bc}	2.24^{cde}	4.20^{ab}	626^{bc}	4.89^{bcde}	0.97^{abc}
PAS2F	7.0^{b}	929^{bc}	2.02^{b}	0.64^{b}	12.8^{abc}	1787^{cdef}	22.9^{def}	2.52^{abc}	6.20^{bcdef}	676^{bc}	4.44^{abcd}	0.95^{abc}
AD_SW1F	11.3^{bc}	1613^{bcd}	3.07^{bcd}	0.45^{bc}	16.3^{bcdef}	1413^{bc}	22.4^{cde}	2.57^{bcde}	7.50^{efg}	1279^{defg}	5.41^{cde}	1^{abc}
AD_SW2F	17.4^{de}	2088de	5.47^{e}	0.54^{bc}	17.8^{def}	2155^{efgh}	25.9^{fgh}	2.72^{bcde}	10.9^{i}	1719^{ghi}	5.94^{ce}	0.96^{abc}
MC1F	17.8^{de}	1905^{cde}	4.85^{de}	0.57^{bc}	20.6^{f}	1185^{abc}	24.1^{efgh}	3.02^{def}	7.80^{fgh}	916^{cde}	6.62^{ef}	1.12^{bcde}
MC2F	17.4^{de}	1512^{bcd}	3.72^{bcde}	0.41^{bc}	31.3^{g}	2053^{efgh}	26.8^{h}	3.79^{cde}	11.2^{i}	924^{cde}	8.26^{f}	1.37^{efg}

Means for treatments that is by the same letter are not significantly different ($P \leq 0.05$).

Table 27 Effect of OA treatments plant micro-nutrient concentration on dry matter basis (n = 72)

Treatment	Grain-Zn (µg kg^{-1})	Grain-Cu (µg kg^{-1})	Shoot-Zn (µg kg^{-1})	Shoot-Cu (µg kg^{-1})	Root-Zn (µg kg^{-1})	Root-Cu (µg kg^{-1})
			OA treatments without inorganic fertilizer			
CNF	NA	NA	21.0^{ac}	1.20^{bcd}	16.0^{abcd}	2.0^{bc}
PM1NF	8.90^{bc}	2.50^{bc}	26.0^{abc}	2.10^{cde}	42.0^{g}	12.0^{e}
PM2NF	7.35^{b}	2.70^{bc}	46.0^{defg}	3.50^{cde}	37.0^{fg}	12.0^{e}
PAS1NF	NA	NA	25.0^{abcd}	2.80^{de}	16.0^{abcd}	2.0^{bcd}
PAS2NF	NA	NA	21.0^{abc}	0.50^{abcd}	33.0^{efg}	4.0^{de}
AD_SW1NF	NA	NA	16.0^{a}	0.10^{a}	17.0^{abcd}	3.0^{cde}
AD_SW2NF	6.65^{b}	1.50^{bc}	20.0^{abc}	0.80^{abcd}	23.0^{bcdef}	5.0^{de}
MC1NF	5.55^{b}	0.85^{b}	22.0^{abc}	0.80^{abcd}	24.0^{cdef}	3.0^{cde}
MC2NF	9.80^{bc}	1.75^{bc}	49.0^{efg}	0.30^{ab}	20.0^{abcde}	4.0^{cde}
			OA treatments with inorganic fertilizer			
CF	6.40^{b}	0.80^{b}	33.0^{bde}	1.00^{abc}	16.0^{abcd}	1.0^{a}
PM1F	6.40^{b}	2.75^{bc}	37.0^{bdef}	2.10^{cde}	27.0^{efg}	9.0^{e}
PM2F	13.85^{c}	1.70^{abc}	93.0^{h}	6.20^{e}	35.0^{fg}	10.0^{e}
PAS1F	7.35^{b}	2.00^{bc}	33.0^{bcdef}	13.0^{cde}	15.0^{ab}	1.0^{bcd}
PAS2F	4.80^{b}	1.50^{bc}	25.0^{abc}	4.0^{abc}	17.0^{abcd}	3.0^{cde}
AD_SW1F	8.10^{b}	2.30^{bc}	28.0^{abcd}	6.0^{abc}	14.0^{a}	1.0^{bcd}
AD_SW2F	9.70^{bc}	3.15^{bc}	36.0^{abcd}	9.0^{abc}	21.0^{abcd}	2.0^{b}
MC1F	10.35^{bc}	3.80^{c}	53.0^{fgh}	2.40^{cde}	16^{abcd}	3.0^{cde}
MC2F	8.60^{bc}	2.05^{bc}	73.0^{gh}	1.70^{bcd}	19^{abcd}	3.0^{cde}

NA = Did not produce any cob, Means for treatments that is by the same letter are not significantly different ($P \leq 0.05$).

For the shoot-Zn concentration, only PM2NF, PM1F/2F, and MC1F/2F treatments had significantly higher Zn concentration as compared the CNF treatment. With the exception of PM2F, the shoot-Cu concentration associated with the OA treatment did not vary significantly as compared with the CNF treatment. Similarly, the OA treatments had no significant effect on the root-Zn and Cu concentration as compared with the CNF except for the PM1NF/2NF and PM1F/2F treatments. The significantly higher Zn and Cu concentrations in the plant shoot and root recorded for the PM treatment as compared with the CNF treatment is attributed to the significantly higher Zn and Cu associated with the PM amendment (Table 11, Sections 3.1.2 and 5.1.10). The non-significant effect on the Zn and Cu concentration associated with the other OA treatments and the CNF is attributed to the high degree of variability in the treatment means (Table 27, Section 7.3.2). The high concentrations of these micronutrients in the PM amendment also contributed to the higher plant performance associated with the PM treatments compared other treatments (Table 11, Section 3.3.1.2).

Overall, the concentrations of Zn in maize shoot and root were higher than that of Cu. This is linked to the high Zn concentrations in the amended soil due to the higher concentrations of Zn that is associated with the OAs applied relative to the Cu concentration (Table 11, Sections 3.1.2 and 5.1.10). Gondek (2010) reported higher Zn uptake in maize shoot and roots following OA application.

Overall, the varied effects the OA treatments had on the plant performance indicators is attributed to the significant differences in the composition (N [TON, NH4-N, Total-P], P [Olsen-P and Total-P], Available-K, Available-Mg, OM, TOC, Cu, Zn and MB_C] of the OAs applied (Table 10, Section 3.3.1.2). This is because SOM content is an important soil property that affects micronutrient availability due to its ability to retain the nutrients in the exchangeable form, thereby increasing their bioavailability (Zeng *et al.*, 2011).

7.3.3 Summary

- With the exception of PAS1NF, PAS2NF and AD_SW1NF, the OA treatments at both application rates had significantly higher Cob_{DW} as compared with the CNF treatment.
- However, with inorganic fertilizer addition, the Cob_{DW} associated with all the OA treatments was significantly higher as compared with the CNF treatment by 100%.
- With the exception of PM1NF/2NF and PAS1NF/2NF, increasing OA application rates without inorganic fertilizer increased ($p < 0.05$) Cob_{DW} by more than 80%.

- Increasing treatment application rates for PM1F/2F and MC1F/2F had no significant effect on the Cob_{DW}. This is due to excess nutrient supply resulting in luxury nutrient uptake without corresponding increase in crop yield. However, the PAS1F and AD_SW1F treatments had significantly higher Cob_{DW} as compared to PAS2F and AD_SW2F treatments.
- Except for PAS1NF, PAS2NF and AD_SW1NF, all other OA treatments significantly increased the cob-NPK concentrations.
- Overall, the type/quality of OA treatments had varied effects on the plant nutrient (NPK, Mg, Zn and Cu) concentrations.

7.4 OA treatment effects on nutrient-uptake

Nitrogen is essential for plant growth and yield Research has confirmed that the most limiting factor to crop performance when other conditions are not limiting is nutrient availability and its uptake by plants (Mittra *et al.*, 2005; Moharana *et al.*, 2012). Following OA application it is anticipated that maize grown in the OA treatments (with or without inorganic fertilizer) will be associated with significantly higher nutrient uptake as compared with the control treatment due to greater supply (availability) of nutrients via the OAs applied.

7.4.1 Effect of OA (without inorganic fertilizer) treatment on N-uptake

As anticipated, at 10 t ha^{-1}, the OA treatments with the exception of PAS1NF had significantly higher N-uptake as compared with the CNF treatment (Figure 59). PM1NF was associated with 40.4, 85.6, 68.2, and 40.4% higher ($p < 0.05$) N-uptake than the CNF, PAS1NF, AD_SW1NF and MC1NF treatments respectively. In contrast, the N-uptake recorded for the PAS1NF treatment was the lowest ($p < 0.05$) as compared with all OA treatments. The significantly varied N-uptake observed across treatments (Figure 59) is attributed to the significant differences in the inherent levels of N supplied via the OAs in addition to the significant differences in MB_C associated with the OA treatments (Table 10, Section 3.3.1.2; Figure 42, Section 6.1). MB_C is responsible for OM decomposition and the release of nutrients (Figures 5 and 6, Section 2.7.3 and 2.7.4).

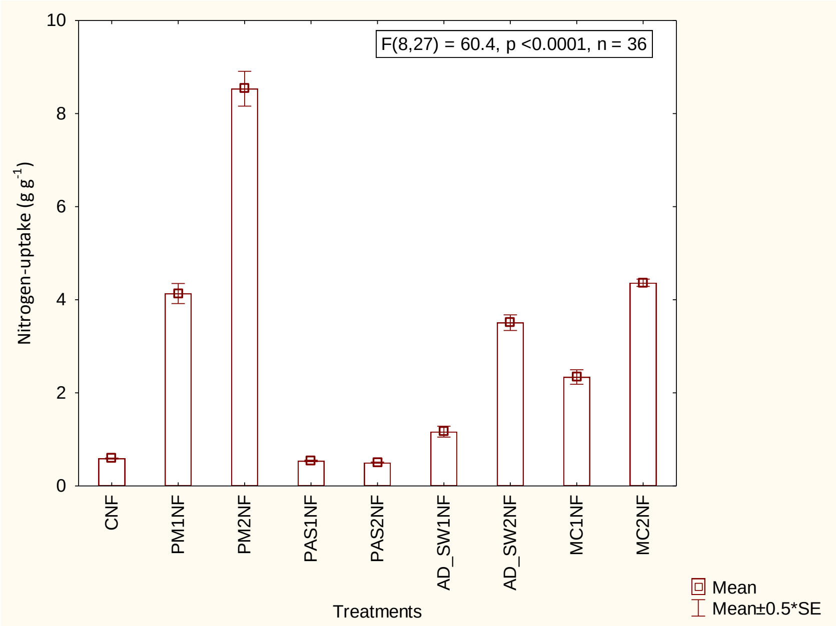


Figure 59 Effect of OA (without inorganic fertilizer) treatments on Plant N-Uptake.

At 30 t ha^{-1}, except for the PAS2NF treatment, all other OA treatments had higher ($p < 0.05$) N-uptake as compared with the CNF treatment. Plant N-uptake was in the order: PM2NF > MC2NF > AD_SW1NF > CNF > PAS1NF. The present results indicate that the higher N-uptake in the OA treatments except PAS, is due to the increased SOM, available nutrients, and higher microbial activities whose activities necessitated the decomposition of organic matter to release nutrients for plant uptake. This is supported by the significant ($p < 0.05$) positive correlation between N-uptake, chemical (Olsen P, r = 0.74, TON = 0.50, Available-K, r = 0.40, Available-Mg, r = 0.61, bioavailable-P, r = 0.73 and SOM, r = 0.52) and biological SQIs [MB_C, r = 0.59 and C_{min}:C_{org}, r = -0. 37 (Table 25, Section 7.2.1).

With the exception of the PAS1NF and PAS2NF treatments (which had statistically the same N-uptake), increase in OA application rates significantly increased the N-uptake across the OA treatments (Figure 62). The high N-uptake from the PM amended treatment can be attributed to the significantly ($p < 0.05$) higher Total-N and NH_4-N and the low C:N associated with the PM amendment (Table 10, Section 3.3.1.2). The significantly higher MB_C (Figure 42, Section 6.1.1) and microbial activity (Table 21, Section 6.2.2) associated with the PM amended treatments is postulated to have facilitated the conversion of NH_4-N to nitrates (NO_3^-, the available form of N) and the release of organically bound N, which then increased N availability and resulted in the observed high N-uptake recorded for the PM amended treatments. Thus, the high N-uptake recorded for the OA treatments in addition to improvement in the physical (Table 15, Section 4.1.1), chemical and (Figures 27, 31, 33, 37, and 39, Sections 5.1.3–5.1.8), and biological SQIs (Figure 42, Sections 6.1.1 and Table 21, Sections 6.2.2) contributed to the high Cob_{DW}, AG_{DB}, and BG_{DB} observed in the PM, AD_SW and MC treatments as compared with the CNF treatment. This is supported by the highly significant ($p < 0.01$) positive correlations ($r = 0.65$, 0.91 and 0.75) between N-uptake and Cob_{DW}, AG_{DB} and BG_{DB}, respectively (Table 28, Section 7.4.2).

As explained in previous sections, the non-significant effect of PAS1NF and PAS2NF on the plant performance is attributed to the similarity of N-uptake for these treatments. It is therefore suggested that the type/quality of OA applied has a highly significant impact on N-availability for plant uptake. The present study supports the existing knowledge that plant N-uptake is a function of N-availability in the soil (Carpici and Celik, 2010; Inamullah *et al.*, 2011; Mariano *et al.*, 2015).

7.4.2 Effect of OA + inorganic fertilizer treatments on N-uptake

At 10 t ha^{-1}, all the OA treatments had significantly higher N-uptake as compared with the CNF treatment (Figure 60). The PM1F and MC1F treatments had the highest ($p < 0.05$) N-uptake compared with CNF, CF, PAS1F and AD_SW1F, respectively. Similarly, at 30 t ha^{-1}, all the OA treatments had significantly ($p < 0.05$) higher N-uptake as compared with the CNF treatment. Further, the PM2F treatment was associated with N-uptake higher ($p < 0.05$) than the CF, CNF PAS2F, AD_SW2F and MC2F treatments. The higher N-uptake in the PAS1F/2F treatments compared with the CNF is attributed to greater N provisioning due to the combined effects of the OA + inorganic fertilizer (Figure 31, Sections 5.1.4–5.1.5).

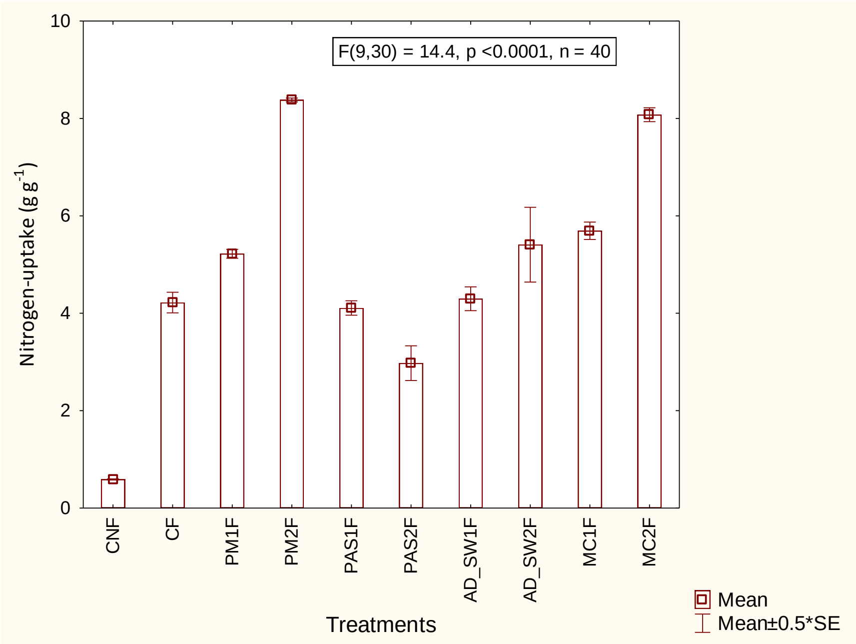


Figure 60 Effect of OA + inorganic fertilizer treatments on N-uptake.

Increasing OA application rates from 10 t ha^{-1} to 30 t ha^{-1} resulted in significant ($p < 0.05$) increases in N-uptake, except for AD_SW1/2F. The PM2F and MC2F treatments had 37.5 and 21.2% higher ($p < 0.05$) N-uptake as compared with the PM1F and MC1F treatments, respectively. In contrast, there was a significant decrease in N-uptake with increasing rates of PAS application. This is attributed to N immobilization due to inherently low N and a high C:N associated with PAS (Table 10, Section 3.3.1.2) which created competition between the microbes and plants for available N. Thus, the PAS2F treatment recorded 40% lower N-uptake as compared with the PAS1F treatment. This accounted for a 50% significant reduction in the Cob_{DW}, and 22.5% and 15.4% lower AG_{DW} and $BG_{DW,}$ respectively, for the PAS2F treatment as compared with the PAS1F treatment (Figure 60, Section 7.4.2).

Yang *et al.* (2014) reported higher maize yield following OA application (with and without NPK fertilizer) which they attributed to higher plant nutrient uptake. Lupwayi *et al.* (2005) reported that plants that received hog manure absorbed more N than the un-amended control treatment and that this enhanced crop yield performance.

Table 28 Correlation coefficients between Cob_{DW}, AG_{DB}, BG_{DB}, PH_T and uptake (n = 72)

	AG_{DB} (g)	BG_{DB} (g)	7 WAP-PH_T (cm)	N-uptake (g g^{-1})	NUE (g g^{-1})	P-uptake (mg g^{-1})	PUE (g g^{-1})	K-uptake (mg g^{-1})	Cu-uptake (µg g^{-1})	Zn-uptake (µg g^{-1})
OA treatments without inorganic fertilizer										
Cob_{DW} (g)	0.68**	0.59**	0.76**	0.65**	0.93**	0.65**	0.96**	0.74**	0.62**	0.83**
AG_{DB} (g)		0.88**	0.93**	0.91**	0.63**	0.91**	0.65**	0.97**	0.80**	0.94**
BG_{DB} (g)			0.81**	0.75**	0.58**	0.83**	0.58**	0.82**	0.66**	0.83**
7 WAP PH_T(cm)				0.78**	0.76**	0.88**	0.75**	0.92**	0.73**	0.90**
N-uptake (g g^{-1})					0.51*	0.84**	0.59**	0.90**	0.86**	0.93**
NUE (g g^{-1})						0.60**	0.95**	0.69**	0.50*	0.72**
P-uptake (mg g^{-1})							0.57**	0.92**	0.82**	0.88**
PUE (g g^{-1})								0.72**	0.48*	0.78**
K-uptake (mg g^{-1})									0.75**	0.93**
Cu-uptake (µg g^{-1})										0.84**
OA treatments with inorganic fertilizer										
Cob_{DW} (g)	0.71**	0.50*	0.73**	0.71**	0.84**	0.62**	0.73**	0.68**	0.57**	0.69**
AG_{DB} (g)		0.72**	0.84**	0.78**	0.62**	0.74**	0.49*	0.91**	0.46*	0.65**
BG_{DB} (g)			0.57**	0.55**	0.51*	0.53*	0.41*	0.67**	0.11ns	0.52*
7 WAP HT (cm)				0.66**	0.69**	0.74**	0.45*	0.78**	0.48*	0.58**
N-uptake (g g^{-1})					0.34*	0.82**	0.36*	0.91**	0.60**	0.92**
NUE (g g^{-1})						0.34*	0.78**	0.44*	0.23ns	0.31*
P-uptake (mg g^{-1})							0.07ns	0.84**	0.71**	0.81**
PUE (g g^{-1})								0.32*	0.07ns	0.29*
K-uptake (mg g^{-1})									0.55*	0.82**
Cu-uptake (µg g^{-1})										0.57**

* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$, ns = not significant.

7.4.3 Effect of OA (without inorganic fertilizer) treatments on P-uptake

Similar to N-uptake, OA treatments were associated with significantly higher P-uptake than the CNF treatment, due to higher SOM, increased nutrient [N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg] availability, improved MB_C, microbial activities, and improved physical SQIs (e.g. lower BD, increased WC_{FC} and AWC). This is evidenced by the significant relationships that exist between SOM, nutrient availability, MB_C, microbial activities and P-uptake. This is evident by the significant ($p < 0.05$) positive correlation between N-uptake, chemical (Olsen P, r = 0.74, TON, r = 0.42, Available-K, r = 0.62, Available-Mg, r = 0.67 and SOM, r = 0.62, bioavailable-P, r = 0.72) and biological SQIs [MB_C, r = 0.55 and C_{min}:$C_{org,}$ r = -0. 45 (Table 25, Section 7.2.1). At 10 ha^{-1}, P-uptake associated with the PM1NF, AD_SW1NF and MC1NF treatments was significantly ($p < 0.05$) higher compared with the CNF treatment (Figure 61). P-uptake was in the order: PM1NF > MC1NF > AD_SW1NF = PAS1NF = CNF. The high P-uptake observed for the PM1NF treatment is due to the significantly ($p < 0.05$) higher Olsen-P and Total-P associated with PM compared with the other OAs (Table 10, Section 3.3.1.2 and Table 18, Section 5.1.10).

As mentioned earlier, plant available-P (Olsen-P) in PM relative to the other OA treatments was significantly higher (Figure 8, Section 3.3.2), even though the P supply at post-incubation was less than the RB209 recommended rates (Figure 29, Section 5.1.3) due to P-adsorption by $CaCO_3$ and immobilization by soil microbes (Figure 5, Section 2.7.3 and Figure 29 A, Section 5.1.3). However, with respect to the Total-P, the P supply was over 80% more than the RB209 P recommended rate (Figure 9, Section 3.3.2 and Figure 29 B, Section 5.1.3). This therefore suggests that the high ($p < 0.05$) MB_C associated with the PM facilitated the release of available-P for plant uptake through mineralization (Figure 5, Section 2.7.3).

At 30 t ha^{-1}, all the OA treatments had significantly higher P-uptake as compared with the CNF treatment. The PM2NF treatment also recorded the highest P-uptake. The result shows that increasing OA application rate resulted in significantly greater P-uptake, due to higher available-P (Figure 27, Section 5.1.3).

The PAS2NF, AD_SW2NF and MC2NF treatments had 16.7%, 62.5% and 41.5% higher P-uptake than the PAS1NF, AD_SW1NF and MC1NF treatments, respectively. In contrast, the PM2NF and PM1NF treatments were not statistically different in their P-uptake levels. Though the PM2NF treatment had significantly higher soil Olsen-P levels than the PM1NF treatment (Figure 27, Section 5.1.3), the non-significant difference in the P-uptake observed between the PM1NF and PM2NF treatments suggests that available-P provided via PM2NF was in excess of what the plant needed (Figure 61).

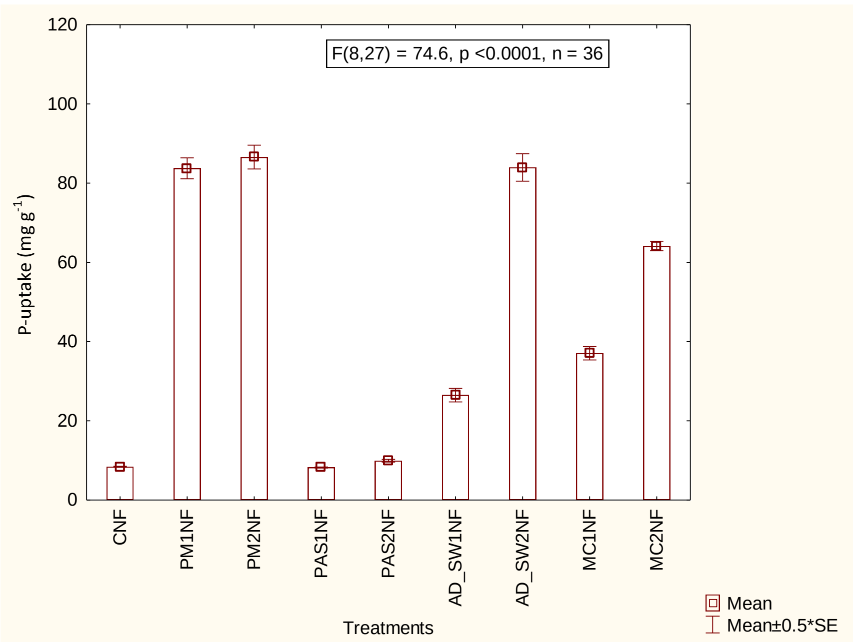


Figure 61 Effect of OA (without inorganic fertilizer) treatments on P-uptake.

7.4.4 Effect of OA +inorganic fertilizer on P-uptake

All OA + inorganic fertilizer treatments at both application rates had significantly higher ($p < 0.05$) P-uptake as compared with the CNF treatment (Figure 62). P-uptake was in the order: PM1F > AD_SW1F ≥ MC1F > PAS1F > CNF. A similar trend was observed at 30 t ha^{-1} (PM2F > AD_SW2F ≥ MC2F > PAS2F > CNF).

The significantly higher P-uptake as compared with the CNF observed for PAS1F, PAS2F and AD_SW1F is attributed the effects of inorganic fertilizer addition which increased the soil P nutrient supplying capacity (Mittra *et al.*, 2005) and the corresponding increased P-uptake. This result can further explain the reason for greater increases in the number of plant leaves, plant height, height at tasselling and, growth stage recorded for AG_{DB} and BG_{DB}, particularly for the PAS amended + inorganic treatments. Other studies have reported similar results. Lupwayi *et al.* (2005) observed that P uptake was greater in plants grown on soils amended with cattle manure and inorganic fertilizer treatments than in the untreated control treatment. The significant ($p < 0.01$) correlations ($r = 0.73$ and 0.44) (Tables 25, Section 7.2.1) that exist between N and P uptake and MB_C confirms that MB_C can be used as an indicator of potential nutrient availability for plant uptake (Jannoura *et al.*, 2013).

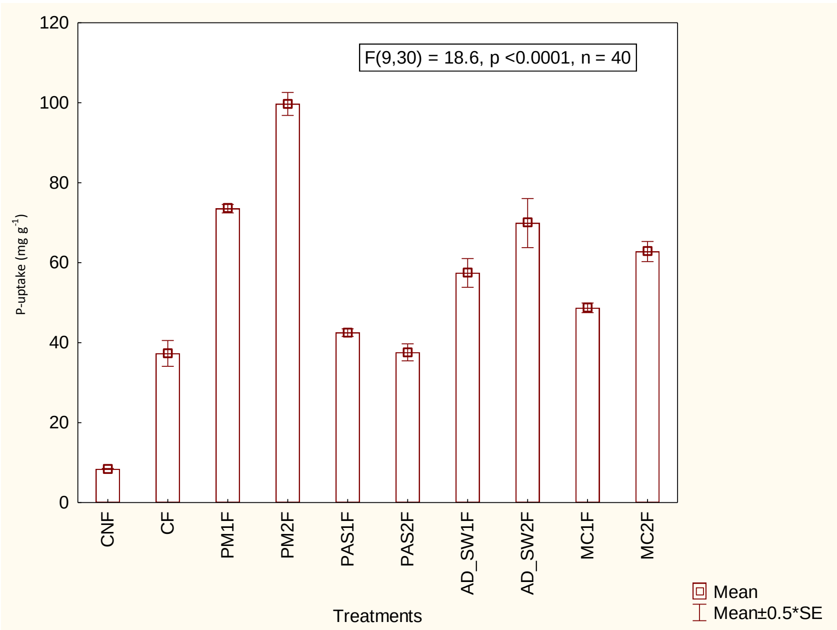


Figure 62 Effect of OA + inorganic fertilizer treatments on P-uptake.

7.4.5 Summary

The results demonstrate the effectiveness of OAs with or without inorganic fertilizer addition in influencing plant nutrient N and P uptake.

- With the exception of the PAS treatments, all other OAs had higher ($p < 0.05$) N and P-uptake as compared with the CNF treatment.
- N and P-uptake associated with the PAS treatment at both application rates was significantly lower than for all other OA treatments.
- With inorganic fertilizer addition, the N and P-uptake from the PAS treatments increased ($p < 0.05$) by over 80% as compared with the CNF treatment. This confirms that the N and P nutrients associated with PAS amendment are deficient and cannot adequately support maize cob production unless inorganic fertilizer is also added. This is evidently supported by the significant correlation that exists between available N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg nutrient, bioavailable-P, nutrient (N and P) uptake, SOM, MB_C and crop performance indicators (Tables 25 and 28, Sections 7.3.1–7.4.2).

7.5 OA treatment effects on N and P utilization efficiency

Nutrient utilization efficiency (NUE) measures the effectiveness of plant nutrient uptake relative to the yield produced. Therefore, NUE is a function of the capacity of the soil system to supply adequate levels of nutrients, and the ability of the plant to acquire, transport and remobilize the nutrients to other parts of the plant (Baligar *et al.*, 2001). Thus, in this study, it is expected that the OA treatments will be associated with higher N and P utilization efficiency [NUE and PUE] as compared with the CNF treatment.

7.5.1 Effect of OA (without inorganic fertilizer) treatments on NUE

With the exception of PAS1NF and AD_SW1NF treatments, the PM1NF and MC1NF treatments had significantly higher NUE as compared with the CNF treatment (Figure 63). The NUE in the PM1NF treatment was 100, 100, 100 and 67% higher than that in the CNF, PAS1NF, AD_SW1NF and MC1NF treatments, respectively. This is attributed to increased N nutrient (Figure 31, Section 5.1.4), SOM (Figure 35; Section 5.1.6), higher MB_C (Figure 42, Section 6.1) and microbial activities (Table 21, Sections 6.2) associated with the PM treatment compared with the other OA treatment. This is further supported by the significant correlations [r = 0.50 and 0.39] that exist between NUE, available N and Total-N nutrients (Table 25, Section 7.2.1). The non-significant difference in NUE observed for the CNF, PAS1NF, PAS1NF and AD_SW1NF treatments is linked to the inability of these treatments to achieve Cob_{DW} since NUE is a ratio of cob yield (DW) to N uptake. The higher NUE associated with the PM1NF treatment can further explain why plants in PM1NF treatment had higher Cob_{DW}, AG_{DB}, and BG_{DB} as compared with the CNF, PAS1NF, AD_SW1NF and MC1NF treatments (Tables 25 and 28, Sections 7.2.1 and 7.4.2). These findings support other studies that found higher NUE by plants enhance crop yields (Baligar *et al.*, 2001).

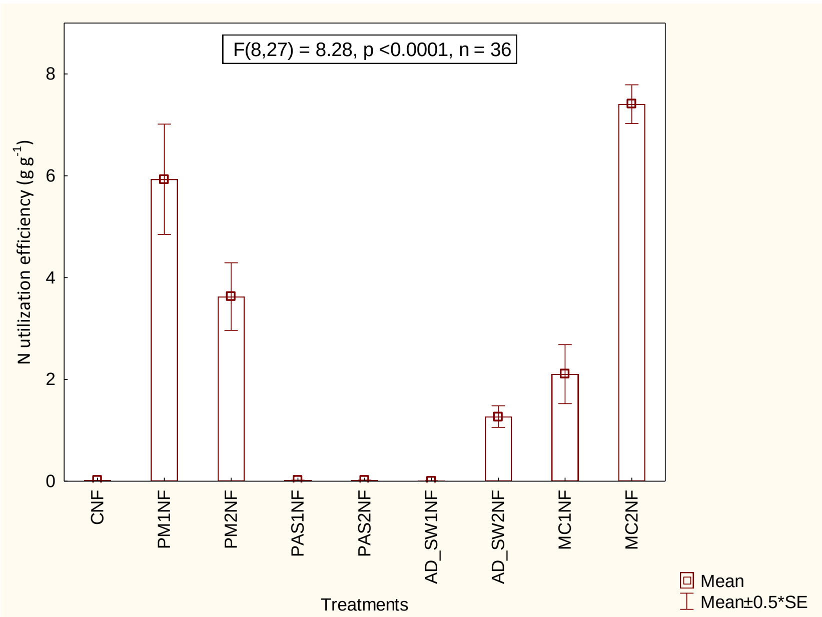


Figure 63 Effect of OA (without inorganic fertilizer) treatments on N-utilization efficiency.

At 30 t ha^{-1} treatment application rate, with the exception of the PAS2NF treatment, all other OA treatments had significantly higher NUE as compared with the CNF treatment (Figure 63). The NUE was in the order PM2NF >

MC2NF > AD_SW2NF > PAS2NF = CNF. Further, increasing treatment application rates from 10 t ha^{-1} to 30 t ha^{-1} was associated with a significant increase in NUE, except between the PAS1NF and PAS2NF treatments which had no significant effect on NUE. In contrast, the NUE in PM2NF treatment was significantly lower as compared with the PM1NF treatment. The significantly lower NUE associated with the PM2NF treatment compared with PM1NF treatment contributed to the non-significant ($p < 0.05$) difference in the AG_{DB} and BG_{DB} observed between PM1NF and PM2NF treatments (Figures 53 and 55, Sections 7.2.1 and 7.2.3). This is evident by the strong correlations between the plant performance attributes and NUE (Table 28, Section 7.4.2). This result thus confirms that the PM2NF treatment supplied N in excess of plant requirement, which resulted in excess uptake of N with no corresponding increase in yield

7.5.2 Effect of OA + inorganic fertilizer treatments on NUE

Following inorganic fertilizer addition, the OA treatments at both application rates had significantly higher NUE as compared with the CNF treatment (Figure 64). The results further indicate that at 10 ha^{-1} application rates, the NUE recorded for the OA + inorganic fertilizer treatments was not statistically different from the CF treatment. The 30 t ha^{-1} OA + inorganic fertilizer treatments had significantly lower NUE as compared with the CF treatment and the OA + inorganic fertilizer treatments applied at 10 t ha^{-1}, respectively. The significantly lower NUE associated with the OA treatments at 30 t ha^{-1} + supplementary inorganic fertilizer is due to the excess N-uptake with no corresponding significant effect on AG_{DB}, BG_{DB}, and Cob_{DW} (Figures 54, 56, and 58, Section 7.2.2, 7.2.4 and 7.3.2, respectively). According to Rezig *et al.* (2013) addition of OAs had a priming effect on inorganic fertilizer use efficiency by enhancing organic matter decomposition and the release of N.

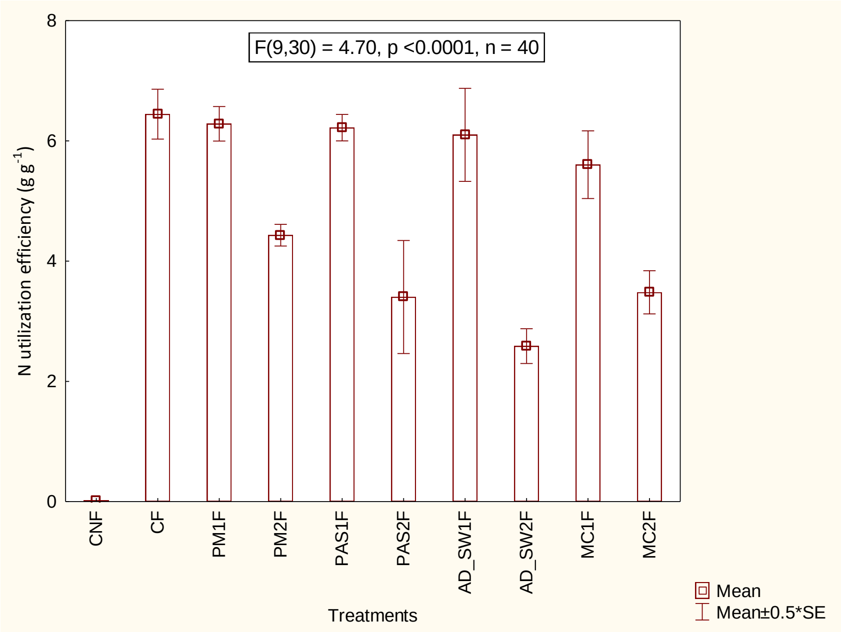


Figure 64 Effect of OA + inorganic fertilizer treatments on N-utilization efficiency.

7.5.3 Effect of OA (without inorganic fertilizer) on treatments PUE

The results show that at 10 t ha^{-1} OA application rate, the OA treatments had significantly higher PUE as compared with the CNF treatment except for PAS1NF treatment, which was not statistically different to the CNF treatment (Figure 65). The PM1NF treatment had 89, 89, 66.7 and 50% higher PUE than the CNF, PAS1NF, AD_SW1NF and MC1NF treatments respectively. At 30 t ha^{-1}, except for the PAS2NF treatment, the PM2NF, AD_SW2NF and MC2NF treatments had significantly higher PUE as compared with the CNF treatment. Increasing OA application rates had varied effects on PUE. For instance, the AD_SW2NF and MC2NF treatments had 68.4 and 40% higher ($p < 0.05$) PUE than the AD_SD1NF and MC1NF treatments, respectively. Meanwhile, the PUE in the PM2NF and PAS2NF treatments did not differ significantly as compared with the PM1NF and PAS1NF treatments, respectively.

The non-significant difference in the PUE observed between PM1NF and PM2NF treatments is explained by their similar P-uptake levels (Figure 61, Section 7.4.3). The result implies that the P supplied via the PM1NF treatment was more effectively utilized by the plant than that from the PM2NF treatment;

suggesting that the available-P levels in PM1NF is sufficient for maize crop production. This is evident by the similarity in the Cob_{DW} observed between PM1NF and PM2NF treatments (Figure 57, Section 7.3.1). Further, the non-significant difference in the PUE between the PM1NF and PM2NF treatments can explain the similarity in the AG_{DB}, and BG_{DB} associated with PM1NF and PM2NF (Figure 53, Sections 7.2.1). The strong correlations between the plant performance attributes and PUE (Table 25, Section 7.2.1) confirms that the available-P provided by the PM1NF treatment met the maize P nutrient requirement for yield production.

The PM2NF treatment appears to supply more nutrients than the plant required, with no corresponding increase in crop performance as compared with the PM1NF treatment. Besides the 'luxury' P-uptake (due to excess P supply via the PM2NF treatment), the residual P associated with PM2NF can be a positive legacy effect for the next crop or possibly pose a pollution risk (Baligar *et al.*, 2001; Roberts, 2008), especially with repeated application of PM at 30 t ha^{-1} (See Chapter 8 for more discussion).

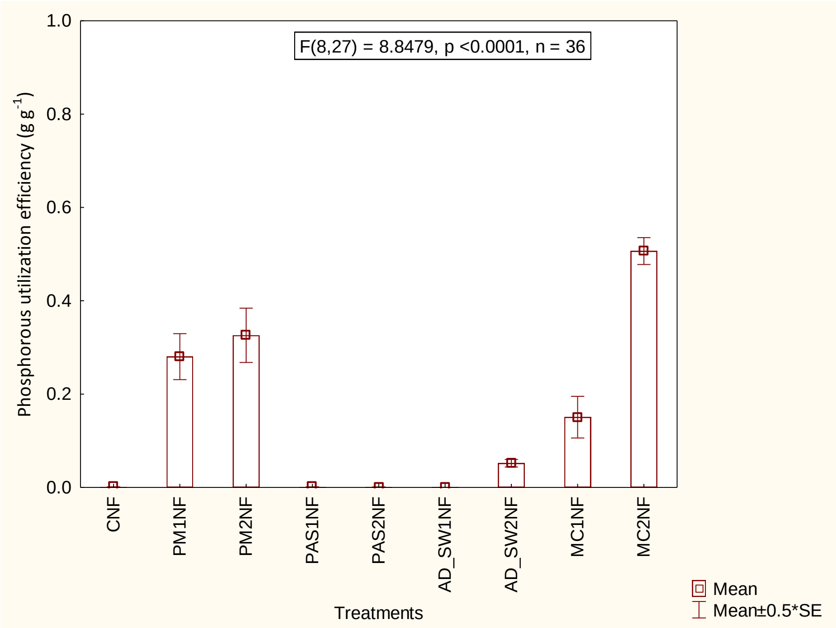


Figure 65 Effect of OA (without inorganic fertilizer) treatments on P utilization efficiency.

7.5.4 Effect of OA + inorganic fertilizer treatments on PUE

At 10 t ha^{-1} and 30 t ha^{-1} the OA with inorganic fertilizer treatments had significantly higher PUE as compared with the CNF treatment (Figure 66). Similar to the NUE result, it was observed that the OA + inorganic fertilizers at 30 t ha^{-1} rates had lower ($p <0.05$) PUE when compared with OA + inorganic fertilizer treatments at 10 t ha^{-1} rate. These significant decreases in PUE at 30 t ha^{-1} following inorganic fertilizer addition are due to excess P supply (Figure 31, Section 5.1.3), which resulted in luxury P-uptake with no significant effect in plant yield (Figure 58, Section 7.6.2 for more discussion). This suggests that the P in the OA + inorganic fertilizer applied at 10 t ha^{-1} was more effectively utilised since the Cob_{DW} in the PM1F and PM2F treatments did not differ significantly (Figure 57, see Section 7.6.1 for more discussion), while both treatments varied significantly in their P-uptake (Figure 62, Section 7.4.4). This result corroborates the findings of Elliott and White (1994) who reported significant reduction in the PUE with increase in the supply of P for red pines seedlings. However, there is insufficient available information on the PUE for arable (cereal) crops. Further, like the NUE, there is no obvious mechanism as to why higher (30 t ha^{-1}) rates of OA treatments + inorganic fertilizer had significantly lower PUE compared with lower rates (10 t ha^{-1}) of OA treatments + inorganic fertilizer. Nevertheless, this result suggests that the P supplied via OA + inorganic fertilizer treatments at 10 t ha^{-1} was better utilised (higher PUE) than the 30 t ha^{-1} OA + inorganic fertilizer treatments.

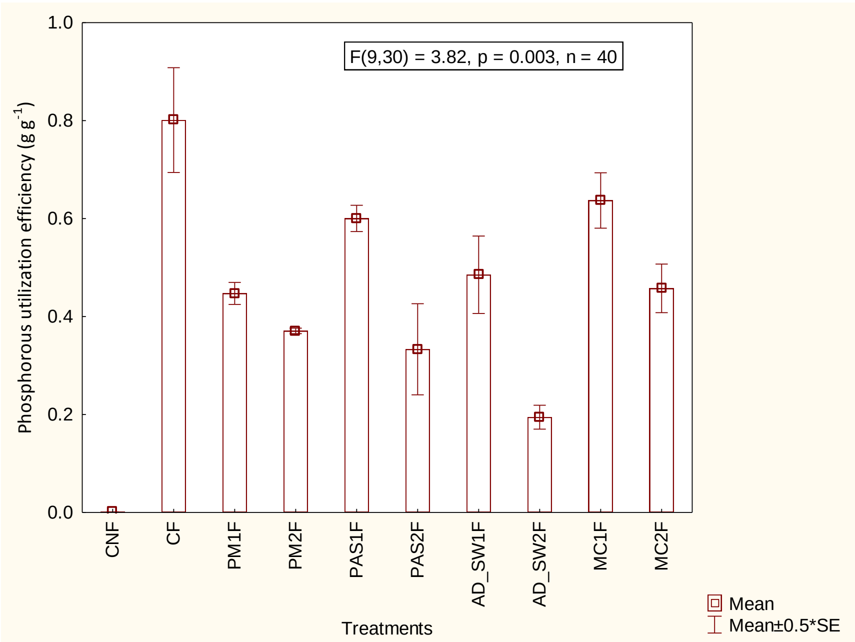


Figure 66 Effect of OA + inorganic fertilizer treatments on P utilization efficiency.

7.5.5 Summary

The results indicate that:

- The OA treatments had significantly higher NUE compared with the CNF treatment with the exception of PASNF.
- With inorganic fertilizer addition, the NUE associated with the PAS treatment was significantly higher than the CNF treatment. This explains why PAS + inorganic fertilizer had higher biomass and cob yields

compared with the CNF treatment (Tables 25 and 63, Sections 7.2.1 and 7.5.1).

- The trends in the NUE and PUE were the same across the OA treatments.
- An increase in OA treatment application rates + inorganic fertilizer addition significantly lowers the NUE and PUE by over 10% and 12%, respectively.
- The study therefore suggests that the type/quality of OA applied affect plant nutrient availability, nutrient uptake, NUE and PUE (Tables 10 and 63, Sections 3.3.1.2 and 7.5.1).

7.6 Conclusions

The results indicate that OA treatments, with the exception of PAS without inorganic fertilizer, had significant, positive effects on plant performance indicators [number of plant leaves, plant height, stem diameter, AG_{DB}, BG_{DB} and Cob_{DW}] as compared with the CNF treatment. Except for PAS1NF/2NF and AD_SW1NF, all other OA treatments increased cob yield by 100% as compared with the CNF treatment. The OA treatments at either application rates without inorganic fertilizer significantly increased plant NP-uptake relative to the CNF treatment by over 40%, except for PAS. OA treatments + inorganic fertilizer addition had marked effects on plant performance, particularly the PAS treatments. This is attributed to the synergistic effect of the immediate release and availability of nutrients associated with NPK fertilizer and the slow release of nutrient associated with OAs. The result suggests that PAS should be supplemented with inorganic fertilizer to reduce microbiological stress and enrich soil with adequate nutrients for crop performance.

Table 29 SQIs that most strongly correlated with the plant performance indicators

SQIs	Cob_{DW} (g)	AG_{DB} (g)	BG_{DB} (g)	PH_T (cm)
		OA treatments without fertilizer		
EC	r* = 0.63	r = 0.57	-	r = 0. 64
TON	r = 0.63	r = 0.56	-	r = 0.55
Olsen-P	r = 0.40	r = 0.67	r = 0.61	r = 0.54
Available-K	-	r = 0. 53	r = 0. 56	r = 0.49
Available-Mg	-	r = 0. 53	-	r = 0.46
Total-N	r = 0.49	r = 0. 64	r = 0.52	r = 0 52
Total-P	-	-	r = 0.52	r = 0.43
Bioavailable-P	r = 0.56	r = 0.64	r = 0.51	r = 0.54
SOM	-	r = 0. 53-	r = 0.52-	r = 0.43
TOC	-	r = 0. 53-	r = 0.49	-
Bioavailable-TOC	-	-	r = 0.72-	r = 0.60
AWC		r = 0.56	r = 0. 46	r = 0.44
BD	r = -0.40	r = -0.51	r = -0.47	r = -0.43
		OA treatments with inorganic fertilizer		
TON	-	r = 0.47	r = 0.51	-
Olsen-P	r = 0.40	-	-	
Available-K	-	r = -0.44	r = 0.44	r = 0.46
Available-Mg	-	-	-	-
Total-N	r = 0.42	r = 0.49	-	r = 0.48
Total-P	-	r = 0.51	-	r = 0.48
Bioavailable-P	-	-	-	r = 0.54
SOM	-	r = 0.45	-	r = 0.45
TOC	-	r = 0.49	-	r = 0.49
Bioavailable-TOC	r = 0.40	-	-	r = 0.46
C_{min}:C_{org}	r = -0.64	r = -0.84	r = -0.62	r = -0.81
AWC		r = 0.47	-	r = 0.53
BD	-	-	-	r = -0.40

r* = Correlation coefficient, AWC = Available water capacity, BD = Bulk density, SOM = Soil organic matter, EC = Electrical conductivity, TON = Total oxides of nitrogen, TOC = Total oxides of carbon, C_{min}:C_{org} = microbial quotient.

Across OA treatments application rates, the SQIs that most strongly correlated with the plant performance indicators are summarized in Table 29 (Section 7.6). The result indicate that the effects of the amendments on key plant performance indicators was in the order: PM > AD_SW ≥ MC > PAS.

The present study demonstrates the efficacy of the OAs in not only improving the physical, chemical and biological SQIs (see Chapters 4, 5, and 6) but also in increasing crop growth and yield performance. It is therefore suggested that OAs (PM and MC in particular) applied at 10 t ha^{-1} + inorganic fertilizer or at 30 t ha^{-1} alone could be economical to farmers, since the Cob_{DW} associated with PM1F/PM2F and MC1F/MC2F did not differ significantly. However, for long term soil health benefits and subsequent greater crop yields, OAs applied at 30 t ha^{-1} is recommended.

8 RESULTS AND DISCUSSION – Residual Effect of OAs on SQIs Post-harvest

As hypothesized, the OA are expected to have significant positive effects on the physical (i.e. increase WC_{FC}, EAW, AWC, porosity and decrease BD), chemical (increase soil nutrients [NPK, Mg, Total-N, Total-P] and SOM contents) and biological SQIs (increase MB_C and microbial activity), as compared with the CNF treatment. This section evaluates the legacy effects of OA application on the SQIs, post-harvest (POH).

8.1 Treatment effects on the physical SQIs at post-harvest

The results indicate that the significantly higher WC_{FC} associated with the OAs relative to CNF at post-incubation (POI) (except for PM1NF/1F and MC1F) was sustained to POH, with the exception of PAS1NF/1F and MC2NF/2F treatments (Table 30, Section 8.1). The high variability in the data meant the PAS1NF, MC2NF and MC2F treatments WC_{FC} were not statistically different from CNF. The EAW associated with the PM2NF/2F, PAS2NF/2F and AD_SW2NF/2F treatments at POI was significantly higher as compared with the CNF treatment. This significant effect was also seen at POH, with the exception of PAS2F (Table 30, Section 8.1). This is attributed to the significantly higher OM content associated with the OAs as compared with the CNF treatment (Table 10, Section 3.3.1.2).

The significant positive effect of PAS2NF and MC2NF/2F on AWC relative to the CNF treatments at POI was not observed at POH (Table 30, Section 8.1). This is due to the high variability (noisy data) within the treatments, and due to the effect of plant root growth. In contrast, the significantly higher AWC associated with PM2NF, PM1F/2F, PAS1F/2F and AD_SW1/F2F at POI was carried over to POH, demonstrating the legacy effect of the OAs.

At POH, with the exception of PAS1NF and MC1F, the OA at both application rates with or without inorganic fertilizer addition significantly lowered the soil BD by 13-53% as compared with the CNF treatment. This follows the trend observed at POI (Table 15, Section 4.1.1). Similar to the result obtained at POI, the PM1NF/2NF, PAS2NF, AD_SW1NF/2NF, and MC2NF, PM1F/2F, PAS2F, AD_SW1/F2F and

MC2F treatments recorded significantly higher soil porosity as compared with the CNF treatment. However, for PAS2NF and MC1F; the significantly higher soil porosity observed at POI was not sustained through to POH. In contrast, PAS1F and MC1NF treatment had significantly higher porosity than the CNF treatment at POH. This is attributed to the effect of plant root growth and root biomass (BG_{DB}) (Figures 55 and 56, Section 7.3.3–7.3.4).

The significantly higher POI AWC associated with CF as compared with CNF was not observed POH. This is due to plant root effects. It can also suggest that the effect of this OA on AWC was temporary. The CF treatment did not significantly affect the BD and soil porosity at POI. However, at POH, CF had 19% lower ($p < 0.05$) soil BD and 33% higher ($p < 0.05$) soil porosity than CNF. This is due to plant root effects, which helped in binding the soil particles, thereby increasing soil total porosity and consequently lowering the soil BD (Miller *et al.,* 2002; Mosaddeghi *et al.,* 2009; Bandyopadhyay *et al.* 2010; Zhou *et al.* 2016; Guo *et al.* 2016; Table 25, Section 7.3.5).

The results also indicate that the CF treatment had no legacy effects on soil water retention relative to the CNF treatment. Further, lower rates of PAS and MC without inorganic fertilizer addition had no legacy effect on soil BD and porosity.

Overall, with the exceptions of PAS1NF, MC1NF/2NF, MC1F/2F, the results support the hypothesis that OA application has a positive legacy effect on physical SQIs, even POH. These positive effects are expected to benefit subsequent crops and also impact on the soil ecosystem services (such as water regulation, Chapter 9) and the overall soil health.

Table 30 Legacy effects on the physical SQIs following OA treatments application

Treatments	WC_{FC} (g g^{-1})	EAW (g g^{-1})	WC_{PWP} † (g g^{-1})	AWC (g g^{-1})	BD † (g cm-^{3})	Porosity (%)	WC_{FC} (g g^{-1})	EAW (g g^{-1})	WC_{PWP} † (g g^{-1})	AWC (g g^{-1})	BD † (g cm^{-3})	Porosity (%)
	POI						POH					
OA treatments without inorganic fertilizer												
CNF	18.1	13.7	10.1	7.99	1.8	37.8	20.0	11.9	8.40	11.6	1.75	29.9
PM1NF	ns	ns	ns	ns	↘	↗	ns	ns	ns	↗	↘	↗
PM2NF	↗	↗	ns	↗	↘	↗	↗	↗	↗	↗	↘	↗
PAS1NF	↗	↘	ns	ns	↘	↗	ns	ns	ns	ns	ns	ns
PAS2NF	↗	↗	↗	↗	↘	↗	↗	↗	ns	ns	↘	↗
AD_SW1NF	ns	ns	↘	↗	↘	↗	↗	↗	ns	↗	↘	↗
AD_SW2NF	↗	↗	ns	↗	↘	↗	↗	↗	↗	↗	↘	↗
MC1NF	ns	ns	ns	↗	ns	ns	ns	ns	ns	ns	↘	↗
MC2NF	↗	ns	ns	↗	↘	↗	ns	ns	ns	ns	↘	↗
OA treatments with inorganic fertilizer												
CF	ns	↘	↘	↗	ns	ns	ns	ns	ns	ns	↘	↗
PM1F	ns	ns	ns	↗	↘	↗	↗	↗	ns	↗	↘	↗
PM2F	↗	↗	ns	↗	↘	↗	↗	↗	↗	↗	↘	↗
PAS1F	↗	ns	ns	↗	ns	ns	ns	ns	ns	↗	↘	↗
PAS2F	↗	↗	↗	↗	↘	↗	↗	ns	ns	↗	↘	↗
AD_SW1F	↗	ns	↘	↗	↘	↗	↗	ns	ns	↗	↘	↗
AD_SW2F	↗	↗	ns	↗	↘	↗	↗	↗	↗	↗	↘	↗
MC1F	↘	↘	↘	ns	ns	↗	ns	ns	ns	ns	ns	ns
MC2F	↗	ns	↘	↗	↘	↗	ns	ns	ns	ns	↘	↗

↘ = significantly lower relative to the CNF treatment; ↗significantly higher relative to the CNF treatment; ns = Not significant relative to the CNF treatment; † = For WC_{PWP} and BD; less is more (positive effect), n = 72; POI = Post-incubation, POH = Post-harvest.

Summary

The study confirms the important roles OAs play in improving the physical SQIs (Mosaddeghi *et al.,* 2009; Bandyopadhyay *et al.*, 2010; Kirkby *et al.*, 2013). The results indicate that:

- With the exception of MC treatments, OA treatments applied at 30 t ha^{-1} with or without inorganic fertilizer addition had significant legacy effect on the WC_{FC} relative to the CNF treatment.
- AD_SW treatments at both application rates with or without inorganic fertilizer addition had significant legacy effect and consistently had significantly higher AWC than the CNF treatment.
- With the exception of PAS1F and MC1F treatments; all other OA treatments at both application rates and with or without inorganic fertilizer addition had a legacy effect on the soil BD and porosity relative to the CNF treatment.
- Overall, the MC amendment had the least effect on the physical SQIs measured as compared with all other OAs while the AD_SW amendment had the most effect on the physical SQIs measured.

Results demonstrate that type/quality of OAs applied have varying effects on the physical SQIs. By reducing the soil BD, increasing soil porosity and water retention capacity soil following OA application, these results therefore suggest that improvement in the physical SQIs will impact on the overall performance of subsequent crops.

8.2 Treatment effects on the chemical SQIs at Post-harvest:

The Olsen-P in the PM1NF/2NF, PAS2NF, AD_SW1NF/2NF and MC2NF treatments was significantly higher than that in the CNF treatment by 61.6, 82.5, 48.4, 54.7 and 60.7%, respectively (Table C-1, Appendix C). The present results mirror the trends observed at post-incubation. However, the PAS1NF and CNF treatments were not statistically different in their Olsen-P. This trend was not observed at POI. This is due to the inherently low Olsen-P associated with the PAS compared with other OAs (Table 10, Section 3.3.1.2) and also due to the effect of P-uptake by plants (Figure 61, Section 7.4.3). This is evidenced by the significantly strong correlation (r = 0.65) between Olsen-P and plant P-uptake (Table 25, Section 7.3.1) and between P-uptake and plant performance indicators (Table 28, Section 7.4.2). Furthermore, with inorganic fertilizer addition, the Olsen-P in the PM1F/2F, AD_SW2F and MC2F treatments was significantly higher as compared with the CNF treatment.

In contrast, the PAS1F/2F, AD_SW1F and MC1F treatments were not associated with significant effects on the Olsen-P as compared with the CNF treatment. This trend was not observed at POI. This is due to above mentioned reason. Overall, the PM treatments applied at either rate (10 t ha^{-1} or 30 t ha^{-1}) with or without inorganic fertilizer addition had significantly higher residual P relative to all other treatments. This is due to inherently high Olsen-P associated with the PM amendment (Table 10, Section 3.3.1.2). The present result is in agreement with other findings. Application of P fertilizers and animal manure increased the Olsen-P content (Shen *et al.*, 2011). Moharana *et al.* (2012) reported a significantly higher Olsen-P with manure either applied alone or in combination with inorganic fertilizer as compared with unfertilised control due to the release of organically bound P during organic matter decomposition. Cabilovski *et al.* (2014) reported significantly higher Olsen-P concentrations in the OA treatments (FYM, mushroom compost and vermicompost) compared with the un-amended control treatment.

The significantly high Olsen-P associated with the OA treatments suggests that the OAs, particularly the PM amendment, is good source of P. Since P is a critical plant nutrient (Yang *et al.*, 2014), the high residual Olsen-P concentration in the OA treatments will have significant positive effects on plant performance for the subsequent (next) crop. Thus, the present study supports the hypothesis that OA application increases the Olsen-P compared with the control treatment. It also demonstrates the potential of the applied OAs in improving the P content of a degraded soil. The present result suggests that high ($p < 0.05$) Olsen-P in the OA treatments will significantly affect the growth and yield performance of the next crop relative to the CNF treatment. However, there is the likelihood of P leaching out of the soil, considering the high residual Olsen-P in the OA treatment at 30 t ha^{-1}.

With the exception of PM1NF/2NF, PM1F, PAS1NF/2F, and AD_SW1F treatments, the EC in the PAS1F/2NF, AD_SW1NF/2NF, AD_SW2F and MC1NF/2NF treatments were significantly higher than the CNF treatment (Table C-1, Appendix C). This result did not follow the same trends observed at POI, especially for the PM1NF/2NF, PM1F and AD_SW1F treatments. This is due to noisy data obtained and also due to the effect of plant nutrient uptake. MC at either application rates with or without inorganic fertilizer addition (MC1NF/2NF and MC1F/2F) had significantly higher EC compared with all the other OA treatments except for PAS2NF treatment. The high EC in the OA treatments, particularly the MC treatments, was below the critical soil EC level (4.0 dS m^{-1} or 4000 µS cm^{-1}) (Ayers and Westcott 1985; White, 2006). This implies that the residual soil EC level will not negatively impact on the growth and yield performance of the next crop.

The OA treatments had varied effects on the soil pH. With the exception of MC1NF and PAS1NF/2NF treatments, all other OA treatments applied at 10 t ha^{-1} and 30 t ha^{-1} rates without inorganic fertilizer addition had no significant effect on the soil pH compared with the CNF treatment (Table C-1, Appendix C). Similar trends were not observed at POI. This is because of the effect of plant root exudates (a complex mixture of organic acid anions, sugars, vitamins, amino acids, inorganic ions (e.g. HCO_3^-, OH^-, H^+), and gaseous molecules [CO_2, H_2]) which have been reported to affect soil pH, due to microbial activities in the rhizosphere (Hinsinger, 2001; Dakora and Phillips, 2002; Shi *et al.*, 2011).

Nitrogen is a critical nutrient for maize production (Yang *et al.*, 2014). The TON in the OA treatments applied at 10 t ha^{-1} did not differ significantly from the CNF treatment, with the exception of AD_SW1NF treatment (Table C-1, Appendix C). This result does not mirror the trend observed at POI (Section 5.1.4) due to effect of plant N-uptake (Table 28, Section 7.4.2). However, at 30 t ha^{-1} OA application rates, the OA treatments had significantly higher TON than CNF. The same trend was observed at POI. This is due to the released of organically bound N during organic matter decomposition by the soil microbes [mineralization process] (Table 17, Section 2.7.4). This is supported by the significant correlation (r = 0.69) between MB_C and SOM and between MB_C and TON (r = 0.67) (Table C-2, Appendix C). A similar trend was observed with OA + inorganic fertilizer treatments. Zhen *et al.* (2014) found higher ($p < 0.05$) available N following the application of cattle manure (applied at 3.75 kg m^{-2} equivalent to 37.5 t ha^{-1}) compared to their control treatment. However, the authors found no difference in the available N between the inorganic fertilizer and control treatments. The present result demonstrates that OA application had positive legacy effects on the soil TON concentration and also that higher rates (30 t ha^{-1}) of OAs are needed to increase TON concentrations.

The NH_4-N associated with the OA treatments at either application rates with or without inorganic fertilizer addition was not significantly different as compared with the CNF treatment, except for the PM2NF and MC2NF/2F treatments. This is due to NH_4-N uptake by the plants and also due to microbial conversion of NH_4-N to TON and subsequently uptake by plants. This is supported by the significant correlation (r = 0.50) between NH_4-N and N-uptake associated with the OA treatments with and without inorganic fertilizer, respectively (Table 25, Sections 7.3.1).

As expected, the Total-N, Total-C and TOC associated with the OA treatments were significantly higher than the CNF treatment. This reflects the trends observed post-incubation. Increasing OA application rates significantly increased the Total-N, Total-C and TOC concentrations, except for the PAS1NF/2NF and PAS1F/2F treatments which did not vary significantly in their Total-N concentration. The non-significant effect on the Total-N observed for the PAS treatments is attributed to the high degree of variability within treatments (Table C-1, Appendix C).

As with the POI results, the significant increases in the Total-C and TOC associated with the OA treatments relative to the CNF treatment are due to increased SOM following OAs application, as evidenced by the significant correlations (r = 0.95 and 0.93) between SOM, Total-C and TOC (Table C-2, Appendix C). This result corroborates the previous studies of Bhattacharyya *et al.* (2008) and Blanco-canqui *et al.* (2014).

The C:N ratios of the OA treatments were significantly higher as compared with the CNF and CF treatments. This is due to the high OM content associated with the OAs (Table 10, Section 3.3.1.2). The same trend was observed post-incubation (Section 5.1.9.2). The C:N of the OA treatments at POH are within the range that will not limit N nutrient availability for plant uptake due to N immobilization by soil microbes. Furthermore, no significant effect on bioavailable-TOC (which is the percentage TOC in Total-C) was observed between the OA treatments and the CNF treatment even though the TOC and Total-C associated with the treatments differ significantly. This is due to the high degree of variability within treatments (Table C-1, Appendix C).

With the exception of PM1NF treatment, all other OA treatments at 10 t ha^{-1} or 30 t ha^{-1} rates with or without inorganic fertilizer had significantly higher Available-K as compared with the CNF and CF treatments. A similar trend was observed at POI, except that all the OA treatments gave higher ($p < 0.05$) Available-K compared with the CNF (Figure 37, Section 5.1.7). The non-significant effect on Available-K associated with the PM1NF treatment at POH is linked to plant K-uptake (Tables 25 and 28 Section 7.3.1 and 7.4.2). Nevertheless, the poor plant performance associated with the PAS1NF/2NF treatments (Figure 44, Section 7.2.1) can account for the high residual Available-K recorded for the PAS1NF treatment, due to poor K-uptake (Tables 25 and 28, Section 7.3.1 and 7.4.2). The Available-Mg associated with OA treatments was significantly higher as compared with the CNF and CF treatments, except for the PAS1F and MC1F treatments. This trend was observed at POI. The high POH Available-K and Available-Mg are significantly and positively correlated (r = 0.62) with post-harvest SOM, with r-values of 0.62

and 0.63 (Table C-2, Appendix C). The same correlation result was observed at POI (Table 17, Section 5.1.2.2).

Overall, the results indicate that OA application increased the soil Available-K concentration by 20-87% and the Available-Mg concentration by 12-73.5% relative to the CNF treatment (Table C-1, Appendix C). This result again demonstrates that increased Available-K and Available-Mg were carried over POH. The high residual Available-K and Available-Mg can reduce the inorganic K and/or Mg fertilizer rates applied to a follow-on crop, thus reducing the cost of fertilizer inputs.

For SOM, all the OA treatments had significantly higher (>25%) SOM compared with the CNF and CF treatments (Table C-1, Appendix C). This is linked to the high OM associated with the OAs applied (Table 10, Section 3.3.1.2). The present study corroborates the findings of Tejada *et al.* (2006), Cherif *et al.* (2009), Larney *et al.* (2011), Moharana *et al.* (2012) and Bedada *et al.* (2014), who all reported significant increases in SOM following OA additions. The present result indicates that the increases in the SOM at POI were not transitory, demonstrating the legacy effects these OAs had on SOM. Further, with the exception of MC2F treatment, the OA treatments did not significantly affect the CEC compared with the CNF treatment (Table C-1, Appendix C). This result is similar to the result obtained at POI (Table 18, Section 5.1.10) which suggests that the OA rates applied were insufficient to significantly affect the CEC. Rezig *et al.* (2013) reported no significant changes in the CEC with the application of crop residues when compared with the control treatment.

The results further indicates that the Total-P in the PAS1NF/2NF, PAS1F/2F and MC1/NF2NF, and MC1F/2F treatments did not differ significantly as compared with the CNF treatment (Table C-1, Appendix C). In contrast, the PM1NF/2NF, PM1F/2F, AD_SW1NF/2NF and AD_SW1F/2F treatments had significantly higher Total-P than CNF and CF. This is attributed to the inherently higher ($p < 0.05$) Total-P in PM and AD_SW OAs than that in PAS and MC OAs (Table 10, Section 3.3.1.2). The results suggest that the rates of PAS and MC treatments applied were insufficient to significantly affect the residual Total-P concentration POH.

8.2.1 Legacy effects of OA treatments on RB209 P, K, and Mg indices

The OA treatments had a substantial effect on the residual P, K and Mg RB209 indices (Table 31, Section 8.2.1). Although the P-Index (3) of the CNF treatment did not differ from that of the baseline soil, the residual Olsen-P in CNF treatment (28.8 mg kg^{-1}) was 12.5% lower than the baseline (32.9 mg kg^{-1}) Olsen-P (Table 32, Section 8.2.1). This is because the CNF treatment received no OAs to replenish the Olsen-P taken up by the plant or immobilized by soil microbes.

The CF, PAS1NF, PAS1F/2F, AD_SW1F and MC1F treatments had no effect on the P-Index relative to the baseline soil. The inability of these treatments to affect the P-Index is attributed to P-uptake by the plants (Tables 22, 25, and 28, Sections 7.2.1, 7.3.1 and 7.4.2). Although these OA treatments did not affect the P-Index, their residual Olsen-P (except for CF treatment) was 12-36% higher than the baseline Olsen-P (Table 32, Section 8.2.1). This suggests that the P nutrient (Olsen-P) provided by these OA treatments were sufficient to replenish the P removed by plant uptake and thus maintain the soil P-Index.

In contrast, the PM1NF/2NF, PM1F/2F, PAS2NF, AD_SW1NF/2NF, AD_SW2F, MC1NF/2NF, and MC2F treatments had a huge shift in the P-Index (Table 31, Section 8.2.1). These OA treatments shifted the P-Index from 3 to up to 7. The PM2NF/2F treatments had the highest P-Index (7). This is due to the significantly high Olsen-P associated with the PM OA as compared with all other OAs (Table 10, Section 3.3.1.2), in exceeded crop requirements.

Table 31 Effect of treatment application on post-harvest RB209 P, K, and Mg indices

Treatments	Baseline Soil	Post-harvest	Baseline Soil	Post-harvest	Baseline Soil	Post-harvest
	P-Index		K-Index		Mg-Index	
OA treatments without inorganic fertilizer						
CNF	3	3	1	1	4	4
PM1NF	3	5	1	1	4	6
PM2NF	3	7	1	3	4	7
PAS1NF	3	3	1	2	4	4
PAS2NF	3	4	1	3	4	5
AD_SW1NF	3	4	1	4	4	5
AD_SW2NF	3	6	1	5	4	6
MC1NF	3	4	1	3	4	4
MC2NF	3	5	1	4	4	5
OA treatments with inorganic fertilizer						
CF	3	3	1	1	4	4
PM1F	3	5	1	2	4	6
PM2F	3	7	1	3	4	7
PAS1F	3	3	1	2	4	4
PAS2F	3	3	1	2	4	4
AD_SW1F	3	3	1	3	4	5
AD_SW2F	3	5	1	4	4	6
MC1F	3	3	1	2	4	4
MC2F	3	5	1	4	4	4

The results indicate that the OA treatments greatly affected the K-index (Table 31, Section 8.2.1) relative to CNF. With the exception of PM1NF and CF treatments, which had no effect on the K-Index, all other OA treatments increased the K-Index from 1 to 4. This is linked to the high Available-K associated with the applied OAs (Table 10, Section 3.3.1.2).

Table 32 Percentage changes in soil nutrient (N, P, K and Mg) following treatment application

Treatments	Baseline Soil	Post-harvest	% change	Baseline Soil	Post-harvest	% change	Baseline Soil	Post-harvest	% change	Baseline Soil	Post-harvest	% change	Baseline Soil	Post-harvest	% change
	TON (mg kg^{-1})			NH4-N (mg kg^{-1})			Olsen-P (mg kg^{-1})			Available-K (mg kg^{-1})			Available-Mg (mg kg^{-1})		
OA treatments without inorganic fertilizer															
CNF	0.45	0.0	-100	4.17	0.0	-100	32.9	28.8	-12.5†	87.3	86	-1.49	179	193	7.82
PM1NF	0.45	0.0	-100	4.17	0.0	-100	32.9	75	128‡	87.3	108	23.7	179	395	121
PM2NF	0.45	9.25	1956	4.17	0.63	-84.9	32.9	166	405	87.3	268	207	179	786	339
PAS1NF	0.45	0.13	-72.2	4.17	0.0	-100	32.9	38.7	17.6	87.3	141	61.5	179	211	17.9
PAS2NF	0.45	0.25	-44.4	4.17	0.0	-100	32.9	56	70.2	87.3	290	232	179	254	41.9
AD_SW1NF	0.45	1.13	150	4.17	0.13	-96.9	32.9	63.8	93.9	87.3	281	222	179	315	76
AD_SW2NF	0.45	2.88	539	4.17	0.0	-100	32.9	106	222	87.3	670	667	179	456	155
MC1NF	0.45	0.0	-100	4.17	0.0	-100	32.9	45.6	38.6	87.3	295	238	179	219	22.3
MC2NF	0.45	0.63	38.9	4.17	0.38	-90.9	32.9	73.3	123	87.3	435	398	179	253	41.3
OA treatments with inorganic fertilizer															
CF	0.45	0.0	-100	4.17	0.0	-100	32.9	30.1	-8.5	87.3	115	31.7	179	182	1.68
PM1F	0.45	1.13	150	4.17	0.0	-100	32.9	90.8	176	87.3	197	126	179	433	142
PM2F	0.45	7.13	1483	4.17	0.38	-90.9	32.9	198	502	87.3	346	296	179	727	306
PAS1F	0.45	0.0	-100	4.17	0.0	-100	32.9	36.9	12.2	87.3	131	50.1	179	199	11.2
PAS2F	0.45	0.0	-100	4.17	0.0	-100	32.9	44.8	36.2	87.3	233	167	179	244	36.3
AD_SW1F	0.45	0.13	-72.2	4.17	0.0	-100	32.9	41	24.6	87.3	305	249	179	296	65.4
AD_SW2F	0.45	3.0	567	4.17	0.25	-94	32.9	86	161	87.3	625	616	179	448	150
MC1F	0.45	0.0	-100	4.17	0.0	-100	32.9	44.7	35.9	87.3	196	125	179	189	5.59
MC2F	0.45	6.88	1428	4.17	0.88	-78.9	32.9	78.5	139	87.3	564	546	179	224	25.1

† = Negative values indicate negative % changes; ‡ = Positive values indicate positive % changes, n = 72.

The OA treatments increased the Mg-Index from 4 to 7. The CF, PAS1NF, MC1NF, PAS1F/2F, and MC1F/2F treatments did not affect the Mg-Index as compared with the CNF treatment. This is due to plant uptake of Available-Mg. With the exception of PAS1F/2F, and MC1F/2F treatments increase in OA treatment application rates increased the Mg-Index by 1 level. Overall, the results indicate that inorganic fertilizer application at 50% the recommended rates had no effect on the P, K and Mg indexes post-harvest. Observed shifts in the P, K and Mg indices were due to the applied OAs. This result demonstrates the effectiveness of OAs in increasing the soil P, K and Mg indices. It is postulated that improvement in the soil P, K and Mg indices will have a positive effect on the performance of the next crop. Further, based on the Fertilizer Manual RB209 (Table 9, Section 3.2.1), the present study suggests that the shift in the soil P, K and Mg indices will provide potential benefits to the farmer with respect to reducing the cost (although cost benefits were not analysed) and quantity of inorganic fertilizer applied.

SUMMARY

These results indicate that:

- The OA treatments at either application rates with or without inorganic fertilizer addition significantly increased the SOM, Total-N, Total-C, and TOC by more than 24, 46, 75 and 81%, respectively, as compared with the CNF treatment respectively.
- The PM2NF, PM1F/2F, PAS2NF, AD_SW1NF/2NF, AD_SW2F, and MC2NF/2F treatments had 100% higher ($p < 0.05$) TON relative to the CNF treatment.
- Olsen-P in PM1NF/2NF, PM1F/2F, PAS2NF, AD_SW1NF/2NF, AD_SW2F and MC2NF/2F treatments was >60% higher ($p < 0.05$) as compared with the CNF treatment.
- With the exception of PAS1NF/2NF, PAS1F/2F, MC1NF/2NF, and MC1F/2F treatments, all other OA treatments applied at 10 t ha^{-1} and 30

t ha^{-1} significantly increased the Total-P by over 8% and 15% as compared with the CNF treatment, respectively.

- Further, with the exception of PM1NF treatment, all other OA treatments had 34-86% higher ($p < 0.05$) Available-K as compared with the CNF treatment.
- The OA treatments, except for PAS1NF/1F and MC1F treatments, had 12-75.4% higher ($p < 0.05$) Available-Mg relative to the CNF treatment.
- OA application positively affected the P, K and Mg indices.
- Overall, the OAs had a positive legacy effect on the soil chemical SQIs.

8.3 Treatment effects on the Biological SQIs at Post-harvest

Soil microbial biomass plays an important role in nutrient cycling in agro-ecosystems (Lupwayi *et al.*, 2005; Hu *et al.*, 2011; Cao *et al.*, 2016). This Section evaluates the POH residual effects of OA application on the biological SQIs namely microbial biomass C [MB_C], microbial activity (microbial respiration [MResp], microbial metabolic quotient [qCO_2] and microbial biomass quotient [C_{mic}:C_{org}]). As earlier hypothesized, the OA treatments are expected to have significant positive effects on biological SQIs due to greater nutrient supply (NPK), increased levels of TOC and SOM via OA application (Table C-1, Appendix C) and that this will impact on the overall soil health will continue post-harvest (Zhen *et al.*, 2014).

Post-harvest MB_C ranges from 22 mg kg^{-1} (CNF treatment) to 578 mg kg^{-1} (AD_SW2NF treatment) (Table 33, Section 8.3). Except for PAS1NF, PAS1F, MC1NF and MC1F, all other OA treatments with or without inorganic fertilizer addition had >72% higher ($p < 0.05$) MB_C than the CNF and CF treatments, respectively. The higher MB_C associated with the OA treatments is due to the nutrients (NPK, Mg) and energy (TOC and SOM, microbial C sources) (Dijkstra *et al.*, 2013; Bhaduri *et al.*, 2015) provided via the OAs applied (Bhaduri *et al.*, 2015). This is supported by the significant positive correlations between MB_C, N, P, K Mg, TOC and SOM (Table C-1, Appendix C). The present result is similar to the trend observed at POI, except that at POI, all the OA treatments were associated with significantly higher MB_C compared with the CNF treatment. The non-significant effect on the MB_C observed for the PAS1NF, PAS1F, MC1NF, and MC1F treatments relative to the CNF treatment at POH is linked firstly to the lower MB_C associated with the PAS and MC amendments as compared with those found in the PM and AD_SW amendments (Table 10, Section 3.3.1.2).

Table 33 Effect of treatment application on post-harvest biological SQIs

Treatments	MB_C (µg g^{-1})	MResp (µg CO_2 g^{-1} day^{-1})	C_{mic}:C_{org} (%)	qCO_2 (%)
OA treatments without inorganic fertilizer				
CNF	22[a]	2.47[abc]	0.11[a]	12.5[g]
PM1NF	321[efg]	3.01[abc]	0.88[fgh]	2.25[cdef]
PM2NF	421[gh]	10.2[d]	1.18[ij]	0.92[ab]
PAS1NF	104[abc]	2.39[abc]	0.41[bcd]	2.25[cdef]
PAS2NF	195[cd]	5.51[abc]	0.50[cde]	2.78[def]
AD_SW1NF	286[def]	3.49[abc]	0.99[ghi]	1.24[abcd]
AD_SW2NF	578[i]	4.1[abc]	1.30[i]	0.74[a]
MC1NF	106[abc]	2.11[ab]	0.39[bcd]	1.99[bcde]
MC2NF	175[bcd]	2.54[abc]	0.42[cd]	1.56[abcd]
OA treatments with inorganic fertilizer				
CF	32.2[a]	1.11[a]	0.17[ab]	5.87[f]
PM1F	271[def]	4.97[bc]	0.77[efg]	1.81[bcde]
PM2F	494[hi]	8.77[d]	1.28[ij]	1.31[abc]
PAS1F	69.5[ab]	2.72[abc]	0.27[abc]	4.21[ef]
PAS2F	225[de]	3.04[abc]	0.63[def]	1.40[abc]
AD_SW1F	198[cd]	1.41[a]	0.73[efg]	1.16[abc]
AD_SW2F	522[hi]	5.00[bc]	1.16[hij]	0.67[a]
MC1F	78.6[abc]	2.99[abc]	0.30[abc]	4.12[ef]
MC2F	358[fg]	4.68[bc]	0.89[fgh]	1.38[abcd]

MBC= Microbial biomass C, MResp = Microbial respiration, C_{mic}:C_{org} = Microbial biomass quotient, qCO_2 = Microbial metabolic quotient, n = 72.

Secondly, reduction in nutrients (NPK and Mg) due to plant uptake and energy sources (SOM and TOC) can contribute to the non-significant effect on MB_C post-harvest. This result indicates that PAS and MC treatments applied at 10 t ha^{-1} rates was insufficient to significantly affect the MB_C relative to the CNF treatment at POH. It therefore suggests that higher rates (30 t ha^{-1}) of PAS and MC OAs are required to achieve significant effect on the MB_C.

The OA treatments at 10 t ha^{-1} application rates with or without inorganic fertilizer had no significant effect on the MResp as compared with the CNF and CF treatments (Table 33). Except for the PM2NF/PM2F treatments, all other OA treatments at 30 t ha^{-1} application rate had no significant effect on the MResp as compared with the CNF and CF treatments. This is firstly attributed to the significantly lower C_{mic}:C_{org} that is associated with the CNF treatment as compared with the OA treatments, with the exception of the PAS1F and MC1F treatments (Table 33, Section 8.3).

As an indicator of stress (Godley, 2007) and changes in the SOM (Maková *et al.*, 2011), the low C_{mic}:C_{org} in the CNF treatment suggests that the soil microbes are stressed due to depletion in the organic carbon and available nutrients (N [TON, NH_4-N, Total-N], P [Olsen-P, Total-P], K and Mg]) (Cheng *et al.*, 2013) and that this contributed to higher MResp recorded for the CNF treatment. This is evidenced by the significant correlations that exist between C_{mic}:C_{org}, available nutrients (N [TON, NH_4-N, Total-N], P Olsen-P, Total-P], K and Mg], SOM, TOC and MB_C (Table C-2, Appendix C). However, the significantly lower C_{mic}:C_{org} observed for the PAS1F and MC1F treatments as compared with all other OA treatments, with the exception of CNF and CF treatments is attributed to a negative priming effect due to inorganic fertilizer addition (Kuzyakov *et al.*, 2000). Priming effect is a short-term change in the SOM in which large amounts of C, N and other nutrients present in the SOM can either be released or immobilized by soil microbes (Kuzyakov *et al.*, 2000). The present result mirrors the trend observed at POI, except for the non-significant effect between PAS1F, MC1F and CNF treatments observed at POH.

The qCO_2 in CNF treatment was significantly higher relative to the OA treatments. This is attributed to microbial stress due to the low available nutrient [NPK and Mg], reduced SOM and TOC associated with the CNF treatment, which increased stressed conditions for the soil microbes (Wardle and Ghani, 1995; Godley, 2007; Bhaduri *et al.*, 2015). Alhough no significant correlation exits between MResp, C_{mic}:C_{org} and qCO_2 for the OA treatment without inorganic fertilizer (Table C-2, Appendix C), the significant correlations (r = 0.48) that exists between MB_C and MResp, and between MB_C, C_{mic}:C_{org} and qCO_2 (r = -0.47, 0.97, respectively) suggest that the non-significant effect on the MResp observed between the OA treatments and the CNF treatment with the exception of PM2NF/PM2F treatments is stress induced (Maková *et al.*, 2011; Bhaduri *et al.*, 2015).

Summary

Soil is a biologically active medium (Figures 5 and 6, Sections 2.7.3–2.7.4), thus the application of OAs influenced the MB_C and microbial activities [measured as MResp, C_{mic}:C_{org} and qCO_2] (Table 33, Section 8.3) due to increased available nutrients, higher SOM and TOC (Table C-2, Appendix C). Therefore, the present results indicate that:

- The OA treatments at either application rates with or without inorganic fertilizer increased the MB_C by >68% and >88% as compared with the CNF treatment, respectively.
- Similarly, the MB_C in 10 t ha^{-1} and 30 t ha^{-1} OA treatments increased by over 53% and 83% compared with the CF treatment, respectively.
- With the exception of PAS1NF/1F treatments, all other OA treatments had significantly higher C_{mic}:C_{org} as compared with the CNF treatment due to greater nutrient availability N [TON, NH_4-N, Total-N], P [Olsen-P, Total-P], K and Mg]) and higher SOM and TOC (Table C-2, Appendix C).
- OA application significantly reduced the qCO_2 (stress due to insufficient nutrient and/or organic C) as compared with the CNF treatment.

- qCO_2 in CF treatment was significantly lower compared with CNF treatment. This can be due to extra supply of nutrients from the plant roots via root exudation (Bhaduri *et al.*, 2015).
- Generally, based on the biological SQIs measured, the OAs that most affected the biological SQIs at POH are in the order PM ≥ AD_SW ≥ MC ≥ PAS.

The present result confirms the hypothesis that OA application has significantly positive effects on biological SQIs. This is because the OAs modified microbial energy requirements due to the provision of organic substrates (SOM and TOC) and nutrients (N [TON, NH_4-N, Total-N], P [Olsen-P, Total-P], K and Mg]) (Moscatelli *et al.*, 2005). This result demonstrates the potency of the OAs applied in improving the biological SQIs of a degraded soil, which will impact significantly on the performance of a subsequent crop.

8.4 Conclusions

The results indicate that OA application continued to positively affect physical SQIs, by increasing WHC and AWC, especially for the PM and AD_SW amendments and reducing soil BD (Table 31, Section 8.1). Further, in general, the OAs had significant positive effects on the majority of the chemical SQIs measured relative to the CNF treatment. Critically, the OA treatments increased the soil P, K and Mg indices relative to that of the baseline soil (Table 31, Section 8.2.1), even following plant nutrient off-take.

Considering the high P-Index associated with PM treatments, repeated application of PM at higher rates can be a potential environmental hazard (due to surface and or ground water pollution) when Olsen-P is lost from the soil system, either by leaching, run off or erosion. However, this depends on soil management.

The biological SQIs also continued to be positively affected by the OA treatments. The result indicates that OA application increased the MB_C by >53% relative to the CNF treatment. Further, except for PAS, all other OAs reduced soil microbial stress, increased C_{mic}:C_{org} and increased the qCO_2 quotient. The present results support the hypothesis that OA application has significant effects on the physical, chemical and biological SQIs. These legacy effects are expected to have significant effects on the growth and yield performance of subsequent crops.

9 SYNTHESIS

9.1 Introduction

As a source and sink of plant nutrients, SOM is one of the critical components in improving soil quality and ensuring agricultural sustainability (Bhaduri *et al.*, 2015). The conceptual diagram of the relationship between OA application and soil health developed through Fuzzy Cognitive Mapping (Figure 2, 7 and 8, Sections 2.3 and 2.10) demonstrates theoretically that OA application can improve SQIs; enhance crop performance and support a range of ecosystem goods and services. This section aims to demonstrate that improvement in the physical, chemical and biological SQIs is associated with improvement in crop yield and performance. This will confirm the research aim that application of OAs are critical to improving soil health of a degraded soil due to the improvement in the physical, chemical and biological SQIs.

9.2 Methodology

9.2.1 Scoring matrix:

In this Chapter, a scoring matrix was devised to critically and systematically evaluate the effects of the OA treatments in improving the physical, chemical and biological SQIs measured. The OA treatments were scored according to their positive or negative effects on the physical, chemical and biological SQIs relative to the CNF treatment which received no OAs or inorganic fertilizer application. The OA treatments were assigned scores based on a 5-point scale [which ranged from -5 to +5] centred on zero (Figure 67, Section 9.2.1). Except for BD, WC_{PWP} and qCO_2, improvements to the SQIs (relative to CNF) were represented by positive scores, while degradation of the SQIs (relative to CNF) was represented by negative scores. Where a treatment received a score of zero, it implied that the treatment had no improvement or degradation effects on the SQI measured relative to the CNF treatment. It is important to state that scores are not the same as treatment data values. Scores are values assigned to a particular treatment based on improvement/degradation of a particular SQI measured, while treatment data values are measured (actual) experimental values.

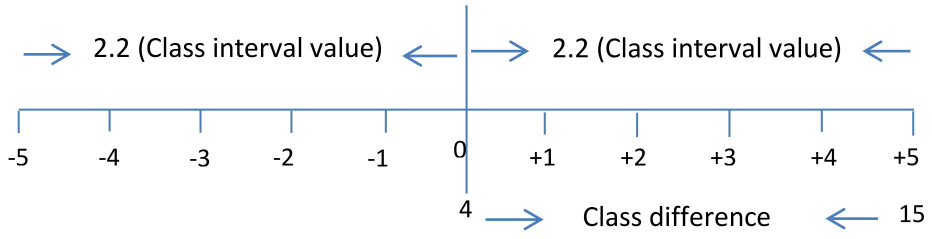


Figure 67 Schematic representation of a 5-point scale used in generating class intervals.

The Class interval value (Figure 67, Section 9.2.1) is a value obtained from a class difference (treatment range).

9.2.2 Class interval

Prior to assigning scores to the treatments, a scoring class interval was generated for each SQI to ensure that all scores were standardized to a 5-point scale. To achieve this, for each SQI except for BD, WC_{PWP}, and qCO_2, the statistically mean value (measured data value) of the CNF treatment was subtracted from the statistically highest mean value (measured data value) each treatment to obtain a treatment range (class difference). Thereafter, the treatment range was divided by 5 (i.e. 5-point scale) to generate the class interval (Figure 67, Section 9.2.1).

After generating the class interval for a given SQI, the measured treatment data values were ‘mapped’ onto the 5-point scale and subsequently a score was assigned to the ‘mapped’ treatment data values depending on its position on the 5-point scale. To further illustrate the scoring matrix, an example of SQI means [TON] for a number of hypothetical treatments is shown in Table 34. The class difference for this example was generated thus:

The highest treatment mean value (measured data) – CNF treatment mean value (measured data) = class difference.

Thus: 15 (MC1NF) – 4 (CNF) = a class difference of 11.
Class difference ÷ 5 units (i.e. 5-point scale) = class interval.
11 ÷ 5 = a class interval of 2.2.

Following the class interval value [2.2] generated from the above calculations, the treatment [measured] data values [e.g. TON] (Table 34, Section 9.2.2.1) were then mapped to the 5-point scale (Figure 67, Section 9.2.1). The following sets of rules were adopted while scoring the treatment data values:

- Where treatment data values fall within a class interval and the values were not significantly different, the treatments were given the same score.
- However, where the treatment data values were statistically different, the treatment data values were allocated a higher or lower score, depending on the magnitude of the difference.
- A 'worst case scenario' approach was adopted while assigning scores to the treatments. This assumption aimed at avoiding ambiguity, especially where treatment data values had high degree of variability [noisy data] for the measured SQIs (Table 34). In such situations, it was assumed that for each of the treatments, the SQI mean values that have the same first statistical letter (i.e. 'homogenous groups' based on Factorial ANOVA followed by *post-hoc* Fisher LSD analysis [Chapters 4, 5, and 6]) regardless of the subsequent letters were statistically the same and the treatments were assigned the same score (Table 34). However, where the treatments differ in their first statistical letter regardless of the subsequent letters, the treatments were assumed to be significantly different and they were assigned different scores, depending on the magnitude of the difference (Table 34, Section 9.2.2.1).

Table 34 Worst case scenario assumption used in the scoring matrix

Treatments	TON (mg kg-^{1})	Scores
CNF	12^{a*}	0
PAS1F	18^{abc}	0
PM1F	35^{bcde}	+1
CF	40^{cde}	+2
MC1F	45^{d}	+3
PM2F	100^{ef}	+4
MC2F	112^{f}	+5

* = Different letters within the column show the mean statistical difference between the treatments. TON = Total oxides of nitrogen; + = Shows improvement in the measured SQI relative to the CNF treatment.

For example, the TON in the CNF and PAS1NF treatments were not statistically different (Table 34). Similarly, PM1NF, PAS1NF, and PAS2NF treatments had statistically the same TON content. However, based on the 'worst case scenario' assumption, it was assumed that the CNF and PAS1NF treatments were statistically the same, since they have the first statistical letter ('homogenous groups'); thus the treatments received the same score. For PM1NF, PM2NF, PAS1NF, and PAS2NF treatments; it was assumed that they were statistically different, since they do not share the same first statistical letter (i.e. they are not 'homogenous groups'). Hence, the PM1NF, PM2NF, PAS1NF, and PAS2NF treatments received different scores, depending on the magnitude of the difference in TON SQI measured (Table 34).

9.2.2.1 Ranking

After assigning scores to the treatments for a particular SQI, the scores were sorted following a top-down approach (that is, the scores were arranged in order from the highest scores to the lowest scores) and thereafter ranked. The treatment with the highest score was ranked as number one (1), the treatment with the next highest score was ranked number two (2) and that order was maintained until all the treatment scores were ranked. However, where two treatments had the same score, the mean (average) rank for the two treatments was used. For instance, in Table 35 (Section 9.2.2.1), PM2NF and PAS1NF treatments have the same TON score of 4. Ideally, both treatments should be in ranks 2 and 3, respectively. But because the treatments have the same TON scores, their rank values are added up and divided by 2 (which is the number of the treatments added).

In this case: 2 + 3 (the ideal ranks of both treatments) = 5.
Then the mean of 5 is: 5 ÷ 2 = 2.5.
Therefore, the two treatments (PM2NF and PAS1NF) are ranked 2.5, respectively.

Table 35 Ranking demonstration table

Treatments	TON score	TON Rank	Olsen-P score	Olsen-P Rank
PM1NF	5	1	5	1
PM2NF	4	2.5	4	2
PAS1NF	4	2.5	3	3
PAS2NF	3	4	2	4
MC1NF	1	5	1	5

After scoring the treatments' SQIs, the scores of the physical SQIs [BD, WC_{FC}, EAW, WC_{PWP}, AWC, and porosity] were summed to generate a combined physical SQI score [this represents a pooled dataset of the physical SQIs measured]. The combined physical SQI score was statistically analysed using the Spearman's rank correlation method (See Section 9.2.3). Similarly, the chemical and biological SQIs were also added up to obtain combined chemical and biological SQIs scores. The combined physical, chemical and biological SQI scores were added up to generate an overall total SQI score; a pooled dataset that represents all the SQIs measured.

9.2.3 Spearman's rank correlation

After ranking the scores, Spearman's rank correlation was used to evaluate the strength of relationship between the SQIs and plant performance indicators (particularly AG_{DB}, BG_{DB}, and Cob_{DW}). This was to verify whether significant treatment effects on the SQIs affected crop performance. The Spearman's rank correlation method was used in this study because the method was designed to measure relationships between variables measured on ordinal scale (that is data that are simply shown in order of magnitude, but without any standard of measurement of differences between the data). Since the results used in this Synthesis Chapter were generated by ranking the SQIs, it is best suited to use the Spearman's rank method for the correlation analysis. This was done by using the formula below:

$$rs = 1 - \frac{6\sum d^2}{n^3 - \mathrm{n}} \quad \textbf{(8)}$$

Where *rs* = Spearman's rank correlation coefficient; d = is the difference in the ranks of each pair of the measured variables; n = number of treatments or variables measured.

The Spearman's rank coefficient (*rs*) values range between -1 and +1. The closer the *rs* is to +1 or -1, the stronger the association while the closer to zero (0), the weaker the association. More so, +1 value indicates a perfectly positive association, while -1 value suggests a perfectly negative association. The strength or significance of the Spearman's rank correlation coefficient result was tested at 95% confidence by comparing the Critical Value ($r_{S\ \mathrm{critical}}$) with the Spearman's rank correlation coefficient value ($r_{S\ \mathrm{statistic}}$) (Table 35) following the hypothesis below:

Null Hypothesis (H_0): There is no correlation between X and Y (that is there is mutual independence between the two variables (where X variable represents the combined physical, chemical, biological SQI ranks and the overall total SQI ranks] and Y variables = plant performance indicators [AG_{DB}, AG_{DB}, and Cob_{DW}]).

Alternative Hypothesis (H_1): There is a correlation between X and Y (that is there is mutual dependence between X and Y).

Decision Rules:

- Reject the Null Hypothesis: if the calculated Spearman's Rank Coefficient (r_s) value is greater than or equal to the critical value ($r_{S\ critical}$). That is if $r_S \geq r_{S\ critical}$ (result is significant).
- Accept the Null Hypothesis: if the calculated Spearman's Rank Coefficient (r_s) value is less than the critical value ($r_{S\ critical}$). That is if $r_S < r_{S\ critical}$ (result is non-significant), e.g., if $r_S = 0.701$ and $r_{S\ critical} = 0.648$ then we reject the Null Hypothesis and accept the alternative Hypothesis

It is important to note that the Spearman's rank correlation method:

- Is less sensitive to bias due to the effect of outliers.
- Does not assume normal distribution.
- It is used when the intervals between data points are problematic. Hence using ranked values instead of the actual values are useful to avoid ambiguity.

9.2.4 Assumptions

A number of assumptions were made while adopting the scoring methodology.

Assumption 1: The physical, chemical and biological SQIs were scored independently of each other, but in reality the SQIs are interrelated and as such change(s) in one SQI also affects another SQI. For example, changes in the SOM content following OA application affect the BD, WHC (physical SQIs), the soil nutrients (chemical SQIs), MB_C and microbial respiration [biological SQIs] (Tables 16 and 17 Sections 4.1.2 and 5.1.2).

Assumption 2: As mentioned in Section 9.2.1, a 'worst case scenario' approach was adopted while assigning scores to the treatment data values.

Assumption 3: The CNF (un-amended) control treatment was always assigned a score of zero since it received no treatment application to indicate the start condition of test soil prior to OA application.

Assumption 4: Improvement in the SQIs measured for the OA treatments relative to the control was assigned a score greater than zero (positive value), and where degradation in the SQI occurs a score less than zero was assigned to that treatment (negative value), with the exception of BD, WC_{PWP} and qCO_2.

Assumption 5: It was assumed that all the SQIs carry the same importance i.e. the SQIs were scored unweighted following the scoring matrix earlier described (Section 9.2.1). Although in reality some SQIs might be more influential than others, as demonstrated by the relationship between the SQIs and plant performance (Table 25, Section 7.3.1).

9.3 Discussion

The research hypothesis is that application of OAs will improve the physical, chemical and biological SQIs of a degraded sandy loam soil as compared with the un-amended control. Further, the improvement in the SQIs following OA application will improve plant performance indicators and soil health.

9.3.1 Effects of OA treatments on combined SQI scores and associated ranking, post-incubation

9.3.1.1 Combined physical SQI scores

The results indicate that application of OAs improved the combined physical SQI score relative to the CNF treatment. Across the treatments, the results show that the OAs had varied effects on the combined physical SQI scores which comprised of BD, porosity, WC_{FC}, EAW, AWC, and WC_{PWP} Table 36, Section 9.3.1.2). For instance, the AD_SW2F and AD_SW2NF had more improvement in the combined physical SQIs compared with the CNF treatment and all other OA treatments. This is attributed to the significantly higher WHC, reduced BD and higher total porosity associated with the AD_SW2F and AD_SW2NF as compared with all other treatments (Table 15, Section 4.1.1).

As expected, increasing OA application rate resulted in an improvement in the combined physical SQIs scores (Table 36, Section 9.3.1.2). This is due to increased SOM content following increase in the rates of OAs applied, which reduced the soil BD, and increased total porosity, AWC, EAW, and WC_{FC} as compared with OAs applied at 10 t ha^{-1}. This is evident by the strong significant relationship between SOM and BD; and that between SOM, AWC and porosity (Figures 16, 19; Sections 4.1.1 and 4.1.8, Table 30, Section 8.1). The increases in the WHC due to reduction of BD and increased soil porosity (Table 15, Section 4.1.1) demonstrates the capability of OAs to improve the porosity of a coarse-textured degraded sandy loam soil and thus improve the soil WHC (Table 15, Section 4.1.1). This result suggests that the OAs have the potential to retain and maintain higher plant available water content during drought periods.

The scoring exercise suggests that the OA type; quality (OM content) and the rate of OA applied are crucial to improving the physical SQIs of a degraded soil. These results demonstrate that improving the physical SQIs will impact on soil function and therefore enhance the water regulatory function associated with soil ecosystem goods and services (Table 37, Section 9.3.1.2). The three treatments that most improved the overall physical SQIs for the OA applied at 30 t ha^{-1} are: AD_SW2F; AD_SW2NF and PM2NF. For OA applied at 10 t ha^{-1}, the order was AD_SW1F; AD_SW1F and MC1NF (Table 36, Sections 9.3.1.2).

9.3.1.2 Combined chemical SQI scores

As anticipated from the positive correlations in Table 17 (Section 5.1.2.2), OA application improved the combined chemical SQI score relative to the CNF treatment (Table 36, Sections 9.3.1.3). The PM2F treatment gave the greatest improvement in combined chemical SQI score. The high performance of PM2F is attributed to its significantly higher Olsen-P, SOM, NH_4-N and Available-Mg as compared with all other treatments (Figure 27, 33, 35 39; Sections 5.1.3, 5.1.5, 5.1.6 and 5.1.8). Further, inorganic fertilizer addition had a marked effect on the SQIs. This is due to the synergistic effects on the chemical SQIs following inorganic fertilizer addition. This result suggests that combined application of OA and inorganic fertilizer produced greater improvement effects on the chemical SQIs than application of either OAs or inorganic fertilizer [applied at 50% the RB209 recommended rate] alone (Table 36, Section 9.3.1.2).

Generally, improvement in the chemical SQIs with OA application is due to increased, SOM, soil nutrients (N [TON, NH_4-N, Total-N], P [Olsen-P and Total-P], K, and Mg), Total-N, TOC and Total-P (Table 36, Section 9.3.1.2) as a result of the influence of soil microbes and microbial activities, which are responsible for the mineralization of nutrients in OAs. This is evidenced by the significant correlations that exist between the chemical and biological SQIs (Tables 17, Sections 5.1.2.3 and Table C-1, Appendix C).

Mkhabela and Warman (2005) found that application of municipal solid compost + NPK fertilizer increased N availability. Juan *et al.* (2008) reported improvements in soil chemical [SOM, Total-N and Total-P] properties with the application of organic and inorganic fertilizers. For Zhen *et al.* (2014), cattle manure amended treatments had significantly higher SOM compared with the un-amended control. Further, the present result indicates that improvement in the combined chemical SQIs scores was greater when OAs were applied at higher (30 t ha^{-1}) rates than at lower (10 t ha^{-1}) rates (Table 36, Section 9.3.1.2). As explained earlier, this is due to increase in nutrient levels [N [TON and NH_4-N], P, K and Mg] associated with increased rates of OA addition (Figures 27, 31, 33, 37, and 39, Sections 5.1.3-5.1.5, 5.1.7 and 5.1.8). However, improvement in the chemical SQIs of the degraded soil varied greatly across the treatments (Table 36, Section 9.3.1.2). This is attributed to the types, qualities (OAs chemical and microbial characteristics) and rates of OAs applied (Table 10, Section 3.3.1.2). This is because nutrient release from OAs vary depending on the C:N ratios and biochemical compositions associated with the OAs (Mittra *et al.*, 2005). These factors influence the soil MB_C and microbial activities (Figure 42 Section 6.1; Table 21, Section 6.2.2) which are crucial for the soil processes (e.g. nutrient cycling) (Figures 5 and 6, Sections 2.7.3 and 2.7.4).

Table 36 Post-incubation results: [a] physical, chemical, biological and overall total SQIs scores (with rankings) and [b] plant performance indicators (mean cob yield [Cob_{DW}] (DW), above-ground biomass [AG_{DB}] (DW), below-ground biomass [BG_{DB}] (DW) and (with rankings) for all treatments.

Treatments	Combined Physical SQIs scores	Combined Physical SQIs Rank	Combined Chemical SQIs scores	Combined Chemical SQIs Rank	Combined Biological SQIs scores	Combined Biological SQIs Rank	Over-all Total SQIs score	Over-all total SQIs Rank	Cob_{DW} (g)	Cob_{DW} Rank	AG_{DB} (g)	AG_{DB} Rank	BG_{DB} (g)	BG_{DB} Rank
	Soil quality indicators [a]								**Plant performance indicators [b]**					
	OA treatments without fertilizer													
CNF	0	17.0	0	18.0	0	17.5	0	18.0	0.01	16.5	36.2	16	5.2	16.0
PM1NF	4	13.5	17	9.0	2	8.0	23	10.5	22.1	10.0	96.6	9.0	40.6	2.0
PM2NF	21	3.0	25	5.0	5	1.5	51	4.0	28.2	5.0	110	1.0	34.1	5.0
PAS1NF	2	15.5	1	17.0	1	13.5	4	17.0	0.01	16.5	27.2	17	4.1	17.0
PAS2NF	8	10.0	4	16.0	2	8.0	14	13.0	0.01	16.5	26.5	18	3.1	18.0
AD_SW1NF	10	8.5	12	12.0	2	8.0	24	8.5	0.01	16.5	46.5	15	7.0	15.0
AD_SW2NF	23	2.0	23	6.0	2	8.0	48	5.0	4.65	14.0	80.3	13	32.3	9.5
MC1NF	5	12.0	13	10.5	1	13.5	19	12.0	5.6	13.0	69.2	14	20.2	14.0
MC2NF	14	5.5	30	3.0	3	4.0	47	6.0	32.2	3.0	98.1	7.0	32.3	9.5
	OA treatments with fertilizer													
CF	6	11.0	5	14.5	0	17.5	11	15.0	26.2	7	91.1	11	32.6	7.5
PM1F	4	13.5	18	8.0	2	8.0	24	8.5	32.7	2	103	4	29.8	10.5
PM2F	14	5.5	44	1.0	5	1.5	63	1.0	37.1	1	97.5	8	32.6	7.5
PAS1F	2	15.5	5	14.5	1	13.5	8	16.0	25.3	8	99.4	6	29.8	10.5
PAS2F	13	7.0	9	13.0	1	13.5	23	10.5	13.4	11	88.5	12	25.6	13.0
AD_SW1F	10	8.5	22	7.0	3	4.0	37	7.0	24.8	9	104	3	48.5	1.0
AD_SW2F	24	1.0	28	4.0	1	13.5	53	2.5	13.3	12	95.1	10	38.1	3.0
MC1F	-2	18.0	13	10.5	1	13.5	12	14.0	30.7	4	100	5	33.1	5.0
MC2F	16	4.0	34	2.0	3	4.0	53	2.5	27.8	6	105	2	35.7	4.0

Table 37 Effect of OA treatments on selected ecosystem goods and services

Treatments	Ecosystem goods and services																				
	Nutrient provisioning							Carbon storage		Nutrient recycling/Biodiversity				Support/Water regulation						Food provisioning	
	TON (mg kg^{-1})	NH4-N (mg kg^{-1})	Olsen-P (mg kg^{-1})	Available-K (mg kg^{-1})	Available-Mg (mg kg^{-1})	Total-N (mg kg^{-1})	Total-P (mg kg^{-1})	TOC (mg kg^{-1})	SOM (%)	MB_C (µg kg^{-1})	MResp (µg CO_2 g^{-1} day^{-1})	qCO_2 ‡ (%)	C_{mic}:C_{org}	BD ‡ (g cm^{-3})	Porosity (%)	WC_{FC} ‡ (g g^{-1})	EAW (g g^{-1})	AWC (g g^{-1})	WC_{PWP} (g g^{-1})	Cob yield (g)	AG_{DB} (g)
CNF†	0	0	30	90	200	370	1710	832	1.9	20	2.5	12.5	0.11	1.75	29.9	20	11.9	11.6	8.4	0	38
PM1NF	ns	ns	↗	↗	↗	↗	↗	↗	↗	↗	ns	↘	↗	↘	ns	ns	ns	↗	ns	↗	↗
PM2NF	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↘	↗	↘	↗	↗	↗	↗	↗	↗	↗
PAS1NF	ns	ns	↗	↗	↗	↗	ns	↗	↗	↗	ns	↘	↗	ns	ns	ns	ns	ns	ns	ns	ns
PAS2NF	↗	ns	↗	↗	↗	↗	ns	↗	↗	↗	↗	↘	↗	↘	↗	↗	ns	ns	ns	ns	ns
AD_SW1NF	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↘	↗	↘	↗	↗	↗	↗	ns	ns	↗
AD_SW2NF	↗	ns	↗	↗	↗	↗	↗	↗	↗	↗	↗	↘	↗	↘	↗	↗	↗	ns	↗	↗	↗
MC1NF	ns	ns	↗	↗	↗	↗	ns	↗	↗	↗	ns	↘	↗	↘	↗	ns	ns	ns	ns	↗	↗
MC2NF	↗	↗	↗	↗	↗	↗	ns	↗	↗	↗	ns	↘	↗	↘	↗	ns	ns	ns	ns	↗	↗
CF	ns	ns	ns	↗	↗	ns	ns	ns	ns	ns	<*	↘	ns	↘	↗	ns	ns	ns	ns	↗	↗
PM1F	↗	ns	↗	↗	↗	↗	↗	↗	↗	↗	↗	↘	↗	↘	↗	↗	ns	↗	↗	↗	↗
PM2F	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↘	↗	↘	↗	↗	↗	↗	↗	↗	↗
PAS1F	ns	ns	↗	↗	↗	↗	ns	↗	↗	↗	↗	↘	ns	<*	↗	ns	ns	↗	ns	↗	↗
PAS2F	ns	ns	↗	↗	↗	↗	ns	↗	↗	↗	↗	↘	↗	↘	↗	↗	ns	↗	ns	↗	↗
AD_SW1F	↗	ns	↗	↗	↗	↗	↗	↗	↗	↗	*	↘	↗	↘	↗	↗	ns	↗	ns	↗	↗
AD_SW2F	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	<*	↘	↗	↘	↗	↗	↗	↗	↗	↗	↗
MC1F	ns	ns	↗	↗	↗	↗	ns	↗	↗	↗	↗	↘	ns	ns	ns	ns	ns	↗	ns	↗	↗
MC2F	↗	↗	↗	↗	↗	↗	ns	↗	↗	↗	↗	↘	↗	↘	↗	ns	↗	↗	ns	↗	↗

† = Control treatment, Ns = Not significant relative to the control treatment, ↘ = significantly lower relative to the control treatment, ↗ = significantly higher relative to the CNF treatment, ‡ = A significantly lower value for these parameteris a positive outcome.

Immobilization or mineralization of organically bound nutrients especially N, is influenced by the C:N ratio of the OAs. This is because soil microbes that decompose OAs with high C:N ratio do not have adequate N to build up as much biomass (Spohn, 2014). Thus, OAs with high C:N ratio is associated with greater nutrient immobilization and this can affect plant available nutrients (Janssen, 1996; Bengtson, 2004). The above reasons can explain the low poor crop yield performance associated with the AD_SW and PAS amendments.

The present results suggest that improvement in the chemical SQIs will significantly affect plant performance due to increased nutrient (NPK and Mg) supply and high SOM content (See Section 9.3.1.5). This implies that improving the chemical SQIs of a degraded soil via OA application will enhance the nutrient provisioning, food provisioning and carbon storage capacity (Table 37, Section 9.3.1.1). The three treatments that best improved the combined chemical SQI score for the OA applied at 30 t ha^{-1} with or without inorganic fertilizer addition are in the order: PM2F > MC2F > MC2NF. The AD_SW1F > PM1F > PM1NF are the three treatments that best improved the combined chemical SQIs when applied at 10 t ha^{-1}.

9.3.1.3 Combined biological SQIs scores

It was hypothesized that OA application would improve the biological SQIs as compared with the CNF un-amended control. The results obtained support the hypothesis (Table 36, Section 9.3.1.2). There was significantly higher MB_C and C_{mic}:C_{org} in the OA treatments as compared with the CNF treatment (Figure 42, Section 6.1; Table 21, Section 6.2). Improvement in the biological SQIs following OA applications is linked to increased nutrient availability and soil carbon [TOC, Total C, SOM] and soil nutrients [N, P, K and Mg, Total-N, and Total-P] (Marinari *et al.*, 2006; Zhen *et al.*, 2014). This is evidenced by the significant correlations that exist between the soil carbon [r = 0.69, 0.64 and 0.59, respectively] and MB_C, and that between soil nutrients [r = 0.38, 0.57, 0.49, 0.53, 0.70, and 0.38, respectively] and MB_C (Table 17, Section 5.1.2.2).

Improvement in the physical and chemical SQIs largely contributed to the improvement in the biological SQIs, as evidenced by the significant correlations that exist between the physical, chemical and biological SQIs (Table 16; 17, and 38, Sections 4.1.2, 5.1.1 and 9.3.1.3). The results obtained confirm the hypothesis that application of OAs will improve the biological SQIs. Improvement in the biological SQIs will enhance soil nutrient cycling, increase plant growth and yield performance due to increased plant nutrient availability. This will contribute towards improving ecosystem goods and services (Table 37, Section 9.3.1.1).

Table 38 Post-incubation Spearman's correlations between the combined physical, chemical, biological, and overall total SQIs

SQIs	Combined physical SQIs	Combined chemical SQIs	Combined biological SQIs	Overall total SQIs	Critical value
		Spearman's coefficient			5% significance level
Combined physical SQIs	1	0.720*	0.632*	0.868*	0.472
Combined chemical SQIs		1	0.750*	0.938*	0.472
Combined biological SQIs			1	0.773*	0.472
Overall total SQIs				1	0.472

Hypothesis: Null Hypothesis (H0): There is no correlation between X and Y (that is there is mutual independence between X and Y).
Decision: Reject the Null Hypothesis: if the calculated Spearman's Rank Coefficient (*rs*) value is greater than or equal to the critical value (*rs* critical); at 5% significant level critical.
* = significantly different at ($p < 0.05$).

Compared with the other treatments, PM2F and PM2NF recorded greater improvement in the biological SQIs (Table 36, Section 9.3.1.2). This is due to a number of factors:

1. High NH_4-N content: the high level of NH_4-N associated with the PM amendment encouraged the growth of soil microbes, especially the autotrophic ammonia-oxidizing bacteria (Chang *et al.*, 2007) that convert

NH_4-N to nitrates. This is supported by the significant positive correlation between MB_C and NH_4-N content (Table 17, Section 5.1.2).

2. High nutrient level: the high levels of Total-N and Total-P (Table 10, Section 3.3.1.2-5.1.10) and Olsen-P (Table 10, Section 3.3.1.2, Figure 27; Section 5.1.3.2) associated with the PM amendment also contributed to the observed greater improvement in combined biological SQIs. This is because, as demonstrated in the N and P-cycles (Figures 5 and 6, Sections 2.7.3–2.7.4), the OAs are a source of N and P for the soil microbes. Thus, the availability of soil nutrients influence the microbial activity and microbial population (Cheng *et al.*, 2013).
3. Low C:N ratio: The low C:N ratio of the PM amendment relative to the other OAs (Table 10, Section 3.3.1.2) is another factor that enhanced improvement in the biological SQIs due to greater nutrient mineralization and availability (Cheng *et al.*, 2013). Soil microbes are crucial in recycling of nutrients (N, P, C and S) contained in OAs (Magdoff and Weil, 2004). As the sink of N nutrients, the C:N of OAs influences the mineralization and immobilization processes and that can affect the rate and amount of nutrient mineralized or immobilized and also the proliferation of soil microbes (Mary *et al*., 1996; Gutser *et al.* 2005; Ahmad *et al.*, 2006). Further, the C:N of an OA can influence the types and dominance of particular soil microbe. For example fungi and bacteria are soil microbes (decomposers) that carry out most of the OM decomposition activity that release available nutrients (Magdoff and Weil, 2004). A high C:N OA favours fungi proliferation, since fungi have high C requirements. However, a low C:N OA favours more bacteria growth because bacteria have high N demand (Magdoff and Weil, 2004). This suggests that the soil microbes degrade OA/residues differently depending on the type (quality) of OA they degrade.
4. Inherently high MB_C: the PM amendment prior to application was associated with significantly higher MB_C (Table 10, Section 3.3.1.2; Figure 42 Section 6 2) as compared with the other OAs. This can further

explain the greater improvement in the biological SQIs associated with the PM treatments.

The CF treatment showed no improvement in the biological SQIs as compared with the CNF treatment. This is because both treatments did not receive any OA application, hence there is no carbon source for the soil microbes to increase microbial influx; thus resulting in no improvement in the biological SQIs. Lee and Jose (2003) showed that biological SQIs (microbial biomass and microbial activities) are strongly related to chemical SQIs, such as soil pH and SOM. Geisseler and Scow (2014) reported a lower metabolic rate (qCO_2) in plots treated with inorganic fertilizer than in OA amended plots. Juan *et al.* (2008) found a positive correlation between key chemical properties (SOM, Total-N, and Total-P) and soil microbial properties.

This study indicates that OA application boosted the MB_C of a degraded soil due to increased C [SOM, TOC and Total-C] and nutrient (N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg] supply (Table 17, Section 5.1.2.2). Improving the biological SQIs will enhance the soil nutrient recycling function and consequently enhance plant performance (Table 25, Section 7.3.1). Therefore, this result demonstrates that OA addition can improve the soil ecosystem goods and services of a degraded sandy loam soil (Table 37, Section 9.3.1.2).

With or without inorganic fertilizer addition, the results indicate that the treatments that had the greatest improvement in the combined biological SQIs scores as compared with the CNF treatment for the OAs applied at 30 t ha^{-1} were PM2F > PM2NF = AD_SW2F = AD_SW2NF. The three treatments that best improved the combined biological SQIs scores at 10 t ha^{-1} were: AD_SW1F > PM1F = PM1NF (Table 36, Section 9.3.1.2).

9.3.1.4 Overall total SQI scores

The overall total SQIs scores (the summation of the combined physical, chemical and biological SQIs scores) represents the overall holistic system wide improvement in the SQIs. In general, OA application improved the overall total

SQIs as compared with the CNF treatment. This is attributed to improvement in the combined physical, chemical and biological SQIs (Table 38, Section 9.3.1.3). The PM2F treatment gave the most improvement in the overall total SQIs score due to its improvement effects in the combined physical, chemical and biological SQIs (Table 36, Section 9.3.1.2). This results support the a *priori* hypothesis that application of OAs will improve the physical, chemical and biological SQIs.

With or without inorganic fertilizer addition, the three treatments that best improved the overall total SQIs for the OA applied at 30 t ha^{-1} were: PM2F > AD_SW2F > MC2F. At 10 t ha^{-1}, the three treatments that best improved the overall total SQIs were: AD_SW1F, AD_SW1NF and PM1F. As observed for the combined physical, chemical and biological SQIs, the trend in the improvement of the overall total SQIs demonstrates that OA types and the rates applied influence the physical, chemical and biological SQIs due to the effects of OAs in reducing the BD, increasing the soil total porosity, AWC, EAW, WC_{FC}, SOM, nutrients and MB_C at higher application rates.

In summary, the study results support the hypotheses that:

1. OAs improved the physical, chemical and biological SQIs of a degraded soil (Table 36).
2. OAs applied at 30 t ha^{-1} rate had a greater improvement effect on the physical, chemical and biological SQIs than OAs applied at 10 t ha^{-1}.
3. Improvement in the measured SQIs varied with the OAs type applied.
4. Application of OAs + inorganic fertilizer addition improved the SQIs better than the sole application of OAs or inorganic fertilizer (Table 36).

The post-incubation results demonstrate the potential of the OAs in improving the SQIs which suggest improvement in soil health of a degraded soil (Figure 2, Section 2.3.5). Therefore, as earlier hypothesized, it is expected that improvements in the SQIs at post-incubation is carried forward in improving plant performance (Cob_{DW}, AG_{DB}, and BG_{DB}) and thus fulfils the ecosystem provisioning function of soil health (Figure 2, Section 2.3; Table 37, Section 9.3.1.4).

9.3.1.5 Relationship between post-incubation treatment SQIs and crop performance

The results show that improvement in the physical SQIs at post-incubation had a positive but weak and non-significant ($p < 5\%$) correlation (r_s = 0.137, 0.217, and 0.344) with Cob_{DW}, AG_{DB} and BG_{DB}, respectively (Table 39, Section 9.3.1.5). This result suggests that improvements in the physical SQIs at post-incubation were not directly associated with improvements in crop performance. This result did not corroborate the significantly weak correlation that exists between individual physical SQIs measured (WC_{FC}, AWC, and BD) and crop performance indicators [Cob_{DW}, AG_{DB} and BG_{DB}] (Table 25, Section 7.2.1). The non-significant correlation observed between the combined physical SQIs and plant performance is attributed to the non-limiting effect of water supply to the plants. This is because the plants received regular supply of water which ensured sufficient moisture to avoid water stress. Water stress is the major cause of grain yield instability in maize (*Zea mays* L.), especially in water limited regions (Bolanos and Edmeades, 1993).

Water stress affects maize photosynthetic capability and thus affects maize yield performance due to a decrease in radiation interception associated with reduced leaf expansion (Bolanos and Edmeades, 1993), foliar senescence and reduction in C fixation per unit leaf area because of stomatal closure (Bruce *et al.*, 2002). Therefore, since water was not a limiting factor in the present study, improvements in the physical SQIs, such as BD, porosity and soil water retention characteristics [WHC, AWC and EAW] showed no significant correlation with plant performance (Table 39, Section 9.3.1.5) even though these parameters were significantly affected by OAs application (Tables 15 and 16, Sections 4.1.1 and 4.1.2).

Table 39 Post-incubation Spearman's correlations between the combined physical, chemical, biological, overall total SQIs and plant performance indicators (Cob_{DW}, AG_{DB} and BG_{DB})

SQIs	Cob_{DW} (g)	AG_{DB} (g)	BG_{DB} (g)	Critical value
	Spearman's coefficient			5% significance level
Combined physical SQIs	0.136^{ns}	0.219^{ns}	0.342^{ns}	0.472
Combined chemical SQIs	0.630*	0.646*	0.672*	0.472
Combined biological SQIs	0.491*	0. 566*	0.394^{ns}	0.472
Overall total SQIs	0.472*	0.549*	0.546*	0.472

Hypothesis: Null Hypothesis (H0): There is no correlation between X and Y (that is there is mutual independence between X and Y).
Decision: Reject the Null Hypothesis: if the calculated Spearman's Rank Coefficient (*rs*) value is greater than or equal to the critical value (*rs* critical); at 5% significant level critical Ns = not significantly different, * = significantly different at ($p < 0.05$)
Cob_{DW} = cob yield (DW), AG_{DB} = Above-ground biomass (DW), BG_{DB} = Below-ground biomass (DW),

As observed in Chapter 4, OAs applied at 10 t ha^{-1} had no significant effect on the physical SQIs except at higher (30 t ha^{-1}) rates which improved the physical SQIs (increased WC_{FC}, AWC, EAW, porosity and reduced BD). The present results suggest that with adequate water supply (maintaining adequate SMC); improvements in the physical SQIs has no obvious (direct) effects on maize performance in a non-limiting water environment and therefore is not critical to improving the maize crop production in the short term if improvements in the chemical and biological SQIs are achieved.

This result accepts the hypothesis that improvement in the physical SQIs improves plant growth and yield performance due to the indirect effects the physical SQIs has on chemical and biological soil properties (Table 39, Section 9.3.1.5). In contrast, improvement in the combined chemical SQIs scores had positive, strong and significant correlations (*rs* = 0.630, 0.646, and 0.672) with Cob_{DW}, AG_{DB} and BG_{DB}, respectively (Table 39, Section 9.3.1.5). This result supports the hypothesis that improvement in the chemical SQIs post-incubation will significantly affect plant growth and yield performance. This is attributed to increased SOM and associated NPK, and Mg (Figures 27, 31, 33, 37 and 39, Sections 5.1.3–5.1.5, 5.1.7 and 5.1.8) which was manifested as improved plant NPK, Mg, Zn and Cu uptake (Tables 26 and 27, Section 7.6.2), NUE and PUE (Figures 63–66 Section 7.5.1–7.5.4) as compared with the CNF control. The study suggests that improving the chemical SQIs of a degraded soil prior to maize planting is critical to improving maize crop performance due to enhanced nutrient (NPK and Mg) supply which helps in early plant establishment as evidenced by the plant vegetative growth stages (Figure 50; Section 7.1.9). This is because lack of or inadequate supply of available nutrients or nutrient imbalances can affect crop performance (Yuan *et al.*, 2011), particularly for maize which is a heavy nutrient feeder (Ahmad *et al.*, 2009). Therefore, these results suggest that the provisioning of adequate and available nutrients via OAs application prior to crop establishment or at early growth stage is critical to improving the growth and yield performance of crops grown in degraded soils (Table 36, Section 9.3.1.2).

The results in Table 36 (Section 9.3.1.2) show that improvement in the combined biological SQIs scores is manifest by improvement in the crop performance as evident by the positively and significant correlations [rs = 0.491 and 0.566] (Table 39, Section 9.3.1.5) with Cob_{DW} and AG_{DB}, respectively. This result supports the proposed hypothesis and demonstrates that achieving improvements in biological SQIs is critically important in improving crop performance. Soil microbes (biological SQIs) and their activities play significant roles in soil ecosystem functions, such as nutrient cycling and decomposition of organic matter (Zhen *et al.*, 2014), releasing nutrients that are organically bound to the OAs for plant uptake as hypothesized in the mechanistic N and P cycling diagrams (Figures 5 and 6, Section 2.7.3–2.7.4). This is because the soil microbes essentially mediate biological activities, including soil N, P and S cycling processes, nutrient mineralization -immobilization processes, and organic matter decomposition, which influence the availability of nutrients for plant uptake. Hence, nutrient availability and its subsequent uptake affect plant performance (Tables 22–27, Sections 7.2.1–7.3.5).

The results of this study confirm that soil microbial biomass (MB_C) and biological activities (enhance nutrient supply to plants through decomposition of OAs. This result corroborates the finding of Cao *et al*. (2015) who observed a significant correlation between microbial activity and maize biomass. The authors further observed higher maize performance following an increase of P supply, which they attributed to the microbial activities which enhanced the P-cycling process. Application of manure compost enhanced soil microbial activities, which then improved crop growth (Zhen *et al.*, 2014). The authors suggested that addition of OAs increased the levels of organic matter and increased nutrient availability as well as biological activity.

Improvement in the total (overall) SQIs (Table 36, Section 9.3.1.2) had strong, positive and significant ($p < 0.05$) correlations with the Cob_{DW}, AG_{DB} and BG_{DB}, respectively [*rs* = 0.472, 0.549, and 0.546, respectively] (Table 39, Section 9.3.1.5). This is due to the strong relationships that exist between crop performance and the chemical, physical and biological SQIs which influence nutrient availability, and enhance both crop establishment and subsequent growth (Figure 50, Section 7.1.9; Tables 22 and 25, Section 7.1.1 and 7.2.1). The results support the research hypothesis that improvement in SQIs will result in improvement in crop performance.

The post-incubation scoring results indicate that improvements in crop performance correlated significantly and positively with the chemical and biological SQIs, but not with the physical SQIs. This suggests that improving the chemical and biological SQIs prior to crop planting through the application of OAs is critical to achieving subsequent improvements in crop performance. The results also indicate that improvement in crop performance is further enhanced by supplementing OAs with inorganic fertilizer addition (Table 36, Section 9.3.1.2). The type, quality and rates of OAs applied have varied effects on SQIs and thus had varied effect on crop performance. This study suggests that adequate soil management measures such as OAs application are essential in improving the productivity of a degraded soil.

9.4 Summary

The results of the present study support the hypothesis that the application of OA improves the physical, chemical and biological SQIs. Contrary to expectation, improvement in the physical SQIs did not significantly correlate with improvement in the crop performance indicators due to earlier explained reasons (Section 9.3.1.5). It is suggested that improvement in the chemical and biological SQIs masked the effects that improvement in physical SQIs had on plant performance. Further, improvement in the combined chemical and biological SQIs at post-incubation correlated significantly with improvements in crop performance. This suggests that levels of nutrients, their availability and microbial activities are essential in improving crop performance and the health of a degraded soil due to reduction in soil microbial stress (Table 25, Section 7.2.1) following OA application.

This result suggests that improving the chemical and biological SQIs prior to crop establishment (that is at post-incubation) is critical to improving maize performance.

Further the results of this study demonstrate that:

1. OAs and the type/quality of OAs applied influenced improvements in the SQIs tested.
2. Increasing OAs application rate (with the exception of PAS amendments for some of the SQIs tested [Table 36]) resulted in significant improvement in almost all the SQIs tested. This therefore suggests that the type, quality and rates of OAs applied are critical to improving the soil health and productivity of a degraded soil.
3. Combined applications of OAs and inorganic fertilizer improved the physical, chemical and biological SQIs better than sole application of either OAs or inorganic fertilizer.
4. OAs applied at 30 t ha^{-1} with or without inorganic fertilizer improved crop performance indicators (cob yield and biomass [AG_{DB}, BG_{DB}]) better than those applied at 10 t ha^{-1}, with the exception of PAS amendment.

Improvement in soil health of a degraded test soil following OA application is demonstrated by the significant improvements in the physical SQIs [such as increases in the WC_{FC}, EAW, AWC, porosity, decreased BD (Table 15, Sections 4.1.1); chemical SQI [which include significant increases in the Olsen P, TON, NH_4-N, SOM, K, Mg, Total-N, Total-P, TOC (Table 18, Section 5.1.9.2)] and biological SQIs [observed higher MB_C, MResp, C_{mic}:C_{org}, reduced qCO_2] as shown in Table 37. This result confirms the hypothesis that OA application will improve the SQIs as compared with the un-amended control. It therefore confirms that OA application is critical to improving the health and productivity of degraded soils (Figure 2, Section 2.3; Table 37, Section 9.3.1.2).

With respect to the varying effects the OA types had in improving the SQIs and crop yield performance; the PM amendment had most effects as compared with PAS, AD_SW and MC amendments and it is therefore recommended (PM2NF and PM1NF/PM1F).

The scoring matrix data (Table 36, Section 9.3.1.2) indicate that holistic improvement in the physical, chemical and biological SQIs following OAs application enhanced the soil's capacity in delivering ecosystem services by improving the soil support (plant growth medium), water regulation, enhancing soil nutrient recycling and carbon sequestration and ensuring optimum food production (Figure 2, Section 2.3 and Table 37, Section 9.3.1.2).

10 OVERALL CONCLUSIONS

The present study demonstrates for the first time the potentials of OAs in holistically improving soil health and productivity of a degraded sandy loam soil. The OAs applied had significantly and varied effects on the SQIs measured due to the inherent differences in their physical, chemical and biological compositions. The study established that:

- At both POI and POH, higher rates (30 t ha^{-1}) of OAs with or without inorganic fertilizer addition had greater ($p < 0.05$) effects on the water release characteristics [WC_{FC}, EAW, AWC] than lower (10 t ha^{-1}) rates of OAs.
- At POH, OA treatments with or without inorganic fertilizer addition had 21–52% higher ($p < 0.05$) WC_{FC}, 40% higher porosity and 55% lower BD than the CNF treatment.
- AD_SW and PM amendments had the greatest effects on physical SQIs relative to the other OAs due to their inherently higher OM content (Table 10, Section 3.3.1.2).
- Overall, at POI, MC treatment applied at 10 t ha^{-1} with or without inorganic fertilizer addition had no significant effect on the physical SQIs relative to the CNF treatment.
- At POI, 1% increase in SOM increased the soil porosity by ca 36% and AWC by 5.31 g g^{-1}.
- Reduction in BD by 1 g cm^{-1} increased the soil WC_{FC} by 36.5 g g^{-1} at POI.
- At POI, an increase in WC_{FC} by 1 g g^{-1} increases the EAW by 2.33 g g^{-1}.

The decreases in soil BD due to OA additions enhanced soil porosity and consequently increased the capacity of the degraded sandy loam soil to retain more water than the un-amended CNF treatment. Thus, these OAs have the potential to reduce the costs of irrigating such soils, showing the capability of OAs in improving a number of ecosystem services [i.e. support and water regulation].

The application of OAs significantly affected the chemical SQIs:

- The OAs increased the SOM, Total-C, and TOC by over 23%, 75% and 81%, respectively, relative to CNF, so increasing soil C sequestration and improving ecosystem benefits.
- At both POI and POH, the Available-K and Available-Mg concentration increased with OA application, thereby potentially reducing the quantity of inorganic K and Mg required for subsequent crops.
- OA application increased ($p < 0.05$) the soil EC content. The EC concentration in MC amendment was higher ($p < 0.05$) than all other OAs. This suggests that subsequent application of MC at high rates can lead to salt build-up and that can negatively affect crop yield performance.
- Two weeks after OA application, Olsen-P concentration in the OA treatments increased by 17–90% relative to the CNF treatment.
- At post-harvest, the residual Olsen-P was 37–45% higher ($p < 0.05$) than the CNF treatment. Olsen-P increased with increase in OA application rates. This suggests that OA application can reduce the quantity of inorganic P needed to grow maize.
- At either application rate with or without inorganic fertilizer, the OA treatments did not significantly affect the CEC compared with CNF treatment.
- Overall, the baseline [soil prior to treatment application] P, K and Mg index was increased following OA application relative to the CNF treatment at POH.
- The P, K and Mg indices increased, across the OA treatments, with increase in application rate at POH.
- The CF had no effect on the P K and Mg Indexes (Table 31, Section 8.2.1). This is attributed to the low rates (50% of the RB209 recommended rate) of inorganic fertilizer applied and plant uptake.

The increases in soil nutrients and SOM content due to the OA additions enhanced the condition of the soil for the following crop. This demonstrates the potency of OAs in improving chemical SQIs and thus confirms the capability of OAs in improving the ecosystem services of a degraded sandy loam soil [i.e. nutrient provisioning and carbon storage soil functions] (Table 37, Section 9.3.1.2).

At POI and POH, OA application had significantly positive effects on biological SQIs:

- Across application rates, with or without inorganic fertilizer addition, OAs increased ($p < 0.05$) the MB_C by over 60% compared with the CNF treatment, 2 weeks after application.
- At POH, the OAs still had an effect on MB_C (72–95% higher ($p < 0.05$) relative to CNF).
- OA application increased microbial activity (MResp, and qCO_2) especially for PM.
- At POH, OA treatments reduced $C_{mic}:C_{org}$ (microbial stress) by 46–94% relative to the CNF treatment. This is due to increased supply of C [TOC, SOM, and Total-C] and nutrients (N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg) (Table 17, Section 5.1.2.2).

These results demonstrate the effectiveness of OAs in improving the biological SQIs and the ecosystem benefits (nutrient recycling) of a degraded sandy loam soil (Table 37, Section 9.3.1.1).

The OA treatments had varied effects on plant growth and crop yield performance. This reflects the OAs effects on soil nutrients which consequently influenced plant nutrient (N and P) uptake, PUE and NUE.

- With the exception of PAS, OAs without inorganic fertilizer treatments increased plant growth performance [plant height, stem diameter, number of plant leaves, vegetative growth stages].
- Across OAs without inorganic fertilizer treatments, plant biomass (AG_{DB} and BG_{DB}) increased by 24–65% and 38–88%, respectively, as compared with the CNF treatment (except for PAS treatments).

- The OA treatments without inorganic fertilizer addition increased Cob_{DW} by 100% as compared with CNF (except for PAS1NF/2NF and AD_SW1NF).
- Across the OA treatments, an increase in OA application rates [without inorganic fertilizer addition] increased ($p < 0.05$) Cob_{DW} by more than 80%, with the exception of PM1NF/2NF and PAS1NF/2NF treatments.
    - PAS treatments without inorganic fertilizer addition at either application rate produced no Cob_{DW} due to low NPK availability (Table 10, Section 3.31).
    - With inorganic fertilizer addition, PAS increased ($p < 0.05$) Cob_{DW} by 100% relative to the CNF treatment. This suggests that PAS amendment alone is not effective as a soil amendment for maize production without inorganic fertilizer addition (Figures 57 and 58, Sections 7.31 and 7.3.2).
    - PM1NF and PM2NF treatments did not differ in their Cob_{DW} due to adequate nutrient provisioning at the lower application rate.
    - A similar trend was observed for PM1F and PM2F, which suggests that PM2NF and PM2F treatments supplied excess plant nutrient with no corresponding increase in Cob_{DW} (Figures 57 and 58, Sections 7.3.1 and 7.3.2).
- Inorganic fertilizer addition had marked effects on the OA treatments, particularly PAS. For instance, with supplementary inorganic fertilizer, the plant N and P-uptake from the PAS treatments increased ($p < 0.05$) by over 80% compared with the CNF treatment.
- AD_SW1NF, PAS1NF, and PAS2NF treatments had delayed maize tasselling initiation and the development of fewer silk (the female flowers) at 7 WAP (Figure 50 A, Section 7.1.9) due to the low N-uptake and NUE and consequently resulted in no Cob_{DW} production (low yield performance).

Overall, application of OAs to a degraded sandy loam soil increased plant growth and crop yield performance due to increased nutrient provisioning via the mineralization actions of the soil microbes (See Chapters 5–7). This also demonstrates the potential of OAs in improving the productivity and ecosystem services [i.e. food provisioning] (Table 37, Section 9.3.1.1) of a degraded sandy loam soil.

It was assumed that improvements in the health and productivity of a degraded soil following OA application results from a concomitant improvement in physical, chemical and biological SQIs (Figure 4, Section 2.10). The present results confirm this hypothesis (Figure 68, Section 10). The red arrows in Figure 68 (Section 10) indicate where the OAs applied significantly affected the relationships between the SQIs. There are some non-significant relationships that occurred (as depicted by the green arrows) which were not expected to happen. These were due to the high variability between replicates (i.e. noisy data) that obscured any significant relationship. As predicted, OA application had significant positive impact on plant performance (Figure 69, Section 10).

The legacy effects on the physical, chemical and biological SQIs following OA application at POH is expected to impact positively on subsequent crops. It is therefore suggested that adequate application of OAs can improve the long term health and productivity of degraded soil. This will enhance crop production, especially in developing countries where soil degradation is increasingly due to insufficient OAs application.

With the exception of PAS, which is only effective when combined with inorganic fertilizers, the present results have shown that PM, AD_SW and MC can be used to enhance soil water retention capacity [WHC, EAW and AWC], increase soil nutrient [N [TON, NH_4-N and Total-N], P [Olsen-P and Total-P], K and Mg] content, SOM, MB_C; and enhance crop yield performance of a degraded sandy loam soil.

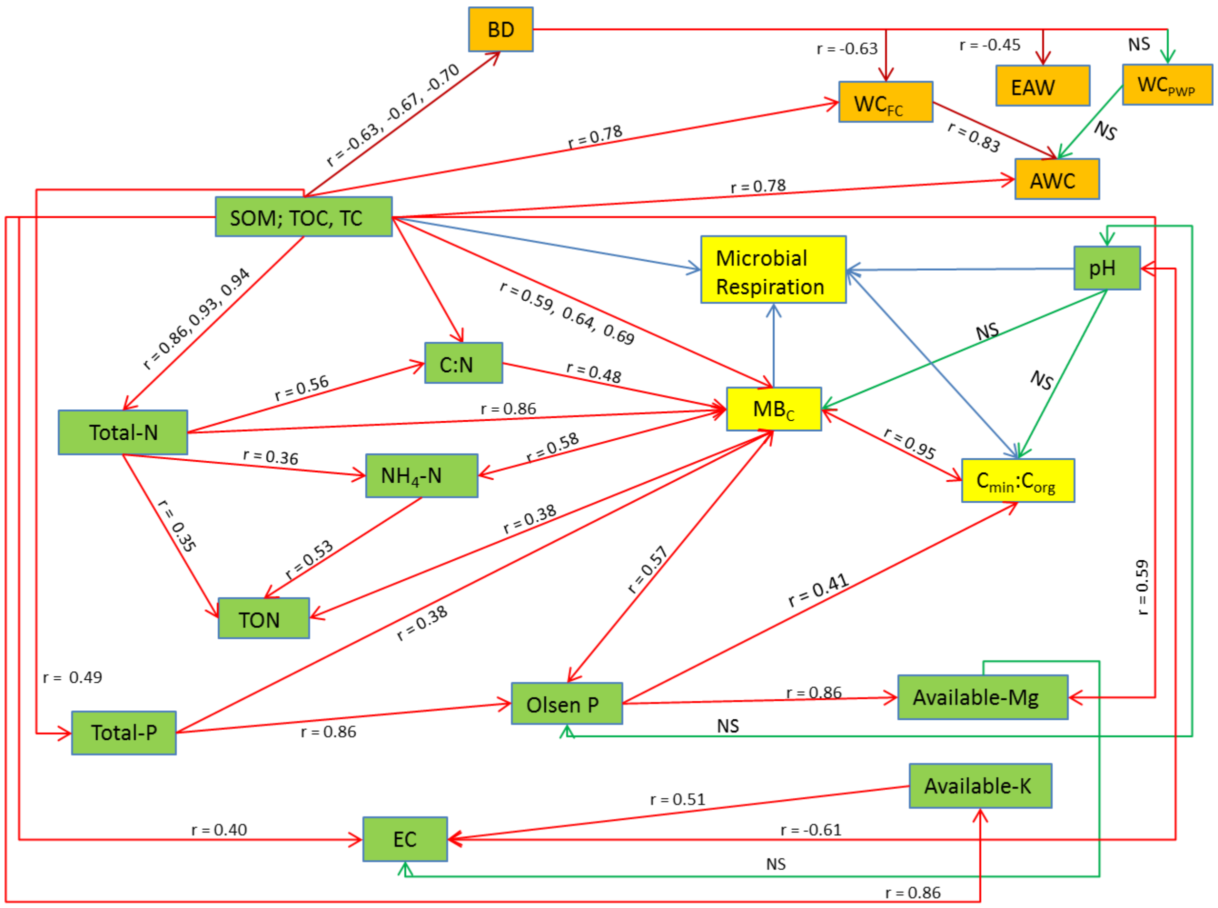


Figure 68 Correlation between the phyiscal, chemical and biological SQIs at post-incubation across all OAs and application rates without inorganic fertilizers.

Red arrows = Significant correlation at p <0.05, Green arrows = non-significant, Blue arrows were not explored, Orange boxes = physical SQIs, Green boxes = chemical SQIs, Yellow boxes = biological SQIs.

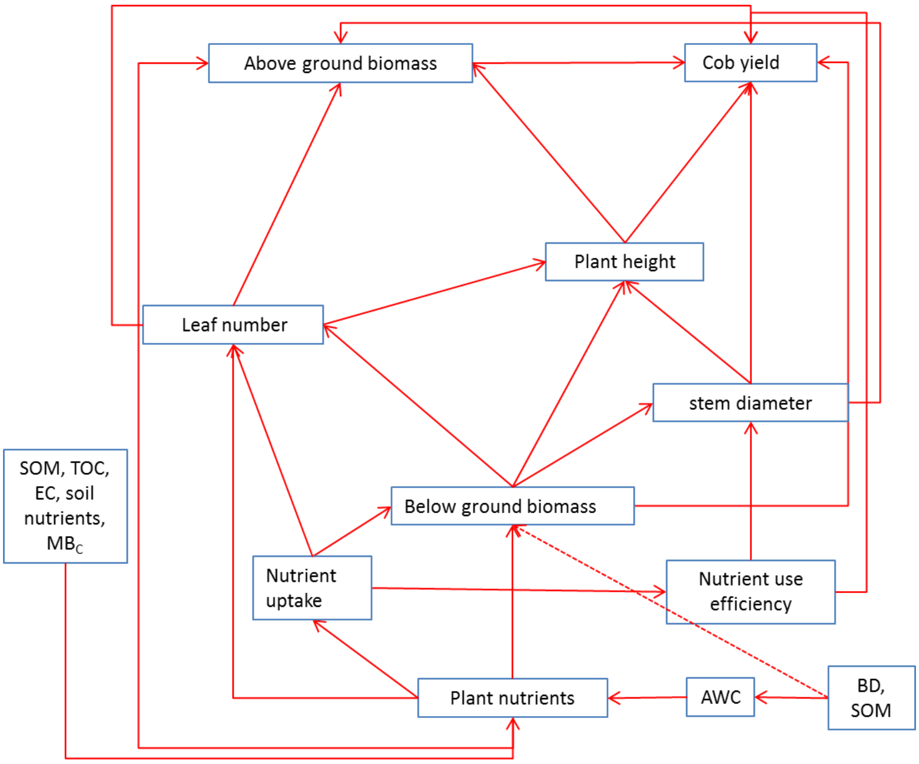


Figure 69 Confirmation of the relationship between selected SQIs and indicators of plant performance at post-incubation across all OAs and application rates with or without inorganic fertilizers.

Red arrows = Significant correlation at $p < 0.05$.

The study suggests that the OA type/quality and the rate of application have varied effects on physical, chemical and biological SQIs. This study demonstrates the ecosystem benefits (Table 37, Section 9.3.1.1) associated with OAs application, even at low application rates, due to their positive effects on the physical, chemical and biological SQIs.

This study provides evidence that OA application at 30 t ha^{-1} without inorganic fertilizer addition is critical to improving the health and productivity of degraded soils. Improving degraded soils will not only reduce the enormous pressure posed on fragile or marginal soils for food production; but it will also contribute towards increasing food supply and ensuring food security. Further, OAs applied at appropriate rates with supplementary inorganic fertilizer will reduce over-dependency on and quantities of inorganic fertilizer required and therefore reduce farm costs and mitigate pollution effects associated with excess inorganic fertilizer application.

To recap; earlier, it was hypothesized that:

1. Application of OAs will improve the soil health by significantly affecting the physical, chemical and biological SQIs as compared with the control (untreated soil).
2. Higher rates of OAs applied will have greater significant effect on the physical, chemical and biological SQIs compared with the lower OAs rates.
3. OAs and the rates applied will significantly affect maize performance (biomass and cob yield) as compared with the control

The results of the present study confirm (accept) these hypotheses, and demonstrate the potency of OAs in restoring the health and productivity of a degraded soil.

10.1 Wider implications and recommendations

The present study demonstrates the positive effects of OAs on physical, chemical and biological SQIs (Figure 68, Section 10). The study suggests that OAs applied at 10 t ha^{-1} + inorganic fertilizer or at 30 t ha^{-1} alone (except PAS) are adequate for maize production. With respect to the legacy effects of OAs, an application rate of 30 t ha^{-1} is strongly recommended, because of the positive residual effect on subsequent plant growth and yield performance (Table 31, Section 8.2.1).

OAs are potentially important agricultural resources and should be used to increase crop productivity, reduce farming costs and maximise profit (farmers' incomes). On this basis, PAS alone is not recommended for crop production unless it is supplemented with inorganic fertilizer. Nevertheless, the significant effects of PAS on soil pH, MB_C, WC_{FC}, AWC and BD suggest that PAS could be used to ameliorate the pH of acid soils and could also be effectively used to improve soil physical and biology SQIs.

10.2 Contributions to knowledge

The present study has addressed some key research questions:

- The P and K nutrients associated with the OA treatments at post-incubation were inadequate for maize production (Figures 29 and 37
- Section 5.1.3 and 5.1.7). However, the significant increases in the plant performance indicators suggest that the MB_C mineralized nutrients in the OAs, making them available for plant uptake, reflecting the significant role of soil biology in nutrient recycling (Figures 5 and 6, Sections 2.7.3 and 2.7.4). This suggests that improving the biological SQIs via OA application is critical to improve the health and productivity of a degraded soil.
- A new innovative scoring and ranking methodology was developed and used to comparatively evaluate whether improvement in the physical, chemical and biological SQIs was concomitantly associated with improvement in plant performance.
- This new methodology also allows physical, chemical, and biological SQIs to be linked to plant performance as well as soil function.
- With the innovative scoring and ranking method, no significant correlation between improvement in the physical SQIs alone and maize performance was found. This is likely to be because water supply was not limiting. Improvement in the physical SQIs is not critical to improving maize crop production in the short term, provided that improvements in the chemical and biological SQIs are achieved.
- The study found that 1% increase in SOM; the soil porosity increased by *circa* 36% and consequently increased the AWC by 5.31 g g^{-1}. This can influence the capability of soil to retain and make water available for plant uptake.
- The study found that for every 1 g cm^{-1} reduction in the soil BD, the soil water content at field capacity [WC_{FC}] increased by 36.5 g g^{-1}. This is remarkable since WC_{FC} affects AWC which is essentially for plant performance.

- Improvement in soil health encompasses a holistic improvement in the overall [combined physical, chemical and biological] SQIs and not necessarily improvement in the individual soil properties.
- This study holistically investigated the effects of OA application on maize performance and robustly corroborated the findings of other studies that OA application is critical to increasing crop yield due to the positive effects of OAs on soil properties.
- The study found that inadequate nutrient supply induces microbial stress, lowers microbial activity and delayed maize tasselling initiation and the production of fewer silk, due to the low N-uptake and NUE (Figure 50, Section 7.1.9). This negatively affected plant growth and yield performance, as evidenced in PAS1NF/2NF and AD_SW1NF treatments.
- The present result suggests that OAs (PM and MC) at applied 10 t ha^{-1} + inorganic fertilizer or at 30 t ha^{-1} alone is economical to farmers. This is because both treatments did not differ significantly in their effect on the Cob_{DW}. The application of OA + inorganic fertilizer treatments at 10 t ha^{-1} rates can compromise other benefits (residual effects) associated with OA treatments applied at higher rates [30 t ha^{-1}], such as reduced BD, increased WC_{FC}, AWC, SOM, NPK, Total-N, Total-P, TOC, and MB_C (See Chapter 8 for more discussion).
- Inadequate nutrient supply induces microbial stress, lowers microbial activity and negatively affects plant growth and yield performance (as evidenced in PAS without inorganic fertilizer treatment).
- The results of this study provide farmers with options and allow them to embark on a decision making process of either choosing crop yield + less input expenses (lower cost) with the application of 10 t ha^{-1} OA + inorganic fertilizer treatments or the option of increasing soil nutrient + wider ecosystem benefits + crop yield for subsequent crops with higher rates (30 t ha^{-1}) of OAs application (Table 36, Section 9.3.1.2).
- The type/quality of OAs applied has varied and significant effects on physical, chemical and biological SQIs and on plant nutrient uptake and

NUE and PUE. In turn, this affects plant performance indicators due to the intrinsic differences of the OAs applied.

- With or without inorganic fertilizer addition, OAs with C:N ≥15 applied at higher (30 t ha^{-1}) application rates reduced crop yield performance as compared with OAs with C:N ≤15 applied at similar rates due to N immobilization . However, at lower (10 t ha^{-1}) application rates + inorganic fertilizer, OAs with C:N ≥15 produced crop yield that is comparative with OAs that have C:N ≤15 (Figure 58, Section 7.3.2).
- With or without inorganic fertilizer addition, an increase in PM treatment application rates from 10 t ha^{-1} to 30 ha^{-1} did not increase ($p < 0.05$) Cob_{DW}. This is due to luxury NP-uptake by the plant with no corresponding increase in yield.
- Across the OAs, higher rates (30 ha^{-1}) of OA + inorganic fertilizer application significantly decreased NUE and PUE by over 30% and 20%, respectively, as compared with lower rates of OA + inorganic fertilizer treatment. This is due to greater supply of nutrient with no corresponding increase in crop yield.
- This study found that improvement in the physical, chemical and biological SQIs improved the overall soil health and ecosystem goods and services (enhanced nutrient recycling/provisioning, increased carbon storage and biodiversity (higher MB_C), provided support for plant growth, enhanced soil retention (water regulation), and increased crop yield [food production]).

10.3 Research limitations and future research

The main limitations of the present study were the scale of the pot experiments and the time to carry out further investigations to address some of the research questions raised by the study. These are:

- The OAs used in the present study differed significantly in their chemical and biological properties which had varied and significant effects on the SQIs tested. Further study is required to evaluate the effects of different combinations of the OAs on the SQIs and subsequent effects on improving the health and productivity of a range of degraded soil types. Achieving an 'optimum blended OA treatment' could further reduce the quantity of inorganic fertilizer applied to agricultural soils and consequently minimize pollution effects due to inorganic fertilizer application.

- To evaluate the effects of different combinations of OAs in improving soil health and productivity.
- Improvement in the biological SQIs was critical in improving plant performance. However, this study did not identify the microbial species or the enzymatic activities that are associated with the OAs applied. Further microbial study is required to identify and understand the microbial population (microbial diversity) and their functionality (enzyme activity) in nutrient recycling. This can be achieved by using molecular techniques, PLFA analysis method and enzyme activity study.
- Significant effects on the physical, chemical and biological SQIs were evident 2 weeks after OA application. Further study is required to understand how quickly OAs improve SQIs after application.
- Long-term effects of OA application are needed to fully understand the SQIs that are critical for sustainable large scale maize production. This will be achieved with replicated field experiments.
- The potential negative impact (pollution effect) of OAs on the above-and-below-ground surface water requires investigation. This will be achieved by setting up an erosion and runoff experiment.
- Inorganic fertilizer addition had a significant effect on the physical SQIs [soil water retention]. Further study is needed to understand this unexpected relationship. Thus, study on the effects of Inorganic fertilizer on physical SQIs, such as aggregate stability, hydraulic conductivity and, pore size distribution, will provide further useful insight.
- Only alkaline soil and maize were considered in this study. Application of OAs to acid soils and a wider range of crops, such sorghum, millet;

cassava, yam, and leafy vegetables, are suggested for evaluation in subsequent studies.

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Appendix A Fuzzy Cognitive Mapping methodology

A.1 Introduction

Fuzzy Cognitive Mapping (FCM) is a cognitive map of graphical representation of thought process that provides a method of organizing and analysing concepts and complex relationships (Özesmi and Özesmi, 2004; Isaac *et al.*, 2009). The FCM was originally developed by Kosko in 1986 (Gray *et al.*, 2015) as a semi-quantitative and dynamic method that structures expert knowledge into a system that visually illustrates relationships between key concepts of the system. In the present study, FCM (Figure 4; Section 2.10) was developed to understand the relationship and interactions that exist between the physical, chemical and biological SQIs. It further helps to understand how changes in these SQIs affect plant performance.

Identification and selection of the SQIs and plant performance indicators (PPIs): The SQIs in the minimum data set (Table 4, Section 2.10) and PPIs (Section 2.9.2) were used in developing the FCM. The SQIs and PPIs were listed on the coloured post-it-notes. Different coloured post-it-notes were used for the SQIs and PPIs for ease of identification when mapping (i.e. sticking the post-it-notes on to a white board.

Cognitive mapping: After listing out the physical, chemical and biological SQIs, they were then linked (i.e. to indicate relationship) based on a ‘cause and effect’ mechanistic approach. For instance; it is evidenced from research that SOM affects soil BD which also influences soil porosity and WHC. Therefore, SOM was linked to BD, porosity and WHC. Thus, based on this mechanistic approach all the SQIs were linked and then mapped to indicate the anticipated relationship between the SQIs (Figure 70 B, Appendix A). Further, the SQIs were linked to the PPIs and then mapped (Figure 70 D, Appendix A).

Figure 70 Fuzzy cognitive map illustrating the relationship between the SQIs and the plant performance indicators.

A = lists the organic amended treatments, B = Shows the interaction between the SQIs, C = lists the plant performance indicators, D = shows how the SQIs affect the PPIs.

Appendix B Inorganic Fertilizer Requirement Calculation

B.1 Calculating the equivalent amount of single NPK fertilizers applied

Fertilizer recommendation manual RB209 recommended the application of 100 kg N ha^{-1}; 55 kg P ha^{-1} and 205 kg ha^{-1} for a soil with an index of 1, 2, and 1, respectively (Table 9, Section 3.3). However, the NPK fertilizers used in this study were Nitram (34.5% N), triple superphosphate [TSP] (46% P_2O_5) and Murate of potash [MOP] (60% K_2O). Because the inorganic fertilizers applied do not contain 100% NPK due to some additives, therefore the appropriate quantities of NPK applied were calculated thus:

For N, kg N ha^{-1} in 100 kg Nitram (34.5% N) is: (100/34.5) x 100 = 289.86 kg N ha^{-1}. For P, kg P ha^{-1} in 55 kg TSP (46% P_2O_5) is: (55/46)*100 = 119.57 kg ha^{-1}. For K, kg K ha^{-1} in 205 kg MOP (60% K_2O) is: (205/60)*100 = 341.67 kg ha^{-1}.

However, only 50% RB209 recommended rate was applied. Therefore the required fertilizer amount (kg ha^{-1}) was:

For N: 289.86 kg ha^{-1} x 50% = 144.94 kg ha^{-1}.

For P: 119.57 kg ha^{-1} x 50% = 59.79 kg ha^{-1}.

For K: 341.67 kg ha^{-1} x 50% = 170.84 kg ha^{-1}.

Note: 1 kg ha^{-1} = 0.1 g m^{-2} or 0.01 mg cm^{-2}. Surface area of the experimental pot is 2352 cm^2. The quantity of inorganic fertilizer applied per pot was thus: 0.01 mg cm^{-2} x 2352 cm^{-2} = 23.52 mg pot^{-1} (0.02352 g pot^{-1}), therefore the quantity of single NPK applied per pot was:

For N: 114.94 kg ha^{-1} x 0.02352 g pot^{-1} = 2.70 g N pot^{-1}.

For P: 59.79 kg ha^{-1} x 0.02352 g pot^{-1} = 1.41 g P pot^{-1}.

For K: 170.84 kg ha^{-1} x 0.02352 g pot^{-1} = 4.01 g K pot^{-1}.

Therefore, the NPK applied per pot was 2.70 g, 1.41 g and 4.01 g, respectively.

Appendix C

Table C-1 Effect treatment application on SQIs at post-harvest

Treatments	Olsen-P (mg kg)	EC (µS/cm)	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available-K (mg kg^{-1})	Available-Mg (mg kg^{-1})	CEC (cmol kg^{-1})	SOM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	TOC (mg kg^{-1})	C : N	Bioavailable-TOC (%)	Total-P (mg kg^{-1})	Bioavailable-P (%)	C:P	N:P
OA treatments without inorganic fertilizer																		
CNF	28.8^{a}	137^{bcde}	8.10^{bcde}	0.00^{a}	0.00^{a}	86^{a}	193^{ab}	17.0^{bcde}	1.97^{a}	370^{a}	1030^{a}	832^{a}	2.87^{a}	89.2^{bcd}	1710^{a}	1.69^{a}	0.60^{a}	0.22^{a}
PM1NF	75.0^{def}	122^{abc}	8.10^{bcde}	0.00^{a}	0.00^{a}	108^{ab}	395^{g}	16.0^{bc}	2.72^{b}	1000^{cde}	5930^{bc}	4919^{b}	5.95^{bc}	87.0^{b}	2130^{cd}	3.53^{efg}	2.79^{bc}	0.47^{bc}
PM2NF	166^{h}	179^{cdef}	8.18^{cdefg}	9.25^{d}	0.63^{b}	268^{defg}	786^{i}	19.5^{ef}	4.76^{f}	2190^{h}	14500de	11517^{c}	7.00^{bcd}	87.8^{bc}	2830^{e}	5.87^{i}	5.03^{de}	0.77^{efg}
PAS1NF	38.7^{ab}	193^{efgh}	8.28^{fg}	0.13^{ab}	0.00^{a}	141^{bc}	211^{bc}	15.3^{b}	2.56^{b}	780^{bcd}	5820^{bc}	4299^{b}	7.51^{cd}	69.7^{a}	1680^{a}	2.30^{abc}	3.47^{c}	0.46^{bc}
PAS2NF	56.0^{bcd}	349^{i}	8.30^{g}	0.25^{bc}	0.00^{a}	290^{fg}	254^{e}	19.2^{def}	3.89^{cde}	1150^{defg}	11100^{d}	10656^{c}	9.77^{de}	95.6^{bcd}	1690^{abcd}	3.34^{defg}	6.65^{ef}	0.68^{defg}
AD_SW1NF	63.8^{cde}	197^{fgh}	8.08^{abcd}	1.13^{cd}	0.13^{ab}	281^{efg}	315^{f}	16.7^{bcde}	2.84^{b}	860^{cd}	5780^{bc}	5287^{b}	6.72^{bcd}	91.8^{bcd}	2030^{cd}	3.14^{cdef}	2.84^{bc}	0.42^{bc}
AD_SW2NF	106^{g}	245^{h}	8.13^{bcdef}	2.88^{d}	0.00^{a}	670^{j}	456^{h}	16.3^{abc}	4.43^{def}	1460^{g}	14300de	13349^{ef}	9.78^{de}	93.8^{bcd}	2160^{cd}	4.95^{hi}	6.62^{ef}	0.68^{def}
MC1NF	45.6^{abc}	317^{i}	8.28^{fg}	0.00^{a}	0.00^{a}	295^{defg}	219^{cd}	15.0^{b}	2.69^{b}	780^{cd}	6510^{c}	5863^{b}	8.29^{de}	90.1^{bcd}	1730^{ab}	2.65^{bcde}	3.77^{cd}	0.46^{bc}
MC2NF	73.3^{def}	790^{k}	7.93^{a}	0.63^{bc}	0.38^{b}	435^{hi}	253^{e}	19.3^{def}	4.09^{cdef}	1490^{g}	14900^{e}	13916^{e}	10.2^{f}	93.4^{bcd}	1880^{abcd}	3.9^{fg}	7.95^{f}	0.79^{fg}
OA treatments with inorganic fertilizer																		
CF	30.1^{a}	70.6^{a}	8.20^{defg}	0.00^{a}	0.00^{a}	115^{ab}	182^{a}	11.9^{a}	1.91^{a}	410^{ab}	920^{a}	763^{a}	2.24^{a}	87.4^{bc}	1730^{a}	1.76^{ab}	0.53^{a}	0.24^{a}
PM1F	90.8^{fg}	125^{abcd}	8.05^{abcd}	1.13^{cd}	0.00^{a}	197^{cde}	433^{gh}	16.7^{bcde}	3.85^{cd}	1010^{cde}	6390^{c}	5661^{b}	6.35^{bc}	94.1^{bcd}	2200^{d}	4.01^{fgh}	2.92^{bc}	0.46^{bc}
PM2F	198^{i}	222^{fgh}	8.10^{bcde}	7.13^{d}	0.38^{ab}	346^{gh}	727^{i}	19.2^{def}	3.98^{cde}	2120^{h}	14800^{e}	13612^{ef}	7.26^{cd}	99.7^{d}	2380^{d}	7.59^{j}	7.52^{ef}	1.01^{g}
PAS1F	36.9^{ab}	115^{ab}	8.20^{defg}	0.00^{a}	0.00^{a}	131^{b}	199^{abc}	16.3^{bcde}	2.59^{b}	1040^{cdef}	4760^{b}	4208^{b}	5.45^{b}	88.6^{bc}	1720^{ab}	2.16^{ab}	2.79^{bc}	0.61^{cde}
PAS2F	44.8^{abc}	171^{bcdef}	8.28^{fg}	0.00^{a}	0.00^{a}	233de	244de	18.5^{cdef}	3.58^{c}	1320^{efg}	12300de	11597^{cd}	9.42^{ef}	94.8^{bcd}	1710^{ab}	2.64^{abcde}	7.17^{f}	0.77^{fg}
AD_SW1F	41.0^{ab}	183^{defg}	8.03^{abc}	0.13^{ab}	0.00^{a}	305^{fgh}	296^{f}	14.3^{ab}	2.74^{b}	690^{abc}	4640^{b}	4487^{b}	6.94^{bcd}	97.3^{cd}	1870^{bcd}	2.19^{abc}	2.51^{b}	0.37^{b}
AD_SW2F	86.0^{efg}	240^{gh}	8.05^{abcd}	3.00^{d}	0.25^{ab}	625^{j}	448^{h}	16.9^{bcde}	4.61^{ef}	1400^{efg}	13500de	13175^{def}	9.64^{de}	97.5^{cd}	2070^{cd}	4.13^{gh}	6.50^{ef}	0.67^{def}
MC1F	44.7^{abc}	317^{i}	8.25^{efg}	0.00^{a}	0.00^{a}	196^{cd}	189^{ab}	15.7^{bc}	2.61^{b}	980^{cde}	6300^{bc}	4591^{b}	6.31^{bc}	93.2^{bcd}	1810^{abc}	2.48^{abcd}	3.47^{bc}	0.54^{cd}
MC2F	78.5^{ef}	712^{j}	8.00^{ab}	6.88^{d}	0.88^{c}	564^{ij}	224^{cd}	20.9^{f}	4.08^{cdef}	1440^{fg}	13800de	12185^{cde}	9.53^{de}	96.3^{bcd}	1940^{abcd}	4.07^{fgh}	7.07^{f}	0.74^{efg}

Table C-2 Relationship between the chemical and biological SQI post-harvest

Treatments	EC (μS cm^{-1})	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available-K (mg kg^{-1})	Available-Mg (mg kg^{-1})	SOM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	C:N	TOC (mg kg^{-1})	Total-P (mg kg^{-1})	MB_C (μg g^{-1})	C:P	Bio-available-P (%)	Bio-available-TOC (%)	MResp. (μg CO_2 g^{-1} day^{-1})	qCO2 (%)	C_{min}:C_{org} (%)
									OA treatments without inorganic fertilizer										
Olsen-P	-0.01^{ns}	-0.21^{ns}	0.69*	0.49*	0.42*	0.92*	0.74*	0.85*	0.68*	0.22^{ns}	0.64*	0.87*	0.75*	0.43*	0.94*	0.15	0.62*	-0.37*	0.58*
EC		-0.33^{ns}	-0.04^{ns}	0.20^{ns}	0.39*	-0.23^{ns}	0.40*	0.28^{ns}	0.56*	0.59*	0.61*	-0.17^{ns}	-0.11^{ns}	0.71*	0.13^{ns}	0.25	-0.12^{ns}	-0.22^{ns}	-0.24^{ns}
pH			-0.08^{ns}	-0.23^{ns}	-0.09^{ns}	-0.17^{ns}	-0.15^{ns}	-0.16^{ns}	-0.23^{ns}	-0.03^{ns}	-0.21^{ns}	-0.28^{ns}	-0.16^{ns}	-0.13^{ns}	-0.18^{ns}	0.04	0.02^{ns}	-0.12^{ns}	-0.14^{ns}
TON				0.04^{ns}	0.45*	0.66*	0.50*	0.73*	0.46*	0.08^{ns}	0.50*	0.59*	0.67*	0.30^{ns}	0.63*	0.23	0.33^{ns}	-0.23^{ns}	0.54*
NH4-N					0.13^{ns}	0.44*	0.43*	0.36*	0.41*	0.14^{ns}	0.33*	0.50*	0.17^{ns}	0.26^{ns}	0.40*	-0.06	0.36*	-0.11^{ns}	0.01^{ns}
Available-K						0.28^{ns}	0.62*	0.43*	0.65*	0.62*	0.72*	0.20^{ns}	0.53*	0.66*	0.55*	0.4	0.15^{ns}	-0.35*	0.35*
Available-Mg							0.63*	0.78*	0.52*	0.04^{ns}	0.46*	0.93*	0.73*	0.23^{ns}	0.77*	0.03	0.64*	-0.30^{ns}	0.61*
SOM								0.78*	0.95*	0.67*	0.93*	0.57*	0.69*	0.84*	0.76*	0.21	0.59*	-0.42*	0.40*
Total-N									0.81*	0.31^{ns}	0.78*	0.74*	0.62*	0.63*	0.78*	0.18	0.59*	-0.41*	0.44*
Total-C										0.74*	0.97*	0.50*	0.63*	0.93*	0.72*	0.17	0.50*	-0.48*	0.36*
C:N											0.76*	-0.02^{ns}	0.34*	0.86*	0.40*	0.19	0.11^{ns}	-0.58*	0.18^{ns}
TOC												0.41*	0.60*	0.95*	0.74*	0.36	0.39*	-0.49*	0.35*
Total-P													0.73*	0.16^{ns}	0.67*	-0.07	0.67*	-0.25^{ns}	0.62*
MB_C														0.43*	0.72*	0.1	0.48*	-0.47*	0.91*
C:P															0.58*	0.27	0.26^{ns}	-0.51*	0.20^{ns}
Bioavailable-P																0.31	0.46*	-0.46*	0.55*
Bioavailable-TOC																	-0.14^{ns}	-0.26^{ns}	0.07^{ns}
MResp																		0.01^{ns}	0.29^{ns}
qCO2																			-0.53*

Treatments	EC (µS cm^{-1})	pH	TON (mg kg^{-1})	NH_4-N (mg kg^{-1})	Available -K (mg kg^{-1})	Available-Mg (mg kg^{-1})	SOM (%)	Total-N (mg kg^{-1})	Total-C (mg kg^{-1})	C:N	TOC (mg kg^{-1})	Total-P (mg kg^{-1})	MB_C (µg g^{-1})	C:P	Bio-available -P (%)	Bio-available -TOC (%)	MResp. (µg CO_2 g^{-1} day^{-1})	qCO2 (%)	C_{min}: C_{org} (%)
OA treatments with inorganic fertilizer																			
Olsen-P	0.17^{ns}	-0.25^{ns}	0.56*	0.34*	0.43*	0.91*	0.55*	0.73*	0.65*	0.33*	0.65*	0.66*	0.74*	0.50*	0.97*	0.13^{ns}	0.83*	-0.30^{ns}	0.71*
EC		-0.29^{ns}	0.51*	0.64*	0.63*	-0.05^{ns}	0.39*	0.37*	0.55*	0.53*	0.49*	0.07^{ns}	0.35*	0.51*	0.25^{ns}	-0.03^{ns}	0.23^{ns}	-0.24^{ns}	0.30^{ns}
pH			-0.20^{ns}	-0.40*	-0.44*	-0.25^{ns}	-0.21^{ns}	-0.11^{ns}	-0.15^{ns}	-0.16^{ns}	-0.17^{ns}	-0.34*	-0.30^{ns}	-0.01^{ns}	-0.24^{ns}	-0.11^{ns}	-0.27^{ns}	-0.10^{ns}	-0.33*
TON				0.36*	0.50*	0.45*	0.41*	0.46*	0.57*	0.38*	0.52*	0.31^{ns}	0.46*	0.49*	0.57*	0.01^{ns}	0.50*	-0.21^{ns}	0.42*
NH4-N					0.57*	0.18^{ns}	0.48*	0.55*	0.54*	0.31^{ns}	0.55*	0.42*	0.30^{ns}	0.35*	0.30^{ns}	0.12^{ns}	0.44*	-0.16^{ns}	0.19^{ns}
Available-K						0.37*	0.68*	0.54*	0.75*	0.72*	0.77*	0.37*	0.77*	0.58*	0.47*	0.27^{ns}	0.39*	-0.45*	0.69*
Available-Mg							0.56*	0.65*	0.58*	0.32*	0.60*	0.59*	0.76*	0.47*	0.88*	0.20^{ns}	0.77*	-0.34*	0.75*
SOM								0.66*	0.80*	0.71*	0.82*	0.38*	0.75*	0.71*	0.60*	0.25^{ns}	0.61*	-0.49*	0.57*
Total-N									0.85*	0.48*	0.83*	0.53*	0.66*	0.70*	0.70*	0.10^{ns}	0.75*	-0.38*	0.58*
Total-C										0.82*	0.97*	0.38*	0.80*	0.90*	0.69*	0.13^{ns}	0.67*	-0.49*	0.71*
C:N											0.81*	0.14^{ns}	0.68*	0.79*	0.44*	0.20^{ns}	0.36*	-0.57*	0.65*
TOC												0.45*	0.81*	0.82*	0.68*	0.34*	0.67*	-0.53*	0.73*
Total-P													0.42*	-0.02^{ns}	0.49*	0.23^{ns}	0.60*	-0.25^{ns}	0.44*
MB_C														0.71*	0.80*	0.25^{ns}	0.64*	-0.53*	0.94*
C:P															0.62*	0.01^{ns}	0.51*	-0.45*	0.61*
Bioavailable-P																0.10^{ns}	0.80*	-0.34*	0.76*
Bioavailable-TOC																	0.07^{ns}	-0.45*	0.28^{ns}
MResp																		-0.13^{ns}	0.59*
qCO2																			-0.58*

*= significant at $p < 0.05$, ns = not significant.