CRANFIELD UNIVERSITY

SCHOOL OF WATER ENERGY AND ENVIRONMENT

PhD THESIS

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EVALUATING PHOSPHORUS DYNAMICS FROM RENEWABLE SOURCES TO MEET CROP DEMAND AND MINIMISE ENVIRONMENTAL POLLUTION IN MALAWI

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Abstract

Like nitrogen (N), phosphorus (P) is an essential plant nutrient. When soils are deficient in P, external P in the form of fertilisers must be applied to increase crop yields. Population growth and changes in dietary needs have resulted in increased demand for P fertiliser for food and feed production, exerting pressure on P reserves. The future availability of P fertilisers is uncertain as reports indicate that the high-grade P reserves will be depleted in the next 100 years. On the other hand, human activities like conventional tillage, continuous cropping, and burning crop residues have led to nutrient leaching, increased soil acidity, increased erosion, reduced organic matter and reduced water holding capacity, all of which have contributed to overall reduced soil productivity. Most Malawian soils have low P, and farmers apply P fertilisers to harvest enough food. The scarcity of P will lead to an increase in fertiliser prices which will in turn, affect food security in Malawi. However, research has shown that organic materials like faecal sludge, organic waste and livestock manure could be used as alternative sources of P in agriculture.

In some highly industrialized countries, P flow charts were developed to identify and quantify the organic P sources for recycling and management. However, until now, there has been no complete P flow analysis in any African country. Furthermore, organic fertilisers that have been tested have only been applied to crops based on N, not P, which may not affect soil health the same way. In addition, it is unclear if P mineralising from the organic fertilisers can maintain the available P concentration in the soil and result in the same crop yield as inorganic fertilisers

Against this background, this project aimed at conducting a P flow analysis (PFA) using STAN Software to characterise and quantify P sources, flows, and sinks to determine options for waste minimisation, recovery, and inorganic fertiliser use reduction in Malawi. After the organic sources were identified, field experiments were implemented to evaluate the effects of organic P sources derived from organic market waste and faecal sludge on soil health in Malawi. Furthermore, the field experiments were used to study P mineralisation and availability from the P-based organic fertilisers during the plant growth period.

The PFA results highlighted that there are 35000 Mg of recyclable organic P available annually, which is over two times Malawi's annual P fertiliser demand (14000 Mg). The total amount of P applied to the soil for crop production per year is 21000 Mg of which 5300 is applied through animal manure, 1700 Mg through the decomposing mulch and faecal sludge, and the rest through inorganic fertilisers. Although 21000 Mg was applied, 25000 Mg left the soil through crop removal (23000 Mg) and soil erosion (2000 Mg), which resulted in a negative P balance of 1 kg P per hectare.

Almost 5000 Mg of P in crop products goes to waste materials during postharvest handling processes, and 1100 Mg is exported in agricultural products. At the consumption level, 100 Mg of P is in food waste and 10000 Mg of P is consumed by the people. Out of the P consumed by people, 91% ended up in pit latrines, and the remaining 9% went to open defecation, WWTPs, and septic tanks. There is also 13000 Mg of P in manure and 4000 Mg in organic waste dumped in unofficial dumpsites, and 500 Mg P in landfills.

Although there is organic P in faecal sludge, manure, and organic waste, only 16% of the organic P is recycled for agriculture. Inorganic P fertiliser represents 66% of the P fertiliser used for crop production. Manure is the most recycled organic P source (38% recycled), followed by organic solid waste (6%) and crop residues (5%). Annually, 9000 Mg of P is transferred to faecal matter, but none is recycled.

In crop trials, the application of the organic P based fertilisers increased soil organic matter by 60% in two seasons at one field site (Bvumbwe) and 82% at the second (Makoka). Soil pH, which affects plant nutrient availability and microbial activities in the soil, increased from 4.75 to 5.82 in two seasons. There were almost six times more earthworms in the soil at Bvumbwe and four times more earthworms at Makoka compared to inorganically fertilised soil. Bulk density decreased only at Bvumbwe, and maize yield was not affected by P sources. The results on P mineralisation showed that available P in the soil from three weeks after planting to nine weeks increase the maize yield. Modelled results indicated that available P in the soil at three weeks accounted for 50%, at six weeks accounted 49%, and nine weeks after counted for 46% of the maize grain yield. At Makoka, at three and six weeks after planting in both seasons, available soil P was the same regardless of P source, but at nine weeks, the NPK treatment had lower available P. At Bvumbwe, in the first season, available P was the same at 3 and 9 weeks after planting but lower in NPK, NPK+MW and NPK+FSMW at six weeks. There was the same available P concentration in all treatments in the second season. In general, the organic P sources maintained available soil P at 25 mg/kg on average, above the threshold available P value for Malawi (18 mg/kg). At both sites, during the first season, PUE was the same. Only NPK and MW at 15 application rates had higher PUE in the second season. A comparison of

PUE between the two sites showed that Bvumbe had a higher PUE than Makoka in both seasons.

These findings indicate that Malawi can reduce its dependence on imported inorganic P by using organic sources that will supply P for crop growth and production just as well as the NPK fertiliser while improving soil health and reducing P losses to the environment.

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As long as we are alive

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Abbreviations

Al - aluminium

ANOVA - analysis of variance

AR - application rate

ATP - adenosine triphosphate

CA - conservation agriculture

Cd - cadmium

CEC - Cation exchange capacity

CFC - chlorofluorocarbon

Cu - copper

DNA - deoxyribonucleic Acid

EC - electroconductivity

FAO - Food and Agriculture Organisation

FAOSTAT - Food and Agriculture Organisation Statistics

Fe - iron

FSMW - faecal sludge market waste

GHG - greenhouse gas

GLOSOLAN - Global Soil Laboratory Network

ICLEI - Local Governments for Sustainability

ICP-MS – inductively coupled plasma mass spectrometry

IFDC - International Fertiliser Development Center

Kg - kilogram

LCA - life cycle assessment

LSD - least significant deference

MFA - material flow analysis

Mg - magnesium

Mg - mega gram

Mn - manganese

MSA - material system analysis

MW - market waste

N - Nitrogen

N_2O - nitrous oxide

NH_3 - ammonia

NPK - nitrogen, phosphorus, and potassium

NRCS - Natural Resources Conservation Service

NSO - National Statistical Office

OCED - he Organisation for Economic Co-operation and Development

ONORM - Austrian national standards

P - phosphorus

Pb - lead

PFA - phosphorus flow analysis

PUE - phosphorus use efficiency

S - sulphur

SDG - sustainable development goals

SOC - soil organic matter

SoHCoM - Soil Health Consortium of Malawi

Sq - soil quality

STAN - software for material flow analysis

UK - United Kingdom

UN - United Nations

USA - United States of America

USDA - United States Department of Agriculture

USGS - United States Geological Survey

UV/VIS - ultraviolet–visible spectroscopy

WWTP - wastewater treatment plant

Zn - zinc

Chapter 1 . Introduction

1.1 Background

Without phosphorus (P), there would be no life on earth (Mullins, 2009). Along with nitrogen, P is one of the limiting plant nutrients (Smit et al., 2010). P is an essential element for life as it plays significant roles in energy production (ATP), genetic reproduction (DNA), and photosynthesis. P is a naturally occurring soil mineral but unevenly spread across the world. In some soils, the concentration is such that an external supplement in the form of fertiliser is required to grow healthy crops. To meet this demand, the world depends on phosphate rock for phosphate fertiliser production (Smit et al., 2010). Globally, significant phosphate rock deposits are in Morocco, China, Russia, the USA, Jordan, and South Africa. Morocco-controlled Western Sahara alone controls 75% of the world's phosphate rock deposits (USGS, 2017).

The bioavailability and concentration of soil phosphorus are very important for plant growth. It is only when phosphorus is bioavailable that it can support plant growth and its availability to plants depends on the forms available and concentration (Horrocks et al., 2016). Plants take up P in soil solution (available P) in the form of orthophosphate ions ($H_2PO_4^-$, HPO_4^{2-}). Available phosphorus makes up only 20 % of the total P. The total P comprises organic and inorganic P. Organic P forms include plant and animal residues and soil micro-organisms. Soil micro-organisms help to mineralise these organic forms of P into plant-available forms. The plant-available P, sorbed P and mineral P make up the inorganic P. Available P refers to the dissolved P ions in the soil solution that the crops can take up. In contrast, sorbed P refers to the P ions attached to Fe, Al and Ca ions that are released slowly into the soil solution. Mineral P is composed of secondary and primary P minerals, for example, apatite, strengite, and variscite. Mineral P forms are unavailable for plants unless the mineral weathers (Prasad and Chakraborty, 2019).

A P concentration of 25 to 50 mg P dm^{-3} in soil solution throughout the growth period of crops is deemed to be the optimum for plant growth (Tisdale *et al*, 1983). However, the P in most agriculture soils ranges from less than 0.01 to 1 mg P dm^{-3}, which is not enough for plant growth and reproduction and has to be replenished (Mullins, 2009). Phosphorus can be replenished using organic or inorganic sources. Crops accumulate most of their P needs in the early growth stages (McKenzie and Middleton, 2013). Therefore, P fertilisers have to be applied early so that crops can access the P when needed most. The yield response upon P fertiliser application is one way of determining the amount of P fertiliser to be applied. The aim is to get the highest yield per amount of P applied. In the 1980s, there were concerns that phosphorus production would reach its peak due to the heavy use of fertilisers in the Soviet Union. In the 1990s, knowledge of the adverse effects of phosphorus on the environment (eutrophication) and the disbandment of the Soviet Union resulted in a reduction in fertiliser use (Daneshgar et al., 2018). However, an increasing human population and changes in dietary needs have resulted in increased fertiliser use, including phosphate fertilisers (Daneshgar et al., 2018). The United Nations (2019) predicted that by the year 2050, there would be around nine billion people on earth. This increase in population will translate into increased food demand which will require the concomitant increase in fertiliser application. However, phosphate rocks, from which phosphorus fertiliser is made, are a non-renewable resource, i.e., the mineable stocks will not last forever (Cordell, 2010; Schröder et al., 2009; Smit et al., 2010). In fact, the world is in danger of phosphorus production peaking and, as a consequence, may not have any reliable sources of financially viable phosphorus in the next 35 to 100 years (Cordell, 2010; Schröder et al., 2009; Smit et al., 2010).

It is against this uncertainty surrounding the future of phosphorus that research into ways of recapturing phosphorus from waste (faecal matter, household waste, municipal wastewater, livestock manure, etc.) to be used in agriculture as fertiliser began. These waste materials contain various concentrations of P (Table 1.1) that can be reused for crop production

Table 1.11. Phosphorus content in different waste materials

Source of recycled P	P content	Reference
Poultry droppings	19400 mg/kg Total P	Amoah et al*.,* 2017
Cattle manure	169.7- 2430 mg/kg total P	Anwar et al., 2017; Soma et al., 2018
Guinea pig manure	160 mg/kg available P	Garfí et al., 2011
Faecal sludge	21 - 3782 mg/kg available P 7500 – 28170 ppm total P	Coutinho et al*.,* 1997; Adamtey et al*.,* 2010; Moya et al*,* 2017; Amoah et al*,* 2017
Municipal wastewater sludge	5000 mg/kg	Tomócsik et al., 2016
Urine	300 – 1070 mg/kg total P	Amoah et al, 2017
Municipal/market waste	3619 – 4600 mg/kg available P	Adamtey et al*.,* 2010; Horrocks et al*.,* 2016; Grau et al*,* 2017

1.2 Phosphorus recycling in agriculture

Knowing the quantity of P in different organic waste materials is just one step towards P recycling. As the world thinks of recycling P, there is also a need to identify the current sinks/stocks from which P can be recycled. Sinks/stocks are places/points where P accumulates and can be recovered for reuse. Although some developed countries like Spain (Álvarez et al., 2018), the United Kingdom (Cooper & Carliell-Marquet, 2013), Australia (Cordell et al., 2013), New Zealand (Li et al., 2015), and Denmark (Klinglmair, Lemming, Stoumann, et al., 2015) have documented their phosphorus sinks and stocks, similar data from African countries is lacking. The work in Europe so far represents a very specific set of livestock, sanitation, and solid waste management systems that are wholly unlike those in African countries. The major P recovery points for the developed countries that did material flow analysis of P/P flow analysis are wastewater treatment plants (WWTP) and animal manure. Cordell et al., (2011) stated that phosphorus problems are country-specific, so each country needs to conduct its P flow analysis.

Material flow analysis (MFA) is a term that is used to describe a group of material accounting tools that use the mass balance concept to assess the movement of materials in and out of a unit area defined in space and time. The space can be a household, company, region or country, while the time can be a day, a week, a month or a year. The choice of the tool to be used depends on the goal of the MFA. For example, substance flow analysis deals with the movement of the periodic table elements (Cu, Cd, Pb, P, etc.) and other compounds like chlorofluorocarbon (CFC) and carbon dioxide. The MFA helps illustrate where the substance of concern, for example, P, accumulates and in what form and quantity before the actual recycling. The results of the MFA are especially useful for decision-makers who require a quantitative overview of where the material is accumulating or lost.In Malawi, almost 80 per cent of the people use pit latrines (NSO, 2017). On average, only 20 per cent of the solid waste produced in the cities of Lilongwe, Blantyre, Zomba, and Mzuzu is collected by the authorities for proper disposal (ICLEI, 2016; Government of Malawi, 2014), and 80 per cent of the livestock are on a free-range system of management (Chintsanya et al., 2004). These differences between Malawi and developed countries indicate that the P flow analysis for developing countries would result in different P flows. Therefore, any P recovery plans in developing countries cannot be based on results from the developed countries.

Nutrient recycling is not a new practice in agriculture; incorporating plant residues, applying animal manure, and other forms of composted manure have been practised for thousands of years. For example, faecal sludge as a fertiliser dates back to ancient times in Britain, China, Greece, and Rome (Buckwell and Nadeu, 2016; Smet and Sudgen, 2006; Shiming, 2002). Currently, composting toilets and wastewater treatment plants are two common ways of recovering P from excreta (Nyirenda and Holm, 2015; Manda, 2009). Organic fertiliser (compost, manure, and faecal sludge) has been applied mainly as a source of nitrogen and in a few instances as a P source. In both situations, these recycled fertilisers have resulted in improved performance of crops like maize (Adamtey et al., 2010; Herrmann et al., 2012; Tomócsik et al, 2016; Cavalli et al., 2016; Horrocks et al., 2016), cabbage, lettuce, tomato, green pea (Begum, 2011; Giannakis et al, 2014; Tomócsik et al, 2016; Amoah et al, 2017; Torgbo et al., 2018), wheat (Abubaker et al., 2012) and forage grass (Coutinho et al, 1997; Horrocks et al., 2016). Yield increases ranging from 1.37 - 550% have been reported (Coutinho et al, 1997; Garfí et al., 2011; Abubaker et al, 2012; Tomócsik et al, 2016; Cavalli et al., 2016; Torgbo et al., 2018).

1.3 The recycling of P from organic materials and faecal sludge is in line with the concept of the "circular economy", which emphasises resource recovery from bio-waste materials in the form of soil amendments, fertilisers, growing media, etc. Landfilling and incineration are discouraged in the circular economy as the nutrients cannot be used. Instead of ending up at landfills and incineration facilities, organic waste materials from agricultural processes, and waste materials from sanitation sectors, should be recycled as P fertilisers.Soil health

Soil health is defined as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans" (USDA-NRCS, 2012) as cited in Cornell University -Soil Health Laboratory (2016). Soil health is adversely affected by human activities like conventional tillage, continuous cropping, and burning of crop residues, leading to soil organic matter loss, increased soil acidity, reduced water holding capacity, and increased soil erosion. The soil should be managed in a way that does not cause it to lose its main functions (Cornell University, 2016), which include retaining and cycling nutrients, sequestering carbon, and supporting food and feed production, among other functions. Soil health encompasses the chemical, physical, and biological aspects of soils (Gugino et al., 2009).

Soil health degradation is one of the challenges Malawi is facing. Malawi has a population density of 202 people/km2 (UN, 2020), with a growth rate of 2.9% (NSO, 2019). This population growth which has resulted in increased food demand has forced farmers to intensify crop production to produce more food since they cannot increase the land size allocated to food production. On average, farmers have one hectare of land for crop production (FAO, 2015). Continuous cropping without rotation, crop residue burning, and acidifying fertiliser application have accelerated the decline of soil health (Snapp, 1998). Soils in Malawi have low concentrations of available P (<18 mg/kg), nitrogen, organic matter and low pH (<5.5) (Maida, 2013; Njoloma et al., 2016; Snapp, 1998). In addition, there is almost 20 tonnes/ha of soil removed every year by soil erosion (Omuto & Ronald, 2018). The decline in soil health, which is exacerbated by climate change which has resulted in increased drought occurrences, has resulted in reduced crop productivity, causing households to be food insecure. For example, in 2020, 10 %% of the population was suffering from food insecurity (IPC, 2020).

However, organic fertilisers have been reported to improve soil health. Increases in soil organic matter, soil pH, available P, and microbe populations, among other parameters, have been reported, although most of the studies used N- based application rates for the organic fertilisers (Adalberto et al., 2018; Debiase et al., 2018; Garbout et al., 2013; Girma, Tesfaye et al., 2019; Hammad et al, 2019; Heoran et al, 2019; Juan & Adriana, 2018; Khorram, Zhang et al., 2018; Munkholm et al, 2013; Parker et al., 2018; Singh et al., 2019). Reduced soil erosion due to increases in soil organic matter has also been reported (Guerra, 1994; Mloza-Banda et al., 2016).

1.4 Organic P and Sustainable Development Goals

Just as other countries, Malawi focuses on achieving sustainable development goals (SDGs). To achieve the SDGs, Malawi has incorporated the SDGs in its national plans (Government of Malawi, 2020a). However, lack of proper waste (solid waste and faecal matter) disposal has been reported to pollute water bodies and cause harm to both life on land and underwater (Kaonga et al., 2013; WaterAid Malawi, 2018; Otu et al., 2011). Yet, these waste materials can be recycled and reused for crop production. Reduced greenhouse gases emissions, minimised water contamination (e.g., eutrophication), and improved soil health is some of the benefits of recycling organic waste materials, in addition to increased crop production at a lower cost (Carbonell et al., 2011; Coale & Cooperband, 2001; Folefack, 2008; Grau et al., 2017; Horrocks et al., 2016; Yeo et al., 2020). In the past ten years (2010 to 2019), the import expense on fertiliser has risen by 420% (Government of Malawi, 2020b). It means if Malawi adopts organic sources of P, it would be reducing fertiliser import costs and also working towards achieving SDGs.

The use of waste-derived fertilisers could reduce the cost of P to farmers who already buy inputs and/or allow farmers who can not afford inorganic inputs to access recycled P, which may increase their yields. If there were enough recycled P available, and farmers could increase their yields, Malawi would be more food secure and closer to achieving SDG 2 (zero hunger). Instead of dumping organic wastes and faecal sludge in rivers and other undesignated areas (which leads to contamination of water bodies and the spread of diseases), the demand for these materials could, through properly designed incentives, encourage safe disposal. Diverting organic waste from rivers and lakes to treatment facilities (e.g. composting) will help to address the SDG for sanitation (SDG 6) as well as SDGs 13 and 14, which focus on protecting life underwater and on land. As composting reduces greenhouse gas (GHG) emissions (compared to uncontrolled, anaerobic decay), the production of compost will help to address SDG 13 (climate action).

1.5 Knowledge gap

Although significant work has been done on P flow analysis in some continents, there is not yet a well-documented P flow analysis at the national level in Africa showing potential sources for P recovery. Only Lederer et al., (2015) did a P flow analysis at the regional level in Uganda, and Xiong et al., (2020) did a P flow analysis at the district level in Tanzania. The two studies are not accurate representations of P flows in developing countries. The focus was not specifically on P recycling, so they left out some critical processes, flows, and sinks/stocks. Developing countries cannot implement P recovery and recycle plans based on the P flow analysis of developed nations. Developed and developing countries are socially and economically different, and their sanitation and soil waste management approaches are not the same. To properly guide policy and interventions, national-level P flow analysis is needed to show the flows and stocks from where P can be recovered and recycled. The P flow analysis will serve as a decision-making tool for P management, recovery and reuse for each country based on its unique characteristics.

Since the aim of the P recovery is to use the recovered P in agriculture for crop production. It is crucial to evaluate its potential to support crop growth, improve productivity and improve soil health. Information exists on how organic fertilisers promote plant growth, increase both available and total P in the soil, and improve soil health in general. However, no previous studies have thoroughly investigated phosphorus mineralisation and availability to meet crop requirements during vegetative and reproductive stages when P-based organic fertiliser is used. Previous studies have focused on evaluating the effectiveness of different recycled products in supplying nitrogen (N) (Abubaker et al., 2012; Amoah et al., 2017; Giannakis et al., 2014; Grau et al., 2017; Moya et al., 2017). In addition to N, other studies evaluated P mineralisation, but the organic fertilisers were applied based on N content (Coutinho et al., 1997; Horrocks et al., 2016), which could affect the mineralisation and capacity of the organic fertilisers to meet P crop requirements as the quantity of P used could be different from the amounts applied using P-based application rates. Furthermore, other studies evaluated the fertiliser potential of these organic fertilisers without a specific element consideration (Alfa et al., 2014; Begum, 2011; Folefack, 2008; Garfí et al., 2011; Torgbo et al., 2018). Soil health benefit results are from studies that applied organic fertilisers not based on P crop requirements, and few studies looked at all components (chemical, physical and biological) of soil health (Acharya & Ghimire, 2019; Debiase et al., 2018; Gosal et al., 2018; Khorram et al., 2018; Parker et al., 2018; Singh et al., 2019). Generally, compost has a higher P content than N. However, and most crops require more N than P. Therefore, N-based applications lead to the over-application of P, which poses a danger to the environment and is not economical. Unlike N, the primary source of P (phosphate rocks) is non-renewable mineral deposits which have to be mined, and its long term future is uncertain. Therefore, P needs to be managed in a sustainable manner.

Therefore, there is a need to understand P mineralisation from P based organic fertilisers during plant growth and compare to inorganic fertilisers. The P mineralisation information will help determine application rates, time of application, and organic fertiliser management to avoid eutrophication. Knowing if the organic fertilisers have the capacity to meet the crop P demand would help to establish if the organic P sources are viable alternative P sources. In addition to supplying P, it is crucial to establish if the P-based organic fertiliser improves soil health. Soil health in Malawi needs to be improved, so if organic fertilisers can be sources of P and improve soil health, crop yield will improve, leading to a secure food nation.

1.6 Aim

The main aim of this research was to evaluate the status of organic P sources and their potential for use in agriculture in Malawi

1.6.1 Specific objectives

Three objectives had been formulated to accomplish the main objective of this project:

1. To characterise and quantify the sources, the flows, and the sinks of phosphorus in Malawi to determine options for waste minimisation, recovery potential, and inorganic fertiliser reduction
2. To evaluate phosphorus mineralisation and phosphorus use efficiency from different recycled sources at key crop growth stages
3. To evaluate the impact of using P organic fertiliser on soil health status and crop yield.

1.7 Schematic linkage of the objectives

The three objectives formulated for this study were all linked together to achieve the study's primary purpose (Figure 1.1). A P flow analysis was conducted to accomplish Objective 1. The flow analysis used data on P fertiliser imports, P imported from food products, P in animal and crop products produced and consumed locally in Malawi, P export through food and agricultural products, and P leaving the country through water bodies. The P flow analysis identified the sinks and stocks from where organic P can be recycled.

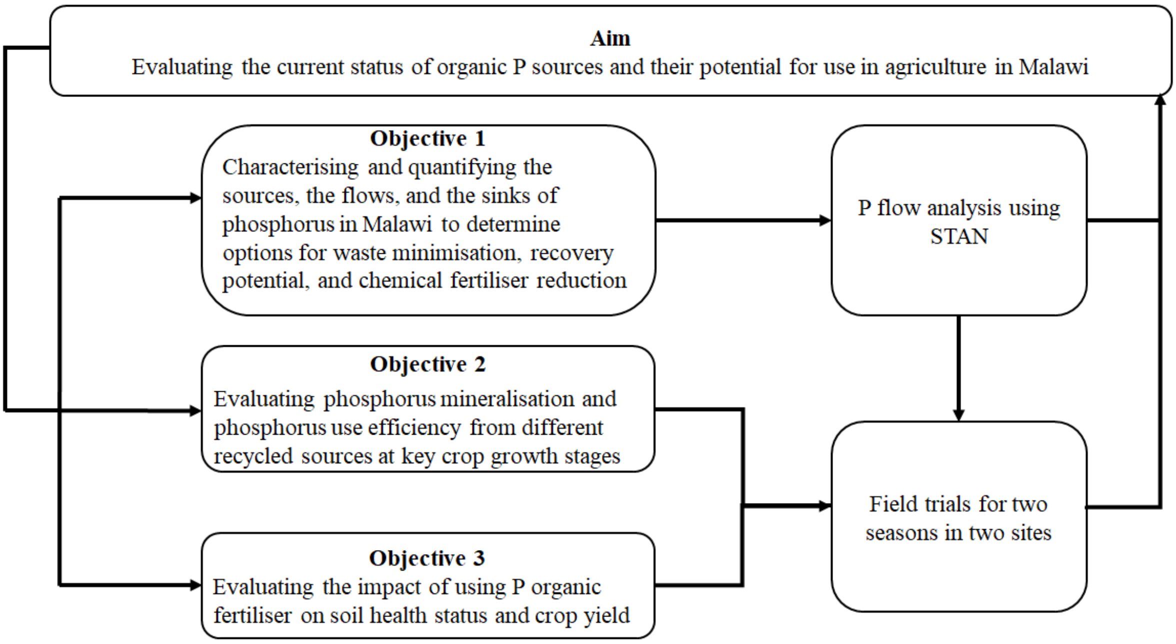

Figure 1.1. Schematic overall preview of the project

The organic materials (market waste and faecal sludge) identified in the P flow analysis were used in field trials to attain Objectives 2&3. The field experiments used compost made from faecal sludge and organic market waste. Data on soil available P, total P in maize, and maize yield were collected for Objective 2. For Objective 3, soil pH, organic matter, earthworm abundance, and soil bulk density data were collected.

1.8 Thesis structure

This thesis takes the form of a succession of chapters (Table 1.2), and Chapters 2 to 4 have been formatted as papers for publication. All chapters were written by Frank Mnthambala, edited, and reviewed by Dr Ruben Sakrabani, Professor Elizabeth Tilley, and Professor Sean Tyrrel. Frank Mnthambala did all the experimental design, field layouts and data analysis and interpretation. The field trials were conducted at Bvumbwe and Makoka research stations during the 2019/2021 and 2020/2021 growing seasons.

Table 1.2. Thesis structure

Chapter	Objective	Focus
1		Introduction, the rationale for the study and objectives
2	1	Phosphorus flow analysis of Malawi
3	2	P mineralisation, plant uptake and use efficiency
4	3	Impact of P organic sources on soil health
5		Synthesising the results from all the objectives and links to the study's primary aim and applying the results on a larger scale.
6		Concluding chapter which highlights the study’s achievements, limitations, and suggestions for future research

Chapter 1 introduces the study area and presents a thorough literature review of the previous studies on P low analysis, P mineralisation, availability and crop uptake, and organic P fertilisers' impact on soil health. Through this research on the current knowledge in the study area, knowledge gaps were identified. To fill/narrow the knowledge gaps, the aim of the study was conceived, which was broken into three objectives. Then two different studies (P flow analysis and field experiments) were conducted to achieve the set objectives, contributing to realising the study's overall aim.

Chapter 2 focuses on P flows in Malawi, and it was published (Table 1.3). Specifically, the model identified the P flows, sinks, and stocks of P in Malawi. The chapter further explores and discusses the current organic P use in Malawi, the future direction, and the impact of using organic P on Malawi's P demand for crop production. Lastly, the chapter discusses the application limitations of the phosphorus flow analysis methodology used.

Chapter 3 addresses the issues of P mineralisation and availability in the soils for crop uptake. The P analysis identified faecal matter, market/municipal organic waste, and animal manure as abundant P sources in Malawi. This chapter focuses on P mineralisation and availability from compost made from organic market waste materials and a combination of organic solid waste and faecal matter. The P availability from organic sources is compared to the P availability from the inorganic source at different application rates at two sites. Further, the chapter also discusses the effect of using the organic P sources on the phosphorus use efficiency of maize and soybean. Currently, Malawi relies on inorganic fertilisers as the primary source of P. Establishing that the organic sources of P can supply and maintain P concentration in soils for plant uptake just as inorganic sources is vital information towards promoting organic fertilisers.

The effect of the organic P sources on soil health is investigated in Chapter 4. The positive impact of organic fertiliser on soil health has been reported in previous studies, but none of the previous studies used the P-based application of the organic fertiliser, and no study used faecal sludge compost. The chapter covers all three components of soil health: physical, chemical, and biological. Specifically, the work summarises impact of organic fertilisers on bulk density, pH, organic matter, earthworm abundance in the soil, and maize yield. Organic matter improves the soil's water-holding capacity, raises soil pH, supplies nutrients, improves soil microbial biomass, and control soil erosion, among other benefits. The pH controls the availability of plants nutrients in the soil; for example, when pH is below 5.5, P is unavailable to plants because soluble P reacts with Fe and Al ions to form solid compounds. Bulk density is an indicator of compaction; compacted soil restricts water, air, and roots movement in the ground, thereby affecting the growth of the crops. Therefore, if the soil's health is improved, crops can better access water and nutrients, leading to increased yields and food security in the country. The results from this objective were accepted for oral presentation at the EUROSOIL 2021 conference in Geneva.

Table 1.3. Publications

Chapter	Title	Status	Journal
2	Phosphorus flow analysis for Malawi: Identifying potential sources of renewable phosphorus recovery	Published	Resources, Conservation & Recycling
3	Evaluation of phosphorus mineralisation and phosphorus use efficiency of maize from different phosphorus sources	Submitted	Compost Science and Utilisation
4	The impact of phosphorus-based organic fertilisers on soil health: a maize study in Malawi	Submitted	Compost Science and Utilisation

Chapter 5 discusses the results from all the papers and explains how the results from individual articles are linked and contribute to achieving the study's overall aim. The chapter also shows how the findings from the current research, if adopted at a large scale (Malawi and other developing countries), can contribute to the hunger-reduction efforts, adaptation to climate change, and mitigation of GHG emissions. It further argues how Malawi's energy, water, and sanitation sectors can benefit from the current study. Lastly, the chapter discusses how the results from this research contribute to the knowledge body. Chapter 6 points out the study's successes, limitations and future study suggestions.

Although this study looked at the positive side of using organic fertiliser, it is essential to acknowledge the existence of pathogens and heavy metals, which are present in faecal sludge, and could be a cause for concern when used for crop production. When faecal sludge is applied, heavy metals and trace elements may accumulate in soils and plant tissues to levels that are harmful to both plants and humans. Elements like Zn, Fe , Cd, are known to be problematic (Carbonell et al., 2011; Giannakis et al., 2014; Anwar et al., 2017). For example, Cd can cause cancer if consumed in amounts exceeding recommended levels. On the operational side, composted faecal materials may exposes both handlers and consumers to pathogens (Kumwenda et al., 2017: Bonetta et al., 2014). Kumwenda et al., (2017) reported high concentrations of colony-forming units of Salmonella (346.2 to 509.1 CFUs) and E. coli (859.1 to 1007.7 CFUs) in faecal sludge from EcoSan toilets (Farling, et al., 2019). Due to the bulkiness of the organic fertilisers (compost), transportation costs to the farmer are higher than inorganic fertilizers. Pit emptying expose workers to aerolosolised pathogens, while the inclusion of plastics into the raw waste, requires additional labour, which may be reflected into the sale price (Babasola et al., 2017: Bekchanov and Mirzabaev,2018; Yesaya et al., 2021).

However, despite these limitations, organic waste recycling is necessary, sustainable, and it contributes to food security and wellbeing of the popualtion.

1.9 References

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Chapter 2 . Phosphorus Flow Analysis for Malawi: Identifying Potential Sources of Renewable Phosphorus Recovery

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Abstract

Population growth and dietary needs changes have exerted pressure on phosphorus (P) reserves, and the future availability of P fertilisers is uncertain. Most Malawian soils have low P and farmers apply P fertilisers to harvest enough food. Scarcity of inorganic P fertilisers and rising prices will affect Malawi's food security. To avert the impact of P future uncertainty a P flow analysis (PFA) was conducted to characterise and quantify sources, flows, and sinks of P to determine options for waste minimisation, recovery, and inorganic fertiliser use reduction for Malawi. The PFA results highlighted that; there are 35000 Mg of recyclable organic P annually, which is over two times Malawi's annual P fertiliser demand (14000 Mg). Currently, only 16% of the organic P is recycled to agriculture. inorganic P fertiliser represents 66% of the P fertiliser used for crop production. Manure is the most recycled organic P source (38% recycled), followed by organic solid waste (6%), and crop residues (5%). Annually, 9000 Mg of P is transferred to faecal matter, but none is recycled. Overall, Malawian soils have a negative P balance of -4000 Mg. Malawi can reduce its dependence on imported inorganic P if recycling of organic P source is adopted. However, regulations should be put in place to control the quality of organic fertilisers.

Keywords: Phosphorus, Malawi, Material Flow Analysis (MFA), Substance Flow Analysis Software (STAN), Stocks

2.1 Introduction

2.1.1 Phosphorus

Just like nitrogen, phosphorus is a limiting plant nutrient (Smit et al*.,* 2010) but the future of this critical non-renewable nutrient is uncertain. High-grade phosphorus ore could be depleted in the next 100 (Walan et al., 2014) to 350 years (Jasinski, 2013), while Cordell et al., (2009) predicted that current (2009) phosphorus ore would reach its peak in 35 years.

Between 2015 and 2017, phosphate rock processing increased from 241,000 Mg to 263,000 Mg: an 8.36% increase. A growing human population and rising demand for meat (which depends heavily on fertilised grain) will likely increase phosphorus fertiliser demand even further (Schröder et al., 2009). However, phosphate rock is a non-renewable resource and will not last forever (Cordell et al., 2009; Schröder et al., 2009; Smit et al., 2010).

The world depends on phosphate rock for phosphate fertiliser production (Smit et al., 2010); almost all phosphorus-containing fertilisers on the market today are produced from phosphate rock (Kauwenbergh, 2010). Globally, the most important phosphorus deposits are in Moroccan-occupied Western Sahara, China, Russia, United States of America (USA), Jordan, and South Africa; Morocco alone controls 75% of the world's phosphate rock deposits (USGS, 2017). Phosphate is found in igneous and sedimentary rocks ranging from 4 to 20 % but can be enriched up to 36 to 40% phosphate (Fixen & Johnston, 2012).

The so-called "peak phosphate" scenario describes the point at which the maximum production rate of phosphorus is reached followed by declining supply. Peak phosphate nearly happened in the 1980s. It was attributed to the heavy use of fertilisers in the Soviet Union, but in the 1990s, there was a reduction in fertiliser use (Daneshgar et al., 2018). Knowledge of the adverse effects of excess phosphorus in natural water bodies (i.e., eutrophication) and the disbandment of the Soviet Union was responsible for decreasing phosphate fertiliser use. Recently, changes in dietary needs/preferences and an increase in the human population has resulted in increased phosphate fertiliser use again (Daneshgar et al., 2018). Another issue is geographical distribution: as only a few countries control phosphorus reserves, any political instability or governance issues in these countries significantly affect the price and availability (Rosemarin & Ekane, 2016).

The United States Geological Survey (2017, 2018) issues annual updates on reserves, and the current phosphate reserves are approximately 70,000,000,000 Mg. The world resource of phosphate rock is over 300 billion Mg, but the reliability of this data is questionable (Cordell et al., 2009; Rosemarin & Ekane, 2016; Schröder et al., 2009). Despite conflicting views on phosphate rock reserves, the world will, at some point run out of a reliable, economically feasible, source of phosphorus and phosphorus has no replacement in agriculture (USGS, 2018).

The depletion of phosphorus reserves will affect global food security (Cordell & White, 2011) and Malawi will not be spared. Malawian farmers practice subsistence farming, and their major food crop is maize. As in most tropical countries, the soils in Malawi are infertile and highly weathered (Maida, 2013). Farmers must apply inorganic fertilizers to harvest enough food to feed their families. Between 2006 and 2016, P fertiliser imports for Malawi increased by 34% (FAO, 2016) and are projected to rise. In the same period, Zambian P fertiliser imports rose by 304 per cent, Tanzania by 170%, Angola by 372%, and Uganda by 51% (FAO, 2016). The growing need for food across the African continent cannot be supported with the decreasing supply of inorganic P: alternative sources of P need to be explored. Almost all the phosphorus in food/feed ends up in faeces and urine (Cordell et al*.,* 2013; Jönsson et al*.,* 2004), animal manure, and food waste, which accounts for almost 30 percent of the total food produced (FAO, 2011). However, these wastes are also potential sources of renewable phosphorus.

MFA studies are done to quantify phosphorus sources and flows and identify areas where phosphorus is lost or accumulates in the system. These types of balances help to identify areas from which phosphorus can be recovered and recycled as an alternative source of phosphorus fertiliser and to assess the potential of human excreta as a source of plant nutrients. Due to variations in the agricultural and food systems in different countries, the effects of phosphorus scarcity will be felt differently (Cordell et al., 2013); therefore, each country must assess its alternatives sources of phosphorus. Phosphorus accumulates in manure (Cooper & Carliell-Marquet, 2013; Cordell et al., 2013; Klinglmair et al., 2015), organic waste (Thitanuwat et al., 2016), and WWTPs (Álvarez et al., 2018) which have all been identified as potential areas of phosphorus recovery.

Although phosphorus flow analysis has been done for a range of contexts, no work has been done at the national level in Africa. Lederer et al., (2015) and Xiong et al., (2020) did an MFA at the regional level in Uganda and Tanzania, respectively, while Xiong et al., (2020) just considered P flow at household level through food consumption. MFAs completed at the national level were done in industrialized countries that are socially and economically different from Malawi and other Sub-Saharan countries. These industrialised countries depend on P imports; have well-developed sewer and solid waste collection systems; and practice intensive animal productions systems which all store and transfer P in very different ways than in most African contexts. Therefore, this paper presents the first phosphorus (material) flow analysis with the aim of characterising and quantifying the sources, flows, and sinks of phosphorus to determine options for waste minimisation, recovery potential, and inorganic fertiliser reduction in one of the poorest, most agriculturally dependent, and landlocked countries in the world. Uniquely, this work explores the importance of pit latrines, free-range livestock management, and unauthorised waste dumping for phosphorus security for a landlocked country with no local phosphorus fertiliser production. This work is important to demonstrate the potential to implement circular economy programs using renewable sources of phosphorus in Malawi.

2.2 Methodology

2.2.1 Material flow analysis (MFA)

MFA describes a group of material accounting tools that use mass balance concepts to assess the movement of materials in and out of a unit area defined in space and time. Space can be a household, company, region, or country while the time can be a day, a week, a month, or a year. The tool choice depends on the goal of the MFA. For example, substance flow analysis is used primarily to understand the movement of the periodic table elements (Cu, Cd, Pb, P, etc.) and other compounds like chlorofluorocarbon (CFC) and carbon dioxide (Brunner & Rechberger, 2016). Material system analysis (MSA) deals with the sustainability and environmental concerns of raw materials or semi-finished products. In contrast, life cycle analysis (LCA) is concerned with the materials required for the production of a specific product, the life cycle of the products and the impact on the environment (Brunner & Rechberger, 2016; Cordell et al., 2013; OECD, 2008).

An MFA is based on a system that has set boundaries, imports, exports, process(s), flows, and stocks/sinks. In this case, Malawi, with its political boundary, is the system (Figure 2.1).

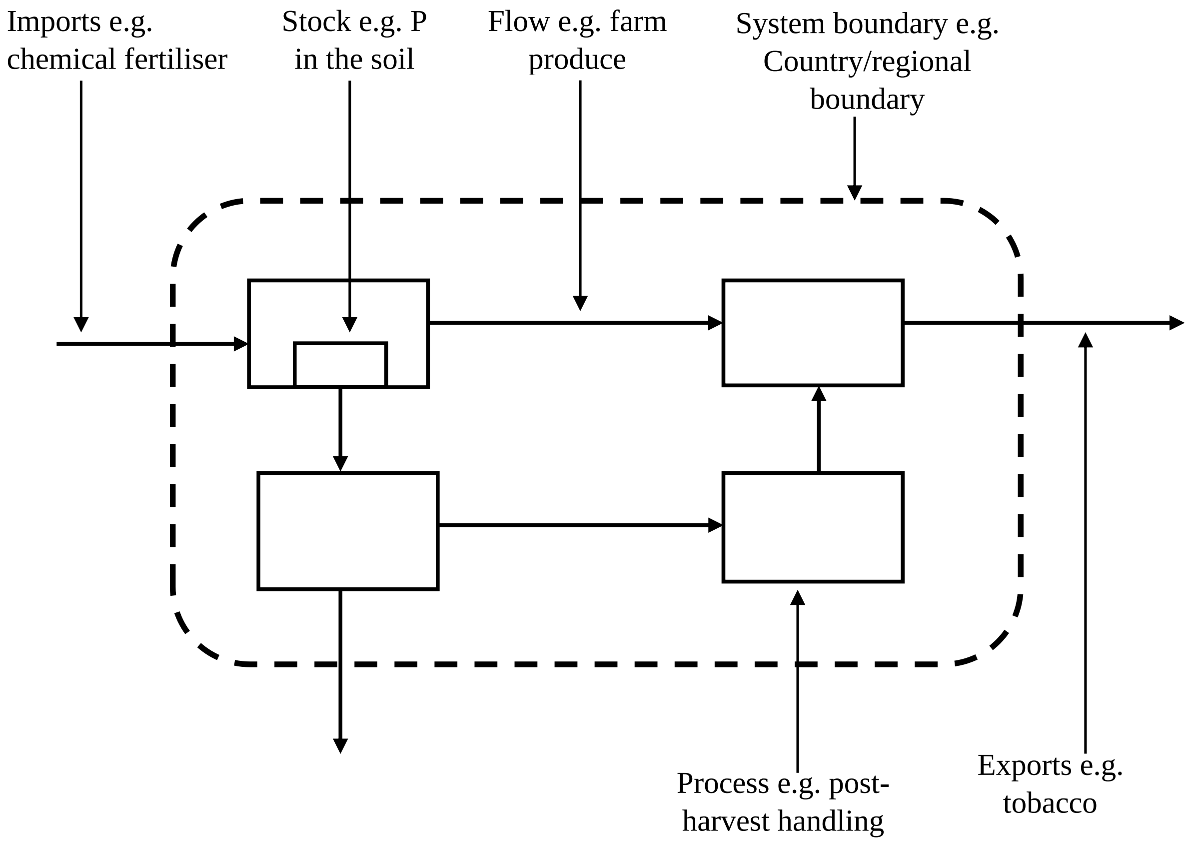

Figure 2.1. A sketch of the material flow analysis system

Imports are materials crossing into the system boundary; exports are materials that leave. A process is where materials or substances are stored or transformed. A flow is the movement of the material/substance from one process to another, and the materials/substances stored within the process over time are called stocks (Brunner & Rechberger, 2016).

In this case of phosphorus flow analysis, the political boundary of Malawi is the system boundary. Imports are all the materials containing phosphorus coming into the country, for example, fertilisers and food items. At the same time, exports are all the foods (beans, fish, meat) containing phosphorus that Malawi sells/exports to other countries. The processes include crop or animal production. In crop production, inorganic phosphorus in fertiliser is transformed into the organic phosphorus in plant biomass. The movement of crop products from crop production to households or crop residues to animal production are flows and the phosphorus stored in soils is a stock.

2.2.2 Malawi

Malawi has almost 18 million people with an annual growth rate of 2.9 (NSO, 2019). Agriculture contributes to almost 80% of jobs and 90% of foreign currency earnings (Government of Malawi, 2010, 2007; NSO, 2017). Nearly 80% of Malawian farmers practice subsistence farming; their major food crop is maize though a few farmers grow legumes like soybean, pigeon peas, and groundnuts for income (IFDC, 2013). As in most tropical countries, Malawi's soils are infertile and highly weathered (Maida, 2013). Subsistence farmers must apply inorganic fertilisers to harvest enough food to feed their families (Omuto & Ronald, 2018). However, the current fertiliser consumption (180,000 Mg/year) is below half of the potential consumption (Government of Malawi, 2007; IFDC, 2013). Malawi imports almost all its fertilisers (280,000 Mg/year) and is a landlocked country. The price of inorganic fertilisers is too high for most smallholder farmers, and prices are expected to continue rising (IFDC, 2013). Malawi already has a fragile economy and struggles with food security which means it will be heavily affected by the depletion of the world's phosphate reserves.

The increasing human population will result in both increased food demand and an increased quantity of waste. As food moves from production to consumption, waste materials containing phosphorus are generated. The phosphorus in the waste materials is either from external inputs (fertilisers) or soil reserves. These organic waste materials, together with human excreta and animal manure, are potential sources of phosphorus. The four major cities in Malawi (Blantyre, Lilongwe, Zomba, and Mzuzu) generate around 500,000 Mg of solid waste per year. Almost 80 per cent of the waste materials are organic (Government of Malawi, 2014; ICLEI, 2016) but the city councils only collect about 30 per cent of the total solid waste generated (Government of Malawi, 2014). Almost 99 per cent of the population is not connected to the sewer system, with the majority using pit latrines (NSO, 2017). Additionally, the country also has over 30 million heads of livestock (FAOSTAT, 2016). All these agricultural and human factors affect phosphorus in the country and no previous attempts have been made in Malawi to assess the phosphorus flows and how phosphorus from organic sources can contribute to sustainable nutrient management and agriculture production.

2.2.3 System description

The MFA covers the whole of Malawi in 2016, including the water bodies. Currently, Malawi does not produce or export phosphate fertilisers. Phosphorus leaves the country through the export of agricultural products, wastewater, landfill discharge (which leaves through water bodies) and agricultural soils (through soil erosion). P in groundwater contribution to the model was considered insignificant and was excluded from the model. In this model, phosphorus flows within the country from agriculture production, imports, waste management, and recycling are all traced. The phosphorus form presented here is phosphorus pentoxide (P_2O_5) in Mg and 2016 is the reference year, although when data were not available in 2016 other years were used. **S**ub**st**ance flow **an**alysis software (STAN) (version: 2.6.801) software was used to perform this phosphorus flow analysis.

2.2.4 STAN software

STAN is a free resource developed by the Technical University of Vienna to supporting material flow analysis (Cencic & Rechberger, 2008). STAN incorporates data uncertainty and several material flow analysis features like graphical modelling, data management, calculations, and graphical presentation of results for the substance/material under investigation. STAN procedures conform to the Austrian standard ÖNORM S 2096 (Cencic & Rechberger, 2008). STAN uses mass balance to calculate the outputs based on the inputs. In instances where inputs and output are not equal a stock is created within a process, as a way of compensating for the difference. The stock can show depletion (more output than input), denoted by a negative sign or accumulation (more input than output) of the substance within the process. For instance, 2000 Mg of P is applied to crops through fertiliser, but after harvesting, there is 2500 Mg of P in crop products and biomass, indicating a negative stock (-500 Mg). On the other hand, 3000 Mg of P may go into the pit latrines through human excreta, but only 500 Mg of P is removed through pit emptying, i.e., an accumulation of 2500 Mg of P pit latrines. Therefore, **Stock = Input – Output**

Several studies that have been done on phosphorus flow analysis in Europe, Asia, and Africa at different district/regional, country and continent levels, for example, various studies from the UK. (Cooper & Carliell-Marquet, 2013), Spain (Álvarez et al., 2018), Denmark (Klinglmair, Lemming, Jensen, et al., 2015), Vietnam (Anh et al., 2016), Netherlands (Smit et al., 2010), and Uganda at district level (Lederer et al., 2015) all used STAN.

2.2.5 Processes, flows, and stocks.

Depending on the objective of the MFA and the system under study, different processes, flows and stocks are used (Álvarez et al., 2018; Bittman, Sheppard, Poon, & Hunt, 2017; Brunner & Rechberger, 2016; Cordell et al., 2013; Jönsson et al., 2004; Lederer et al., 2015; Senthilkumar, Nesme, Mollier, & Pellerin, 2012; Smit et al., 2010; van Dijk et al., 2016). In terms of phosphorus, inorganic fertilisers, imported food products, and washing chemicals are the common flows into a country (Álvarez et al., 2018; Cordell et al., 2013; Dijk et al., 2015; Smit et al., 2010). Inorganic phosphorus in the fertilisers and the phosphorus from the soil reserves are taken up into crop products. Animals and people consume these products, and some are exported (Cooper & Carliell-Marquet, 2013). Farm products (including animal products), waste materials produced along the farm products value chain, and household waste are the most important phosphorus flows (Álvarez et al., 2018; Bittman et al., 2017; Klinglmair et al., 2015; Lifset et al, 2016). For example, Cooper & Carliell-Marquet, (2013) and Li et al., (2015) identified fertilisers, crop uptake, animal manure, crop and animal products, animal feed, food, and feed processing waste, waste to landfill, sewage sludge to agriculture, soil erosion, and imported food and feed as some of the possible flows of phosphorus. In addition to flows, processes where phosphorus may accumulate, pass through, or be depleted also need to be identified. The most explored processes are agricultural soils, households/humans, WWTPs, landfills, water bodies, animals, and incineration plants (Bi, Chen, Zhang, & Yuan, 2013; Cooper & Carliell-Marquet, 2013; Klinglmair et al., 2015; Li et al., 2015; Smit et al., 2010; Thitanuwat, Polprasert, & Englande, 2016) and pit latrines (Lederer et al., 2015).

This MFA was based on the approach described above but considering that most of these phosphorus flow analyses were done in developed countries, some flows/processes were either added or dropped to suit Malawi's situation as shown in Appendix (Table A.1) and Table 2.1. For example, there is no (engineered) waste incineration in Malawi, the majority of the population use pit latrines (NSO-Malawi, 2017), most animals feed on natural pasture (Chintsanya et al., 2004), people still practise open defecation (NSO-Malawi, 2017), and city councils collect only 30 per cent of the waste generated (Government of Malawi, 2014). Therefore, this MFA is designed to describe the situation in Malawi and may also be adaptable for many developing countries in Sub-Saharan African. Additional processes flows and stocks almost certainly exist but have been excluded from the MFA on the grounds that they are assumed to be irrelevant within the context of the magnitude of error inherent in this analysis.

2.2.6 Phosphorus flow analysis

All the flows and data sources used in this analysis and how they were calculated are presented in Appendix (Table A.1). The flows are categorised into three: imports (into Malawi), internal flows, and exports (out of Malawi). Just like any other material flow analysis, the law of conservation of mass is observed, **input = change in stock + output**

Table 2.1. Process description

Process	Description
Imported fertiliser	The mass of P imported in the form of inorganic fertiliser meant for crop production.
Cropland soils	Agricultural soils on which crops are grown and absorb P. In addition to inherent P in soil, P is added through inorganic fertiliser, manure, decomposing mulch, ash after crop residues are burnt, and faecal sludge, and compost. Furthermore, some P is lost to water through soil erosion.
National crops	The collection of all P containing crops produced locally (from cropland soils) including crop biomass. The crop residues are used as animal feed and soil mulch. The P-containing crop products go to post-harvest handling (processing, transporting, storage, etc.)
Food products processing and handling	P from both locally produced and imported crop products and animal products arrive here. As the crops are processed, transported, or stored, there are organic waste materials produced. These P-containing waste materials end up at the waste collection process. Another part of P leaves the country through exports of crop products, e.g., tea and tobacco.
Waste collection	All organic waste materials from food handling, food processing and households converge here. The waste materials go either to official landfills or unauthorised dumping sites.
Unauthorised dumping site	Places not designed for waste dumping: roadsides, public markets, private yards, rivers, etc. The organic waste here are mixed with plastics and other inorganic materials. P is lost from here through leaching, the loss of ash from burning, and erosion.
Landfills	The designated places for waste materials dumping. P is lost from the landfills to water bodies through leachate.
Households	It is the place where people consume crop and animal products after post-harvest handling and processing.
People	People consume P-containing crop and animal products and fish. The body absorbs some of the P while the rest is excreted. When humans die, the phosphorus they contain is transferred to the soil when they are buried.
Pit latrines	Pit latrines are one of the onsite sanitation facilities where human excreta are contained. Some of the P is lost from the pit latrines when they flood or are emptied.
WWTPs	Some human excreta go to WWTPs through the sewer system, while the excreta that is emptied from pits and septic tanks are delivered mechanically. The P-containing wastewater is discharged into rivers.
Septic tanks	Septic tanks are one of the onsite sanitation facilities where human excreta are contained. P leaves the septic tanks through emptying and leaching.
Livestock	Animals consume P-containing feed from processed crop products, crop residues, and natural pasture. P leaves livestock through animal products like eggs and meat, and also through manure, feathers, and bones.
Burning	Crop residues are burnt for fuel, tobacco curing, field clearing, and mice hunting, among other reasons. Some of the P is returned to the soil in the form of ash and used by the crop but the rest is lost to water bodies by wind and water erosion.

Natural pasture	Naturally growing pasture without intentional, external P application. The pasture utilises P from the soil reserves and livestock droppings. P leaves the natural pasture to livestock through grazing and the animals fertilise the pasture through droppings as they graze.
Collected manure	Animals are normally housed during the night and the night droppings are easily collected. Some of the collected manure is left unused while some are applied to soils for crop production. P is lost from unused manure mostly through leaching.
Water bodies	All rivers and lakes in Malawi to which P is lost from processes through water and wind erosion. Some P goes back to the household for consumption through fish; some P leaves the country through rivers that run beyond the country boundaries.

2.2.7 Data uncertainty and errors

Data uncertainty and error always occur in MFA and need to be acknowledged (Cooper & Carliell-Marquet, 2013b). In experiments that involve replications, it is easy to calculate errors and standard deviations, but in MFA most of the data are from one source or the available data are not independent (Hedbrant & Sorme, 2001). It is difficult to determine the original uncertainties, but several methods and approaches are available to deal with data uncertainty in MFA like those used by Cooper & Carliell-Marquet, (2013), Álvarez et al. (2018), Klinglmair et al., (2015) and Laner et al., (2015). Uncertainty is usually expressed as Y ±b, where “Y” is a mean value and “b” is standard deviation. In MFA, some data have a single source (no repeated independent measurements), and the uncertainty of some data tends to be larger than the actual mean value. Hedbrant & Sorme, (2001) argued that if large uncertainty is expressed symmetrically may result in a negative lower limit. Therefore, it was necessary to present the uncertainties in MFA as factors. For example, if the uncertainty factor is 1.2. then Y may be Y×1.2 or Y ÷ 1.2 and the symbols used are ‘×÷’.

Almost all studies in MFA base their uncertainty calculation on the procedure developed by Hedbrant and Sörme (2001). The method, which was developed through experience with their data, showed that uncertainty differs depending on the source of the data (official statistics, published literature, and expert judgment) and Antikainen et al., (2005) modified this approach according to their data. These authors categorised data sources into different levels (1 to 8), and then assigned different uncertainty intervals to each data level. For example (Table 2.2), data in Level 1, which is data from official statistical offices at the national level e.g., human population, are multiplied or divided by 1 (×÷1). Level 2 also includes data from national statistics at national level e.g., an agricultural land area, and are multiplied or divided by 1.05

and so on up to level 8 which contains data from literature e.g., N_2O emissions with the uncertainty of ×÷4.

For example, if the national statistics reported that a country has 10,000,000 people, then its uncertainty is ×÷1, but if national crop yield was 200,000 Mg, then its uncertainty is ×÷1.1. In situations where data sets are being added or multiplied, the uncertainty was calculated using equations outlined by Antikainen et al., (2005). Data uncertainty increases when data sets are multiplied and decreases when data sets are added (Antikainen et al., 2005).

Table 2.2. Uncertainty levels and data sources (Antikainen et al., 2005)

Level	Uncertainty factor	Data source	Example data
1	×÷1	Official statistics on the national level	Human population
2	×÷1.05	Official statistics on the national level	Foreign trade, amount of produced milk and eggs, area of agricultural land, fertilisation
3	×÷1.1	Official statistics on the national level.	Number of animals, crop yield
		Information from facilities subjected to permit requirement	Mass of Nitrogen (N) and P in treated wastewaters
		Values from literature	Mass of N and P in treated wastewaters
4	×÷1.2	Official statistics on the national level	Feed consumption in balance sheets for food commodities
		Values from literature	N and P contents in products (e.g., hay, horses, poultry)
5	×÷1.33	Modelled data	N deposition on soil
		Values from literature	N and P contents in products (e.g., fur animals, fish, organic waste)
6	×÷1.5	Monitored data	P deposition on soil
		Values from literature	NH_3 emission factors, leaching from agricultural soil
7	×÷2	Factors from literature	Biological N fixation, N_2O emission factors
8	×÷4	Factors from literature	N_2O emission factors

When different datasets are multiplied the uncertainty factors are not multiplied as well, are calculated using the following equation:

$$Uncertainty\ factor\ = 1 + \sqrt{(f_a - 1)^2 + (f_b - 1)^2}$$ (Antikainen et al., 2005)

f_a = assigned uncertainty interval for the P flow 1

f_b = assigned uncertainty interval for the P flow 2

For example, if 500,000 ×÷1.2 kg of maize was harvested in 2016 in Malawi and maize's phosphorus is content 250×÷1.25 mg/kg then the amount of phosphorus was 125 kg, and the uncertainty can be calculated as follows:

$$Uncertainty\ factor\ = 1 + \sqrt{(1.2 - 1)^2 + (1.25 - 1)^2}$$

$$= 1.32$$

The final value of phosphorus will be 125×÷1.32

Likewise, when different datasets are added the uncertainty factors are not added too, are calculated using the following equation:

$$Uncertainty\ \ factor = 1 + \frac{\sqrt{[m_a.(f_a - 1)]^2 + [m_b.(f_b - 1)]^2}}{m_a + m_b}$$

(Antikainen et al., 2005)

m_a = Mass phosphorus 1

m_b = Mass phosphorus 2

and f = assigned uncertainty interval

For example, if phosphorus applied to crops through manure is manure is 300×÷1.4 kg and through fertiliser is 2000×÷1.2 kg then total phosphorus applied is 2300 kg, and the uncertainty can be calculated as follows:

$$Uncertainty\ \ factor = 1 + \frac{\sqrt{[300.(1.4 - 1)]^2 + [2000.(1.2 - 1)]^2}}{300 + 2000}$$

$$= 1.18$$

Then phosphorus applied is 2300×÷1.18

Cooper & Carliell-Marquet, (2013b) converted the ×÷ uncertainty range to ± range to simplify the model balancing and the entering of the uncertainties in STAN software. The ×÷1.32 was changed to ±32%, then ×/÷1.18 to ±18%, this method maintains the upper limit but extends the lower limit (Cooper & Carliell-Marquet, 2013).

In the current study, official data from FAOSTAT, the Malawi National Statistical Office, the United States Department of Agriculture, literature from national and international sources, personal communications, and experts' assumptions were used. Data uncertainty was dealt with by following the approach used by Antikainen et al., (2005) and (Cooper & Carliell-Marquet, 2013). Just like previous studies, the data were adapted to different uncertainty levels depending on data sources (Table 2.3). In STAN software, data uncertainty is incorporated by using the Gauss error propagation for independent variables method to calculate uncertainty values (Cencic, 2016) for flows and stocks.

Table 2.3**.** Data uncertainty interval

Level	Interval factor	Data source	Example data
1	×÷1.2	Official statistics from the Food and Agriculture Organisation of the United Nations and Malawi National Statistics Office	Fertiliser imports, human population, crop production, and livestock statistics.
2	×÷1.25	Data from the local and international literature	Phosphorus content in food products. Phosphorus content in manure
3	×÷1.33	Expert guesses and assumptions	Manure and compost being recycled to agriculture.

Adapted from (Cooper & Carliell-Marquet, 2013)

2.3 Results and discussion

2.3.1 Material flow Analysis

Overall Phosphorus flow in Malawi the MFA (Figure 2.2) showed that P enters Malawi mainly through imported inorganic fertilisers and imported food products (Appendix, TableA.1). In the year 2016, Malawi imported approximately 17,000 Mg of P of which 14,000 came through inorganic fertilisers and, 2,300 Mg came through imported foods and washing products.

Crop production in Malawi used almost 21,000 Mg of P, which were applied to the soils. The P in inorganic fertilisers contributed 66% of the P applied to the soils for Malawi's crop production. Approximately 5300 Mg of P, which represents 25% of the P applied to the soils for crop production came from animal manure. In contrast, faecal sludge, compost, P in wastewater and decayed mulch contributed to the remaining 9% of the P applied. Although

21,000 Mg of P was applied to the soils, 25,000 Mg of P left the soils of which 2,000 Mg went to water bodies through soil erosion and 23,000 Mg were utilised by crops. This showed that extra 4,000 Mg of P were taken from the soil reserves every year translating into 1 kg of P mined per hectare per year from the agricultural land.

Of the 23,000 Mg of P absorbed by the crops, approximately 7,410 Mg of P were in crop residues. Almost 410 Mg of the P in crop residues were retained in the fields through mulching, 5,000 Mg were burnt in crop residues, 2,000 Mg were fed to animals. Out of the 5,000 Mg of P in burnt residues, 4,000 Mg were lost to water bodies and 1,000 Mg were returned to the soil. Almost 15,000 Mg of phosphorus went into post-harvest handling processes (processing, storage, distribution/transportation), which includes the P in fish, animal products, and P in imported food products. Approximately, 19,000 Mg of P entered into the post-harvesting processes, and from these post-handling processes, 5000 Mg of P ended up in food waste, 1100 Mg of P were exported through crop and animal products, 2400 Mg of P were in animal feed and 10000 Mg of P were in food for human consumption within the country. Out of the 10000 Mg of P for human consumption, 100 Mg were lost to food waste.

The P in organic waste materials is taken to official landfills and unofficial landfills (roadsides, rivers, and other undesignated places). Approximately 5,100 Mg of P are in waste materials every year, and 4500 Mg were dumped at unofficial landfills. The remaining 500 Mg were dumped at official landfills. Out of the 5,000 Mg of P that were dumped at the landfills, 800 Mg from unofficial dumpsites and 80 Mg from landfills were lost to water bodies through liquid discharging. The MFA shows that there are almost 4000 Mg and 400 Mg of P accumulating every year in unofficial and official landfills.

People utilised nearly 10,000 Mg of P yearly, of which 1000 Mg were incorporated into the bodies. Dead people take 4 Mg of P away with them when they are buried. The rest of the consumed P was excreted, of which, approximately, 91% was deposited in pit latrines and the remaining 9% went to septic tanks, WWTPs, and water bodies through open defecation. Almost all P that went to pit latrines accumulated (9000 Mg) as there is little P lost to water bodies through overflowing in the rainy season or as faecal sludge which is taken to WWTPs. In addition to receiving P from people through the sewer system, WWTPs receive P through septic tanks and pit latrines emptying. All the P (107 Mg) that arrived at the WWTPs left the facility to water bodies (106), and some (1 Mg) were recycled to agriculture. The septic tanks received almost 220 Mg of P yearly. Through emptying, 11 Mg went to WWTPs while 50 Mg went to water bodies due to the dumping of faecal sludge from septic tanks into rivers. Almost 159 Mg remain of P remain in the septic tanks.

Livestock consumed 27000 Mg of P, of which 2000 Mg came from crop residues, 2400 Mg came from the processed feed, and the rest came from natural pasture (Appendix, Table A.1). P left livestock through animal products (eggs, meat, and milk), bones, feathers, and manure. The manure was either dropped directly onto natural pasture while grazing or dropped when the animals are housed at night. In total, 26000 Mg of P left the livestock through the manure of which 13000 Mg went to natural pasture, and the other 13000 Mg went to manure collection. Of the manure collected, 5000 Mg were applied to the soils for crop production, 2000 Mg were lost to water bodies and 6000 Mg remained unused. Natural pasture received 13000 Mg of P from manure and 1600 Mg were lost to water bodies. Animal grazing consumed almost 23000 Mg of P from natural pasture.

In this MFA, water bodies in Malawi received P from WWTPs, cropland soils, and landfills among other processes (Appendix, Table A.1). Yearly, the water bodies receive almost 11000 Mg P from landfills, WWTPs, septic tanks, manure, pit latrines, ashes, unauthorised dumpsites, soil erosion and open defecation, of which 3700 Mg went beyond the MFA system boundary through flowing water and 260 Mg were in harvested fish. This means there were almost combined 7000 Mg of P in sediments and in Malawian water bodies.

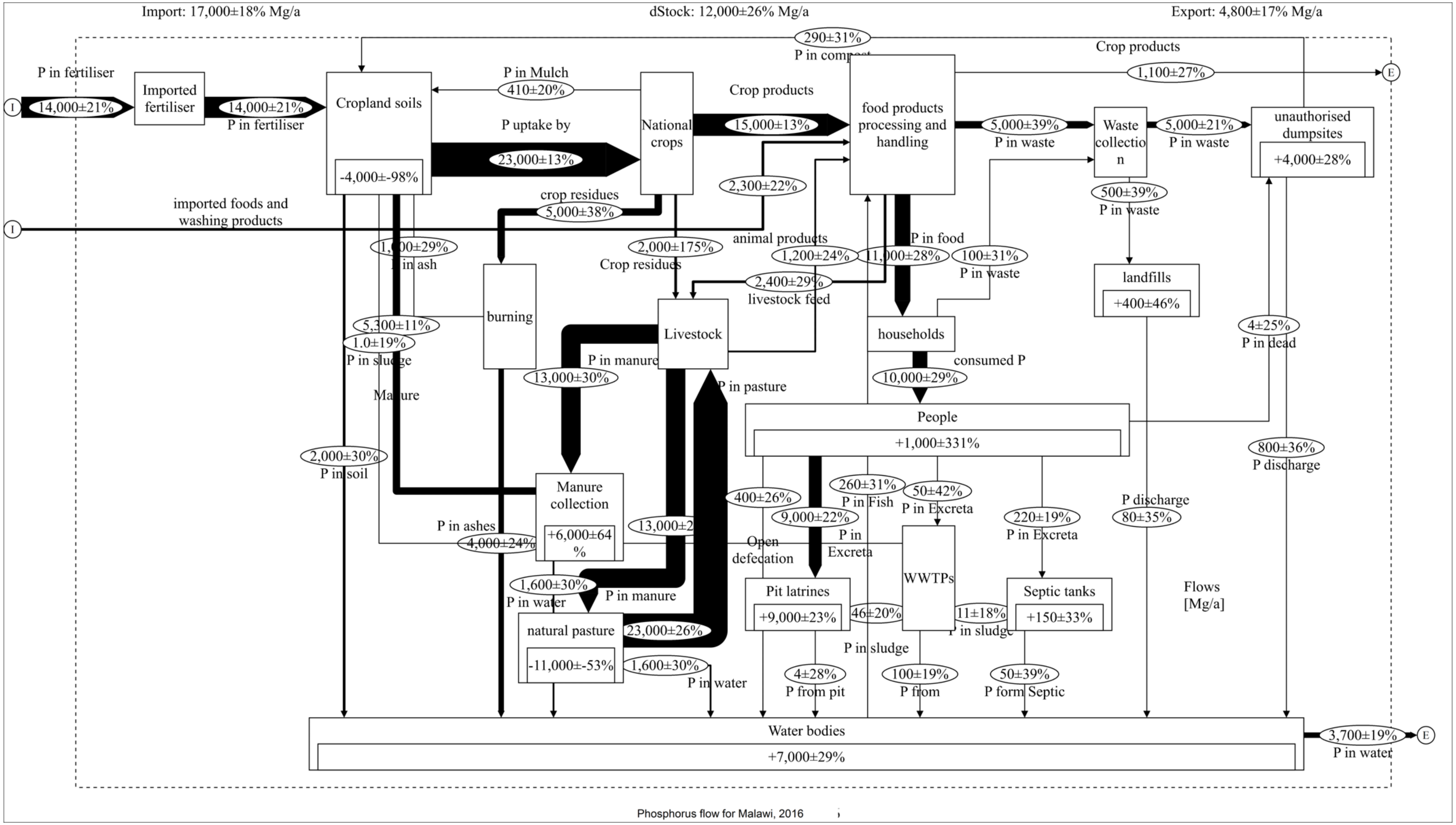

Figure 2.2. The Malawian phosphorus flow model V1.0 shows the primary inputs (Mg/year), outputs (Mg/year), internal flows (Mg/year), processes, and stocks/sinks (Mg) of phosphorus in Malawi in 2016.

2.3.2 Crop production, phosphorus inputs and recycling

The results show that 33% of the phosphorus used in Malawi comes from renewable sources. Malawi depends mostly on imported inorganic phosphorus which contributes 66% of the total P used for crop production every year. The over-dependence on imported inorganic phosphorus, which is a non-renewable resource, puts the dependent countries' food security at risk (Rosemarin & Ekane, 2016; Schröder et al., 2009; P. Walan et al., 2014; Petter Walan, 2013). Malawi's farming sector is dominated by the resource-poor smallholder farmers who are already struggling to buy fertiliser and depend on the government farm input subsidy programme (FISP) to access fertiliser. The FISP is not sustainable, and the Government of Malawi, (2007) and (2010) emphasised the need for recycling and the use of organic fertiliser.

The country produces approximately 35000 Mg of organic P annually that can be recycled and used for crop production. The P that can be recycled is almost over two times the P that Malawi imports in inorganic fertilisers for crop production. Currently, only 16% of the organic P is recycled to agriculture with animal manure contributing 14%. There is little or no recycling of P from municipal organic waste, crop residues, or faecal sludge (Table 2.4).

Table 2.4. Potential and actual P recycled in Malawi

Subsystem	**Potential P (Mg) that can be recycled per year**	**P containing material**	**P recycled to agriculture**	
			Mg P/year	**%**
National crops	7600	Crop residues	400	5
Manure production	13000	Manure	5000	38
Landfills	500	Municipal organic waste	0	0
Unauthorised dumping	5000	Municipal organic waste	290	6
Pit latrines	9000	Faecal sludge	0	0
WWTPs	100	Wastewater and faecal sludge	0	0
Septic tank	220	Wastewater and faecal sludge	0	0
Total	35420		5690	16

Although Malawi depends on imported inorganic fertiliser as a source of P, the mass of P imported does not meet the crop demand which resulting in a negative P balance in the soil.

There are almost 4000 Mg of P mined from the soil every year which translate to -1 kg P/ha. These results agree with previous studies which found negative P balances. Henao & Baanante, (1999) reported -16 kg P/ha, Stoorvogel & Smaling (1990) reported -10 kg P/ha and Sheldrick & Lingard (2004) reported -4 kg P/ha soil balances for Malawi which are higher than the value calculated here. The previous studies used crop nutrient uptake indices (Henao & Baanante, 1999) to estimate P output in crops while the current study used the P content in crops to estimate P output from the soils. Furthermore, this study used inorganic fertilisers, manure, mulch, compost, ash, and sewage as the inputs for P. It was only Sheldrick & Lingard (2004) who included sewage in addition to inorganic fertilisers, manure, and deposition as inputs for P, (Henao & Baanante, 1999) and Stoorvogel & Smaling (1990) used inorganic fertiliser, manure, and deposition as inputs sources for P. It is also important to note the increase in animal population from 13 million in 1990 to around 30 million in 2016 (FAO, 2016) which may imply increased manure production and utilisation in Malawi.

Although P is mined every year from the cropland, almost 30,000 Mg of P in organic waste materials are left unused. If recycling is promoted, the P in organic sources in long run will be able to offset the negative soil P balance in the cropland soil. Table 4 shows that there is no recycling of P from landfills, pit latrines, septic tanks and WWTPs. Animal manure and crop residues are the only sources of P that are currently recycled.

2.3.3 Phosphorus accumulation and loss

Just considering available P at 20 cm depth, the soil has 241,000 Mg±72000, which is the most extensive stock of all. As noted earlier, the available soil P content in Malawi is not enough to fully support crop growth, and as such, external P has to be applied (Omuto & Ronald, 2018). However, the P inputs that go into the soil are less than the output (Table A.2 in Appendix). It means that in addition to the P from the external sources, the crops are also using P from the soil reserves. If the P inputs and outputs are not balanced, it will lead to the depletion of the soil reserves and the soil will not be able to support crop growth in years to come.

In Malawi, almost 80% of the livestock feed on unmanaged pasture (Chintsanya et al., 2004). The unmanaged pasture utilises P from the soil reserves. The size of the P stock in the soils supporting the natural pasture is unknown, and almost 11,000 Mg of P are removed every year through animal grazing (Table A.2 in Appendix). In the long run, these soils will be unable to support pasture growth, leading to a reduction in the animal population, especially goats and cattle. Although it was assumed that P in animal manure (dropped during grazing), decay plant materials, soil erosion and flooding water replenishes P absorbed by plants that are consumed by the animals. Still, P is incorporated in animal bodies, and manure which are excreted away from the pasture (in confinement at night). Annually, there is almost 25,000 (Table 2 in Appendix) Mg of P from the natural pasture of which 13,000 Mg are in manure that can be used for crop production. Natural pasture plays a significant role in moving phosphorus from the soils through animals, but the lack of circular movement of P to replace the removed P poses a threat to the future ability of the ranges to support livestock production.

Human excreta in pit latrines, septic tanks are another source of P. The P stock in pit latrines and septic is almost 9200 Mg every year. The pit latrines represent 98% of the P in human excreta. Despite that 91% of Malawians use pit latrines (NSO-Malawi, 2017), 97% of the sludge dumped at the wastewater treatment plants in Blantyre is from septic tanks (Yesaya & Tilley, 2021), i.e., pit latrines are rarely emptied, or if they are, the sludge is not disposed of safely. These results agree with the finding of Collet et al., (2018) and WaterAid Malawi, (2018) which found 24% and 64% of faecal matter unemptied in Blantyre and Kasungu respectively. To have a clear picture of the P stock in pit latrines and septic tanks, the current (2016) accumulations of 9000 Mg for latrines and 140 Mg for septic tanks of P and assumed constant accumulation in the past ten years (from 2006 to 2016) was used. As of 2016 Malawi had 91,500 Mg of P in faecal sludge buried under the ground. In the past 12 years (2006 to 2018), Malawi imported 19,000 Mg of P on average every year (FAO, 2016): in the past 10 years (2006 to 2016) there has been an accumulation of P in faecal sludge which is equivalent to almost 5 years of P imports to Malawi.

Approximately 38% of P from collected manure is used for crop production, which is higher than the 5% from crop residues and 6% from organic market waste (Table 2.4). However, over 6000 Mg of P in manure accumulated in the year 2016. Assuming ten years (2006 to 2016) of accumulating, the current P in manure would be equivalent to Malawi’s P import demand of 3 years.

Organic waste materials generated in households and markets are other sources of P (Davila et al., 2019). The councils in Malawi collect 30 per cent of the waste produced (Government of Malawi, 2014) meaning landfills are not the critical stock of P in organic waste. The landfills contain 10% of the total P in organic waste material produced in Malawi, the rest is in unauthorised dumpsites (backyard, markets, river, roads etc.). Annually, there is accumulation of 4000 Mg of P in unauthorised dumpsites and 400 Mg of P in landfills. Assuming ten years at the same accumulation rate, then approximately 44000 Mg of P will have accumulated which is equivalent to 2 years of inorganic P imports.

Water is the sink for almost all P lost from the other stocks and processes. Nearly 11,000 Mg of P went into the water bodies. Although P supports life in the water, an excess of it causes eutrophication. In the last ten years (2006 to 2016), almost 70,000 Mg of P has built up the water bodies (bulk water, sediments, and living organisms) in Malawi. Unlike other stocks, P in water bodies can be either in a soluble form, a solid form after reacting with other elements, or incorporated into tissues of aquatic animals and plants.

The P outputs presented in Appendix (Table A.2) include P, which is goes to water bodies. If the flows of P to water bodies are prevented or reduced, the P stocks (soil, manure, WWPTs etc) would increase. For example, out of the 25000 Mg P output from the soil, 6000 Mg of P went to water bodies through soil erosion (2000 Mg) and ashes erosion (4000 Mg) after burning of crop residues. All the P output from landfills went to water bodied while 68% of the output from unauthorised dumpsites went to water bodies. Just like landfills, P output from pit latrines and septic tanks went to water bodies. 29% of the P output from manure went to water. The model depicts that the output of P from water bodies is through fish and water running beyond the system's boundary. However, irrigation brings P from the water to the crops, but irrigation only covers 2 % of the cropland in Malawi (FAO, 2016).

Applying organic fertiliser does not only improve soil nutrients status but also soil aggregates (Carbonell et al., 2011; Giannakis et al.,, 2014; Soma et al., 2018) through the binding effects of organic matter. Well aggregated soil has reduced erosion potential which means even P lost through erosion from the fields will be reduced if organic fertiliser is used. Reducing the losses of P from the stocks and processes will not only increase the amount of P to be recycled to agriculture but also reduce water contamination.

The Malawian government encourages the use of organic fertilisers (Government of Malawi, 2007) but the lack of fertiliser policy, and specifically the lack of policy for organic fertilisers, makes its enforcement a problem: the potential of organic fertiliser remain unrealised in Malawi (Simtowe, 2016).

2.3.4 Limitations and challenges of the current MFA

Although the current MFA has revealed the magnitude of flow, and sinks/stocks of P in Malawi, it does not indicate the stocks' location. Furthermore, this MFA does not specify how much of the P in the stock can be recycled and the challenges that may be encountered in the attempt to recover the P from the accumulation sites. For example, out of the current or yearly P in human excreta, landfills, manure how much can be recovered and the drawbacks.

P flow analysis demands that the data of P-containing materials are available. However, in this case, not all data sources were from Malawi, which they ideally, should be. Some data sources were from international sources, including data from the United States Department of Agricultural database (https://fdc.nal.usda.gov) (Table A.1 in Appendix), which mostly contained data on the P content of products like fruits and vegetables. Although the international data may not be an accurate reflection local situation, the international data had its own uncertainty factor, which was used to make sure the results represent the local situation. However, Malawi needs to set up a database for the nutritional content of all the agricultural products. Such a database would ensure that future P flow analysis and flow analysis of other substances are produced with less uncertainty

The MFA shows the P that is in different organic sources and can be potentially used for crop production. However, is not all the P in organic sources that is readily available for crop uptake and mineralisation and availability of P in these products depend on soil pH, texture, and presence of oxides (Al and Fe oxides)

2.4 Conclusions

This MFA has revealed that there is P mining in Malawian soils caused by low input of P and high output of P through crop uptake. The situation is like to be exacerbated by P fertiliser's continued rising prices, limiting smallholder farmers' access to inorganic P fertilisers. Furthermore, around 66 per cent of P used in crop production is imported inorganic P. The high dependency on imported P is likely to affect Malawi's food security. However, P in solid organic waste, faecal matter, manure, and crop residues can be recycled back to agriculture. The yearly (from 2016) accumulation of P in manure, faecal sludge, and organic solid waste is almost two times annually P imported in inorganic fertiliser. If the stocks are ranked based on yearly P accumulation, then the faecal matter would come first followed by manure and organic solid waste materials

Although this study showed that Malawi has organic P stocks, still some issues need to be addressed. Currently, Malawi has no regulations addressing the production or quality of organic fertiliser products. An organic fertiliser policy must be formulated to define criteria for producers to follow to ensure high quality (nutrient-dense, hygienic) recycled P fertilisers if Malawi's soils and food security are to be sustained in the face of increasingly expensive imported P and a growing population. The government should promote the sorting of organic waste materials at source to reduce the cost of compost production from market waste. Furthermore, extension outreach and training should be promoted to encourage farmers to adopt the production and use of organic fertilisers.

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2.6 Appendix

Table A. 1. Flows description, calculations, and data sources

Flow	Flow description	From	To	Data used	Data sources	Calculations, assumptions
Import flows						
inorganic fertiliser	P imported in inorganic fertiliser	Outside Malawi	Imported fertiliser	P in fertiliser, Mass of imported fertiliser	FAOSTAT, 2016	Mass of P in NPK fertiliser
Imported foods and washing products	P imported in food and washing products	Outside Malawi	Food processing/ distribution and retailers	Mass of imported fruits, processed food, wheat flour, fish, etc. Mass of imported washing products P content of imported food P content in washing products	FAOSTAT, 2016 WITS, 2019 USDA, 2021 Pattusamy et al., 2013	Mass of Food imported x P content (mg/kg)
Internal flows						
Inorganic fertilisers	P in inorganic fertiliser applied to crops	Imported fertiliser	Cropland soils	P fertiliser used in agriculture	FAOSTAT, 2016	The difference between P applied (inorganic fertilisers, manure, and compost) and P lost (soil erosion) and absorbed (crops) from the soil to the soils Produced by STAN mass balance

Crops	Nationally produced P-containing crops including residues (maize, wheat, and rice)	Cropland soils	National crops	Mass of harvested cereals, legumes, fruits, vegetables, etc. Hectarage under maize production	FAOSTAT, 2016	Crop and residues harvested x P content
				P content of each crop product	USDA, 2021	
				P content in maize residues	FAO, 2006	
				Mass of maize residues per ha	Kabambe et al., 2018	
Crop products	P in crop products that go to post-harvest handling	National crops	Crop /animal products processing and handling	Mass of P in crop products Mass of P in crop residues (mostly maize)		Mass of P from cropland (soils) – Mass P in crop residues (feed, mulch, and burnt)
Mulch (residues)	P returned to the soil through soil mulching	National crops	Cropland soils	Hectarage under conservation agriculture (C.A.)	Kassam et al., 2015	The area under C.A. x maize residues yield x P content
Crop residues (animal feed)	P consumed by animals from crop residues, e.g., maize stalks	National crops	Livestock	Mass of maize crop residues		Assumption: 20% of the total P in crop residues
Crop residues	P in crop residues to be burnt for fuel, nursery curing, mice hunting, and land clearing.	National crops	Burning	Mass of burnt crop residues	FAO, 2016	Mass of residues burnt x P content
				P in crop residues	FAO, 2006	

Ash	P in ash after burning of crop residues	Burning	Water bodies	Percentage of nutrient loss from burnt biomass	Dobermann & Fairhurst, 2002	Assumption: 80% of P in burnt biomass
				Mass of biomass burnt	FAOSTAT, 2016	
Ash	P in ash after burning of crop residues	Burning	Cropland soils	Percentage of nutrient loss from burnt biomass	Dobermann & Fairhurst, 2002	Assumption: 20% of P in burnt biomass
				Mass of biomass burnt	FAOSTAT, 2016	
Food products	P in food products going into households	Crop/animal products processing and handling	Households	Mass of food products		The difference between the mass of P in food products (in post-harvest handling) and the mass of P in food waste, feed, and food exports. Produced by STAN mass balance
Waste materials	P in organic waste	Crop/animal products processing and handling	Waste collection	Percentage of food waste for Sub-Saharan Africa in four processes (agriculture, post-harvest handling, processing, distribution,)	FAO, 2011b	Amount of wasted food x P content
				P content in food	USDA, 2021	
Waste materials	P in organic waste	Households	Waste collection	Percentage of food waste for Sub-Saharan Africa in during consumption	FAO, 2011	Percentage of food waste x total in household
Waste materials	P in organic waste	Waste collection	Landfills	Mass solid waste composition data	ICLEI, 2016	Assumption:10% of the total P in organic waste

				Percentage of waste collected in city councils	Government of Malawi, 2014	
Waste materials	P in organic waste	Waste collection	Unauthorised dumpsites	Mass solid waste composition data	ICLEI, 2016	Assumption:90% of the total P in organic waste
				Percentage of waste collected in city councils	Government of Malawi, 2014	
Consumed P	P in food consumed by people	Households	People	Mass of food products going to households	FAO, 2011	Percentage of food waste at household x mass of food going to households STAN mass balance
Excreta	P excreted from humans to pit latrines	People	Pit latrines	Percentage of P absorbed by the human body	Jönsson et al., 2004	P consumed by people - P absorbed by the human body. Then the difference multiplied by the percentage of the population using pit latrines
				Percentage of the population using pit latrines	NSO, 2017	
Excreta	P excreted from humans to WWTPs	People	WWTPs	Population connected to an off-site sanitation system	NSO, 2017	Percentage of people using off-site sanitation x P in human excreta
Excreta (septic tanks)	P excreted from humans to septic tanks	People	Septic tanks	Population using septic tanks	NSO, 2017	P in human excreta x percentage of the population using septic tanks
Excreta (open defecation)	P excreted by humans onto open land/water	People	Water	Population with no sanitation facility		P in human excreta x percentage of the population using no sanitation facilities

Animal Products	P in animal products	Livestock	Crop/animal products processing and handling	Mass of meat and chickens, the volume of milk, etc	NSO, 2017	Sum of the tonnage of meat products multiplied by their P content minus P in waste food
				P content in meat products	USDA, 2021	
Livestock feed	P in feed for animals	Crop/animal products processing and handling	Livestock	Mass of crop products used for animal feed	FAO, 2006	Mass of crop products used x P content in the crop products
Manure	P excreted by animals	Livestock	Collected manure	Livestock population	NSO, 2017	Livestock population x manure production per animal x manure P content
				Mass manure production per cow	Onmeremadu et al., 2007	
				Mass manure production per goat	Osuhor et al., 2002	
				Mass manure production per 1000 heads of chickens	Williams, n.d.	
				P content in manure	Neina et al., 2016; Ryssen, 2001	
Manure	P excreted by animals	Livestock	Natural pasture (soils)	Livestock population	NSO, 2017	Livestock population x manure production per animal x manure P content
				Mass manure production per cow	Onmeremadu et al., 2007	
				Mass manure production per goat	Osuhor et al., 2002	
				Mass manure production per 1000 heads of chickens	Williams, n.d.	

				P content in manure	Neina et al., 2016; Ryssen, 2001	
Pasture	P in grazing pasture	Natural pasture (soils)	Livestock	Livestock management	Chintsanya et al., 2004	STAN mass balance
Manure	P in manure applied to cropland	Manure collection	Cropland	Mass of manure collected		Assumption: 20% of the P in manure collection
Soil erosion	P carried by water from agricultural fields to water bodies	Cropland soils	Water bodies	Hectares of agricultural land	FAO, 2016	Land area x P lost per hectare
				Mass of P lost per hectare per year through soil erosion	Omuto & Ronald, 2018	
Leachate discharge	P leaving unauthorised dumpsites	Unauthorised dumpsites	Water bodies	P content leachates	Cheng et al, 2011	Assumption: 20 % of P in unauthorised dumpsites
Leachate discharge	P leaving official landfills	Landfills	Water bodies	P content leachates	Cheng et al, 2011	Assumption: 20 % of P in landfills
Faecal sludge	P in human excreta emptied from pit latrines	Pit latrines	WWTPs	Population using pit latrines	NSO, 2019	Assumption: 0.5% of P in pit latrines
				Percentage of pit emptied	Manda, 2009 *Chipeta* et al., 2017	
Faecal sludge	P from septic tank emptying	Septic tanks	WWTPs	Percentage of septic tank emptied	Collet et al., 2018 WaterAid Malawi, 2018	5% of P in Septic tanks
Wastewater	P from leaving WWTPs	WWTPs	Water bodies	Percentage of wastewater treated	Government of Malawi 2014	Assumption: 99% of P at WWTPs

					The World Bank, 2017	
Leachate discharge from manure	P in leachates from manure	Manure collection	Water bodies	Percentage of P loss from uncovered manure	Nicholson, Rollett, & Chambers, 2011 Tittonell, Rufino, Janssen, & Giller, 2010	P loss factor multiplied by P in unused manure
Fish	P from water bodies through fish	Water bodies	Crop/animal products processing and handling	Mass of fish harvested	FAO, 2017	Mass of fish harvested multiplied by P content (mg/kg)
				P content in fish, tilapia as reference	USDA, 2021	
Compost	P in compost applied to cropland soils	Waste collection	Cropland	Mass of solid organic waste		Assumption: 5% of P in unauthorised dumping sites
Discharge	P from flooding pit latrines	Pit latrines	Water bodies	Percentage of P discharge from pit latrines	Kiptum and Ndambuki, 2012, Kiptum and Ndambuki 2012, Manda 2009	Assumption: 0.4% of P in pit latrines
Faecal sludge (Septic tank emptying)	P from septic tank emptying	Septic tanks	Water bodies	Percentage of septic tank emptied	Collet et al., 2018 Water Aid Malawi, 2018	23 % of P in septic tanks (based on Kasungu district data)
Faecal sludge	P from WWTPs that is used for crop production.	WWTPs	Cropland soils	Mass of P in WWTPs		Assumption: 1 % of P from WWTPs

P in water	P lost from manure dropped during grazing	Natural pastureland	Water bodies	Mass of P in manure	Nicholson, Rollett, & Chambers, 2011 Tittonell, Rufino, Janssen, & Giller, 2010	Assumption: 50% of the P in manure dropped
Cadavers	P in dead human bodies	Peoples	Unauthorised dumpsites	Number of dead people	U.N. 2016	Percentage of dead people x total P absorbed by people.
Export flows (P leaving the country)						
Crop/animal products (exports)	P in exported crop/animal products	Crop/animal and fish products processing and handling	Outside the country	Mass of exported crop products	FAO, 2017	Mass of crop products exported x P content
				P content in crops	USDA, 2021	
Water	P in water leaving the country	Water bodies	Outside the country	Flowrate in Shire river P content in Shire river water	Shela, 2000	Amount of water leaving flowing in a year multiplied by P content in water

Table A. 2. Existing stocks, inputs, and outputs of phosphorus in Malawi (as of 2016)

Process name	References	Stock calculations and assumptions	Existing stock (Tg)	Inputs (Tg/yr.)	Outputs (Tg yr.)	Accumulation (Tg/yr.)
Agricultural land (soils)	Mloza-Banda, Makwiza, & Mloza-Banda, 2016; Njoloma, Sileshi, Geoffrey, Nalivata, & Nyoka, 2016; FAOSTAT, 2016	Soil bulk density x soil depth (20cm) x crop ha x available P (20cm depth)	241±72	21±3	25±3	-4±4
Unauthorised dumping sites	Based on the current P flow analysis	4000 Mg of P accumulating per year.	40±11	5±1	1±3	4±1
Landfills	Based on the current P flow analysis	400 Mg of P accumulating per year.	4±2	.5±0.2	.0100±0.04	0.4±0.2
Pit latrines	Based on the current P flow analysis	9000 Mg of P accumulating per year in latrines.	90±21	9±2	0.05±0.01	9±2.
Septic tanks	Based on the current P flow analysis	9000 Mg of P accumulating per year in latrines.	1.5±0.5	0.200±0.04	0.060±0.02	0.140±0.5
Collected manure	Based on the current P flow analysis	6000 Mg of manure accumulating every year.	60±38	13±4	7±.8	6±4
Water	Based on the current P flow analysis	7000 Mg of P accumulating per year.	70±20	11±1.4	4±.7	7±2
Natural pasture		No data	Unknown	13±3	25±6	-11±6

Key: Tg = Teragram

Chapter 3 . Evaluation of phosphorus mineralisation and use efficiency from various organic sources

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Abstract

Phosphorus (P) is an essential plant nutrient in addition to nitrogen (N). When soils are deficient in P, external P in the form of fertilisers has to be applied to increase crop yields. The world depends on mined P for P fertilisers, and recent reports indicate that increase in the human population has led to rising demand for P fertilisers. Due to the increasing demand and depletion of high-grade P reserves, the sustainability of P inorganic fertiliser supply in the future is uncertain. When there is less P, the prices may go up; producing countries may limit exports, leading to food insecurity in dependent countries. However, organic waste materials (organic market waste, animal manure, faecal sludge) contain P, which would replace inorganic P. However, it is unclear if the P from the organic fertilisers can maintain the available P concentration in the soil as well as inorganic fertilisers do to maintain or improve the current maize yields. Specifically, the phosphorus use efficiency (PUE) for each organic P source and its impact on maize yield must be determined. Previously, organic materials have been used as organic fertilisers to supply N and even P, but the application rates were not based on P, which resulted in inconsistent results that were not comparable. Therefore, this research was carried out to understand P mineralisation and availability from the P-based organic fertilisers application during the plant growth period (vegetative and reproductive stages). Furthermore, the study evaluated the effect of these organic sources on the PUE of maize. The results showed that available P in the soil from three weeks after planting to nine weeks affects the maize. The regression of available P and maize yield showed that, available P in the soil at 3 weeks accounted for 50%, 6 weeks accounted for 49%, and 9 weeks counted for 46% of the maize grain yield. The organic P sources were maintained soil available P above the threshold available P value (18 mg/kg) in Malawi just as inorganic fertilisers did. The P source did not affect the maize PUE. The results indicate that organic P sources could be used as alternative P sources for maize production in Malawi since they could maintain the concentration of P in soil solution just like NPK fertiliser.

Key words: organic waste, faecal sludge, organic phosphorus, phosphorus use efficiency, Malawi

3.1 Introduction

The bioavailability and concentration of soil phosphorus (P) are both significant for plant growth (Horrocks et al., 2016). Among other factors, soil pH controls the bioavailability of phosphorus: in low pH/acidic soils, P forms stable compounds after reacting with aluminium and iron oxides, while in high pH/alkaline soils, P reacts with calcium. These reactions remove P from the solution (the aqueous phase) and make it difficult for the plant to access (Hopkins and Ellsworth, 2005). When soil pH is less than 7.2, plants take up P as $H_2PO_4^-$, and as HPO_4^{2-} when the pH is more than 7.2. A concentration ranging from 0.003 to 0.3 mg P/L in soil solution throughout the growth period of crops is the optimum P concentration for plant growth. Still, most agricultural soils have P ranging from less than 0.01 to 1 mg/L, which is insufficient to support plant growth throughout the season and has to be replenished (Mullins, 2009). P can be replaced using inorganic fertiliser that contains P or organic sources like animal manure, faecal sludge, or compost.

3.1.1 Phosphorus: the global situation

The future of inorganic P fertiliser, which mainly comes from phosphate mines, is uncertain: the resource is finite, but the quantity of economically viable resources is still disputed (Rosemarin & Ekane, 2016; Schröder, Cordell, Smit, & Rosemarin, 2009; Walan, Davidsson, Johansson, & Höök, 2014; Walan, 2013). Morocco-controlled Western Sahara is home to 75% of the world phosphate reserves; the rest are in the United States of America, Jordan, China, and South Africa (USGS, 2018). Between 2009 and 2019, phosphate mining increased by 51% (USGS, 2010, 2021). Despite the reports on P depletion, The United States Geological Survey (USGS) claims there are more than 300 billion tons of phosphate rock reserves, and there is no danger of a P shortage (USGS, 2021). Despite the claim by the USGS, other authors question the reliability of their data (P. E. Fixen & Johnston, 2012; Ward, 2008). Regardless of whether P will run out sooner or later, it is still a non-renewable resource that will not be available forever. There is no replacement for P in agriculture (USGS, 2018). For adequate future food supply, the world needs to sustainably manage the current phosphate reserves and explore alternative sources of phosphate, one of which could be made from organic waste materials.

3.1.2 P use efficiency

Plants do not absorb all P that is applied. The amount of P taken absorbed by the plant depends on several factors like soil pH, crop variety, the P source, etc. (Bationo & Kumar, 2002). Knowing how much the planting takes up helps to decide to increase or reduce the application rate to maximise plant yield and protect the environment. Phosphorus use efficiency (PUE) measures how well the crop utilises applied P and turns it into yield, for example, grain yield for maize. The P not taken up the plant is either fixed in the soil or carried away by erosion, contaminating the water. The typical PUE for cereals, including maize, is 15 – 40% when recommended management is used, and other plant nutrients, e.g., potassium, are within optimal ranges (P. Fixen et al., 2015). Therefore, the impact of P on crop production is assessed by calculating the PUE. PUE is calculated as follows:

$$PUE = \frac{P\ in\ grains \times 100}{P\ added}$$

The effect of organic P sources on PUE has been reported to equal or be greater than that of inorganic fertilisers. The P in inorganic fertilisers is readily available for the plant to take up, theoretically translating into a higher PUE than the organic fertilisers. Therefore, if organic fertilisers can match the PUE of inorganic fertilisers, the crop performance will not be affected. However, in situations where the soil fixes P, organic fertilisers can improve the PUE of crops due to the presence of organic acids molecules that chelate the metal ions (Adamtey et al., 2010; Amoah et al., 2017). However, there is no consistency in the results. The variations might be due to the type of P source (raw manure, composted manure, crop residues compost, faecal sludge compost, etc.), application rate, type of crop, or soil type. Komiyama & Saigusa (2014) reported a maize PUE of 7.3% after applying cattle manure compost and 3.4% after applying poultry manure compost. A PUE of up to 75% by maize was reported by Xin et al., (2017b) after crop residue compost was applied. In the same study, wheat was reported to have up to 45% PUE. However, these PUE values were not significantly different from the PUE when inorganic fertiliser was used.

There are limited data on the effect of organic fertiliser on the PUE in maize. The studies referred to in this paper have contrasting results: one had a high PUE of up to 75% (Xin et al., 2017), while another reported a PUE of 3.4% (Komiyama et al., 2014). In both studies, organic fertilisers performed the same way as inorganic fertilisers. The differences in soil type and soil pH may be the reason for the contrasting results. Xin et al., (2017b) conducted trials on iceptisols of pH 8.6, while Komiyama et al., (2014) did a trial on andosols of pH 5.9. The most common soils in Malawi are lixisols (Dijkshoorn et al., 2016) with pH of less than 5.5 (Njoloma et al., 2016). As PUE depends on various factors like soil, crop, P sources, there is a need to understand how the use of organic P sources affect the PUE of maize to utilise the full potential of the organic fertilisers and better P management

3.1.3 Bioavailability of P from recycled sources

Plant nutrient bioavailability refers to the proportion of the applied nutrient that becomes available for plant uptake and utilisation. The P content and bioavailability in recycled sources like organic waste, poultry droppings, faecal sludge, urine, cattle, and pig manure, etc., varies by source. Comparing the P status of soils that have been treated with different recycled P sources is difficult because P bioavailability is affected by a variety of factors like soil pH, soil type, temperature, and interaction with other plant nutrients (Rollett et al*.,* 2017). When using animal manure, animal species, diet, age, and storage also affect the P content (Rollett et al., 2017). However, the application of recycled P sources has been shown to increase both plant-available P and plant P uptake (Coutinho et al*.,* 1997; Begum, 2011; Giannakis et al., 2014; Horrocks et al*.,* 2016).

3.1.4 Availability of phosphorus in the soil after applying organic sources

Various authors had reported increasing available P in the soil when organic fertilisers were used (Table 3.1). The organic application rates ranged from 3 Mg/ha to 100 Mg/ha. All the application rates raised the available P content of the soil compared to the control (no organic P application).

Although the available P increased, the available P was measured at the end of the growing season when the crops were harvested. Measuring P at the end of the growing season could not explain the P availability when the plant was growing and taking up P. It is also important to note that different organic P sources affected the soil P status differently. For example, 100 Mg of municipal compost increase available P by 79%, while 100 Mg of faecal sludge increased available P by 430%. The difference in the P increase in soil shows that different organic P sources need to be evaluated to develop the right application rates to meet the crops' P requirement.

Table 3.1. Available P content in the soil applying different organic P sources

Organic P source	Application rate basis	Application rate (Mg/ha) or N/ha	Available P content in the soil (mg/kg)	Source
Municipal compost	Assessing fertiliser potential	0	77	Giannakis et al., 2014
		50	123	
		100	138	
Compost (manure and crop residues)	Nitrogen content	0	2.4	Buchanan & Gliessman, 1990
		3	4.2	
		7.5	7.1	
		30	8.7	
Faecal sludge (heated)	Farmer's practice	0	120	Houben et al., 2019
		4.7	400	
Faecal sludge (composted)	Farmer's practice	0	120	
		4.7	200	
Faecal sludge	Assessing fertiliser potential	0	7.5	Jamil et al., 2006
		10	16	
		20	22	
		40	29	
		60	34	
		80	38	
		100	40	
Organic waste compost	Nitrogen requirement	260*	443	Case & Jensen, 2019
Organic waste compost	Nitrogen requirement	0	6.9	Singh et al., 2019
		120*	18.2	
Compost	P based	0	~55	Komiyama et al., 2014
		8.52	~90	
Compost	P based	27.8	30	Horta et al., 2018

*Application based on nitrogen

Although previous studies evaluated organic fertilisers' impact on P availability, few studies used P based application rates (Horta et al., 2018; Komiyama et al., 2014); instead, they measured available P in the soil after harvesting the crops. The other studies' application rates were based on N requirements (Case & Jensen, 2019; Singh et al., 2019) and farmers practice (Houben et al., 2019). Sometimes, the organic fertilisers were applied to evaluate their potential to supply plant nutrients, so the application rates were not nutrient requirement based (Giannakis et al., 2014; Jamil et al., 2006). When the organic fertilisers are applied not based on P, the amount of P applied would be different from P based application. If the amount used is different, then the P bioavailability should be different too, which ,may be more or less than crop requirements. For example, Komiyama et al., (2014) found 90 mg/kg available P in the soil when compost was applied based on P, and 115 mg/kg available P when compost was applied based on nitrogen. When applying a fertiliser based on its N-content it results in a P application that exceeds the crop's requirements. Excess P may contaminate water, and it is not economical, especially for subsistence farmers. When less than required P is applied the crops would not perform to their full potential. Hence an application based on P was deployed in this study.

3.1.5 Phosphorus uptake by plants after applying organic sources

The impact of applying co-compost (i.e., compost produced from multiple sources, e.g., faecal sludge and municipal waste, or poultry droppings and urine, etc.) on P plant uptake has been inconsistent in previous studies: the organic fertiliser was not applied based on P, which means the reported P uptake by the plant would have been different if the organic fertiliser were applied based on P requirement. For example, a combination of poultry droppings and urine and a mixture of poultry droppings and NPK fertilisers resulted in no statistically different P uptake of 13.2 and 10.6 kg P per hectare by cabbages when co-compost corresponding to 12 kg N per hectare was applied (Amoah et al*.,* 2017). Furthermore, the N application of faecal sludge and municipal waste co-compost to maize resulted in a P uptake of 88 mg/plant compared to 48.1 mg/plant for the control. Co-compost, enriched compost and control resulted in 84.8 mg P/plant for co-compost, 119.8 mg P/plant for enriched compost, and 48.1 mg P/plant control (Adamtey et al., 2010). In another study, Anwar et al*.,* (2017), observed an increase in P uptake by spinach, and the increase was more pronounced in sandy loam soils. P content increased by 106 per cent in sandy loam and 86 per cent in silty loam when compost was used. The results of Anwar et al*.,* (2017) highlight the effect of soils on P availability and uptake by plants. Sandy loam soils are well aerated, which encouraged organic matter mineralisation, thereby releasing P for plant uptake. Adamtey et al*.,* (2010); Amoah et al*.,* (2017) suggested that competition amongst dissolved carbon, humic acids, fluvic acids, and P for sorption sites from the organic fertilisers encourage P availability and uptake.

Although previous studies have demonstrated that organic P sources (sewage sludge, animal manure, organic waste compost, etc.) improve available P in soils and encourage P uptake by plants, few experiments have investigated the availability of P from organic sources during the growing period of the crops. Usually, soil P is analysed at the beginning and the end of the experiment, which may not necessarily explain P availability during the growing period of the crops (Bationo & Kumar, 2002). In addition, the P organic sources were not P based applications which mean more or less than the required P was applied. There are reports of slow P release from organic P sources during the early weeks after planting, which may affect plant growth and production as most plants needs P during the early growth stages, e.g., wheat (Römer & Schilling, 1986). Previous studies show that the use of organic sources of P improves PUE (Bationo & Kumar, 2002). Still, there is no consistency in the results because different P sources affect the PUE of crops differently: specifically, there is little information on the PUE of maize treated with organic sources of P and how applying a mixture of inorganic and organic sources P can improve PUE.

Therefore, this research was carried out to evaluate PUE derived from market waste compost and co-compost of faecal sludge and market waste to determine its efficacy as fertiliser to meet crop demands. It was hypothesised that soil available P during the early growing stages (three, six and nine weeks) of maize would have postive impact on maize yeild, available P concentration in the soil is affected by the P source, and P sources influence PUE of maize

3.2 Methodology

3.2.1 Site

The field trials were conducted at two research stations with two different soil types: Bvumbwe (in Thyolo District), Makoka (in Zomba District) shown in Figure 3.1 and 3.2. Both sites are run by the Department of Agricultural Research Services in the Ministry of Agriculture, Irrigation, and Water Development.

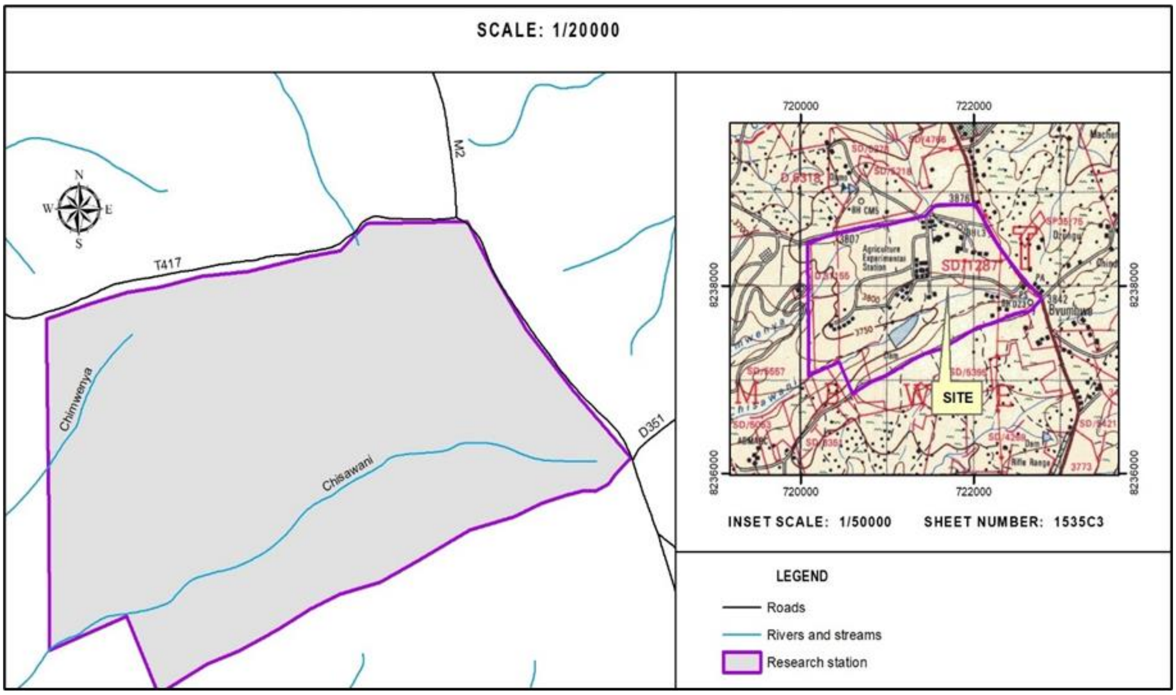

Figure 3.1. Bvumbwe research station in Thyolo district

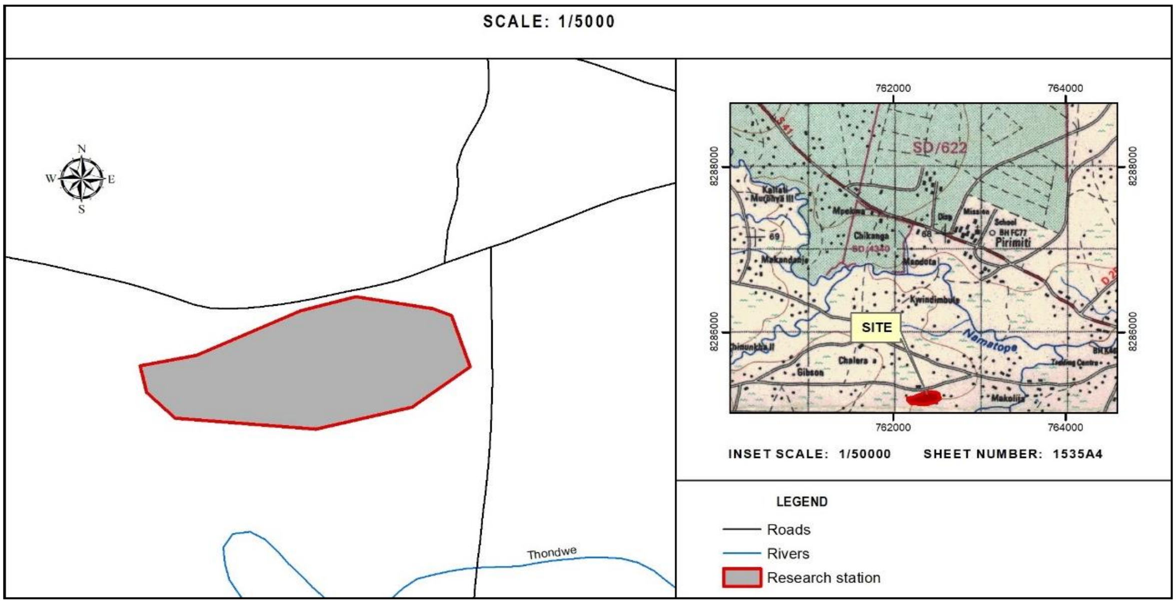

Figure 3.2. Makoka research station in Zomba district

Bvumbwe and Makoka research stations both have acidic, dark red lixisols (Dijkshoorn et al.,2016). Sandy loam soils dominate Makoka with patches of heavy clays. The temperature ranges from 15.6 to 25 degrees Celsius, receives 1,044 mm of rainfall annually and is located on the latitude 15˚ 32´ South and longitude 35˚ 11´East at an altitude 1,029 m above sea level. Bvumbwe gets 1,219 mm of rain annually, and the soils are primarily sandy clay. Bvumbwe is located at the southern end of the Blantyre escarpment at an altitude of between 1,228 and 1,174 m above sea level, latitude 15˚ 55´South and longitude 35˚ 04´ East

3.2.2 Experimental design

The maize experiment was a 5x4 factorial design, i.e., five P sources, each with four application rates. The plots were laid out in a complete randomised block design with four replicates to reduce variability and increase confidence levels. Before conducting the experiment, a P flow analysis was conducted to identify the source of organic P in Malawi (Mnthambala et al., 2021). The organic P sources used in this study were based on that study, market waste and faecal sludge, were based on that study. The sources were chosen because there were major sources of organic P in Malawi but underutilised. The treatments were i) market waste compost (MW), ii) faecal sludge-market waste compost (FSMW), iii) market waste + NPK fertilizer (MW+NPK), iv) faecal sludge-market compost + NPK (FSMW+NPK), and v) NPK fertiliser, each with four application rates: 0 kg P/ha (0AR), 15 kg P/ha (15AR, 30 kg P/ha (30AR), and 45 kg P/ha (35AR). These application rates were based on total P. Due to the beliefs, taboos and health risks associated with handling and utilisation of human excreta, a pure faecal sludge treatment was not included. Mixing faecal sludge and organic waste was hypothesized to be a more socially-acceptable form of applying faecal sludge.

The field plot included three 6m ridges spaced at 0.75 m (3 x 6 m x 0.75 m). Planting stations were 0.75 m apart, and three maize seeds were planted for per planting station. The plots were ploughed to a standard depth of 30 cm, and the recycled P materials were mixed manually to a depth of 20 cm because maize and soybean roots are concentrated in this region. The crop was grown under a rainfed system during the 2019/2020 and 2020/2021 growing seasons. Nitrogen was applied at 92 kg N per hectare, using urea (46% N) to ensure N was not a limiting nutrient as recommended (Ministry of Agriculture and Food Security, 2012). All crop husbandry practices (weeding, disease control, etc.) were followed so that the only source of variations should be the effects of the treatments.

3.2.3 Soil and compost characterisation

Soil samples were collected from both sites using a random zigzag pattern at a constant depth of 0-20 cm for chemical and physical analysis (Table 3.2). The field was divided into four blocks (replicates), and from each block, four composite soil samples were collected, air-dried, and passed through a 2 mm sieve. The compost samples from market waste anf faecal sludge compost were also collected (Table 3.3). The following chemical and physical properties were analysed: soil pH (Blakemore et al., 1987), soil texture (Ashworth et al., 2007), organic carbon (GLOSOLAN, 2019), total P (Murphy & Riley, 1962; Okalebo et al., 2002), available P using a Mehlich 3 solution (Murphy & Riley, 1962), and metals (K, Ca, Zn, Cu, Fe, Al, etc.). The available and total P was analysed using a Perkin Elmer Lambda 25 UV/VIS spectrometer. The metals (Cu, Zn, etc.) were extracted using aqua regia and run on ICP-MS as described by (Turek et al., 2019).

Table 3.2. Chemical and physical properties of soils at Bvumbwe and Makoka sites

Parameter	**Makoka**	**Bvumbwe**
Available P (mg/kg)	23.86 ±4.20	15.92 ±3.35
pH (water)	4.97±0.12	4.73 ±0.35
Al (g/kg)	43.66 ±4.48	68.45 ±5.44
Fe (g/kg)	43.5 ±10.80	81.81 ±4.72
Organic matter (%)	0.92 ±0.11	1.17± 0.06
Ca (mg/kg)	597.97 ±112.0	545.45 ±81.23
K (mg/kg)	692.94 ±155.5	659.18 ±65.67
Mg (mg/kg)	930.52 ±88.64	1002.49 ±111.3
Silt (%)	7.33 ±1.03	10.00 ±1.27
Clay (%)	21.33 ±3.72	42.00 ±2.83
Sand (%)	71.30 ±3.27	48.00 ±3.35

The numbers after ± are standard errors

Table 3.3. Chemical characteristics of the faecal sludge-market waste and market waste compost

Parameter	Market waste-faecal sludge compost	Market waste compost
$pH_{(water)}$	7.20 ± 0.07	8.82 ± 0.09
Organic matter (%)	14.86 ± 0.87	13.17 ± 1.23
Total P(mg/kg)	4906.76 ± 384.80	3522.22 ± 430.10
Available P(mg/kg)	132.69 ± 9.85	113.68 ± 7.62
Ca (g/kg)	11.60 ±0.46	15.20 ± 2.49
K (g/kg)	4.64 ± 0.62	5.24 ±0.61
Mg (g/kg)	4.21 ±0.52	3.80 ±0.18

The numbers after ± are standard errors

3.2.4 Data collection and analysis

Changes in available soil P were monitored by taking soil samples at weeks 3, 6, and 9 after planting. After harvesting, grain weight was recorded to determine grain yield (kg/ha) for maize and samples were collected and milled for total P analysis in the grains. The total P in the grain and maize yield data were used to calculate P uptake (kg/ha) and PUE (%).

PUE indicates how the crop is utilising P, and measuring PUE during the crop's early growth stages could help establish PUE of each growth stage. The knowledge PUE of each growth stage could be used to determine the growth stages that P is actively taken up by the crop. In this study, PUE was determined after harvesting since the ultimate goal of the study was to determine how the P applied (through various P sources) contributes to grain yield. When it comes to maize growing in Malawi, farmers are interested in yield, That’s why this study ignored other crop properties during the early growth stages and just focused on PUE and maize yield.

In Malawi, fertilisers for maize is composed of N, P, K as macronutrients, S and Zn as micronutrients. In this study recommended rate of N (92 kg N) was applied to all the treatments through Urea (46%N). When the P source was NPK, Zn and S were applied too, since NPK fertilisers contain S and Zn. On the other hand, the application of organic sources P came with enough K, Zn and S (Table 3.3) to meet recommended rates of 5 kg K/ha, 6 kg S/ha, and 1 kg Zn/ha. For example, 15 kg P/ha was met by applying approximately 3000 tons of organic fertiliser while the same 3000 tons supplied around 15 kg K/ha, 9 kg S/ha, and 1.5 kg Zn/ha. Therefore, no micronutrients were analysed from the soil, and it was assumed that maize performance would be determined by the availability of P from the different sources. There were no limiting levels for N, K, S and Zn and that is why only P doses were adjusted in this study to assess its effects in soil and crop yield.

Regression in Genstat 20th edition software was performed to determine the impact of available P at different weeks on maize yield. One-way and Two-way ANOVA were used to test if the mean values of available P and PUE were the same from all the P sources. When differences were detected, a Fisher's protected least significant difference test was used to identified means which were different or the same.

3.3 Results and discussion

3.3.1 Linking P availability and maize yield

A regression analysis was conducted to establish the impact of available P in the soil at different weeks, the site, and the season on maize yield. The results (Table 3.4) showed that available P at 3, 6, and 9 weeks after planting significantly impacted maize grain yield. The constant was high and significant, predicting a yield at Bvumbwe, for example (Column 1) with no input, of

3945 kg/ha maize compared to 1846 (3945-2099) kg/ha from Makoka. The difference in yield potential in those two sites is consistent for each of the three regression models; yields at Makoka were predicted to be about 2200 kg/ha lower than Bvumbwe, *ceteris paribus.*

Table 3.4. Regression analysis results for the effect of site, season, and available P at weeks 3, 6 and 9 after planting maize on maize grain yield (kg/ha)

Parameters	**(1)**	**(2)**	**(3)**
Constant	3945*** (227)	3331*** (204)	3361*** (221)
Site (Makoka)	-2099*** (188)	-2275*** (205)	-2339*** (225)
Season (1)	481** (182)	231 (195)	357 (196)
Available P at week 3 (mg/kg)	31*** (5)		
Available P at week 6 (mg/kg)		37*** (7)	
Available P at week 9 (mg/kg)			38*** (8)
R^2	0.50	0.49	0.46
N	144	144	144

***p- value < 0.001, **p- value < 0.05. The figures in parenthesis are standard errors

The effect of the site on maize yield may be due to local environmental conditions like temperature, rainfall, and soils, as both areas were treated the same. However, the regression suggests that with the continued application of organic fertiliser, maize yield will increase as the season parameter is significant (Column 1), indicating that the second season was responsible for an increase of 481 kg/ha (but not in all models). The R-squared values indicate a good degree of specification and fit. As available P depends on the previous value measured, the terms (P at weeks 3, 6, and 9) are serially correlated; therefore, three different models were run separately to identify the impact of available P each week. The results indicate that the available P at each week is always a significant predictor of yield.

The results suggest that the P available in the soil during three to nine weeks after planting affects maize yield. Sufficient plant nutrients during the early growth stages of the crop are crucial to maximising yield. Crops accumulate nutrients they need between germination and flowering, and of these nutrients are used for seed development (Jones et al., 2015). In the first six weeks, the maize crop is actively growing and transitioning from the vegetative to the reproductive stage, and during this time, plants are actively taking up phosphorus (Kahiluoto et al., 2015). The phosphorus taken up at this time is used for graining filling, which is why available P at three, six, and nine weeks affected maize yield in the current study. Therefore, it is crucial to make sure the organic P sources maintain sufficient levels of available P in the soil, most importantly during the early stages of maize development. Therefore, a further analysis was conducted to see if organic fertiliser can maintain available P concentration in the soil the same way as inorganic fertiliser.

3.3.2 Effects of P sources on available P in the soil

Every three weeks after planting (three weeks to nine weeks), the available P in the soil was measured and compared (ANOVA) to determine if there were differences in available P concentration in the soil with reference to the P sources used. At Makoka, the ANOVA showed that the available P in the soil at three and six weeks after planting was the same from all the treatments in the first seasons. The mean values of available P in the soil are shown in Figure 3.3. It was only at week nine that available P concentration in the soil was different. Therefore, further analysis using Fisher's protected least significant difference test was done. The results showed that NPK resulted in 24 mg/kg available P at nine weeks in the first season, significantly lower than 37 mg/kg available P in FSMW and 34 mg/kg available in MW (Table 3.5).

Table 3.5. Differences between available P (mg/kg) means and pairwise comparison at 9 weeks after planting in the first season at Makoka. Differences larger than LSD (8.5) are significant at p-value = 0.05

P sources	**P content (mg/kg)**	**FSMW**	**FSMW+NPK**	**MW**	**MW+NPK**	**NPK**
FSMW	37		2	3	8	13*
FSMW+NPK	35			1	6	11*
MW	34				5	10*
MW+NPK	29					5
NPK	24					

*= Significant

In the second season, at three and six weeks after planting, there were no differences in available P concentration regarding P sources. At nine weeks in the second season, NPK treatment had 30 mg/kg available P, significantly lower than available P in MW, MW+NPK, treated plots (Table 3.6).

Table 3.6. Differences between available P (mg/kg) means and pairwise comparison at 9 weeks after planting in the second season at Makoka. Differences larger than LSD (10) are significant at p-value = 0.05

P sources	**P content (mg/kg)**	**FSMW**	**FSMW+NPK**	**MW**	**MW+NPK**	**NPK**
FSMW	36		2	8	8	6
FSMW+NPK	38			6	6	8
MW	44				0	14*
MW+NPK	44					14*
NPK	30					

* = Significant

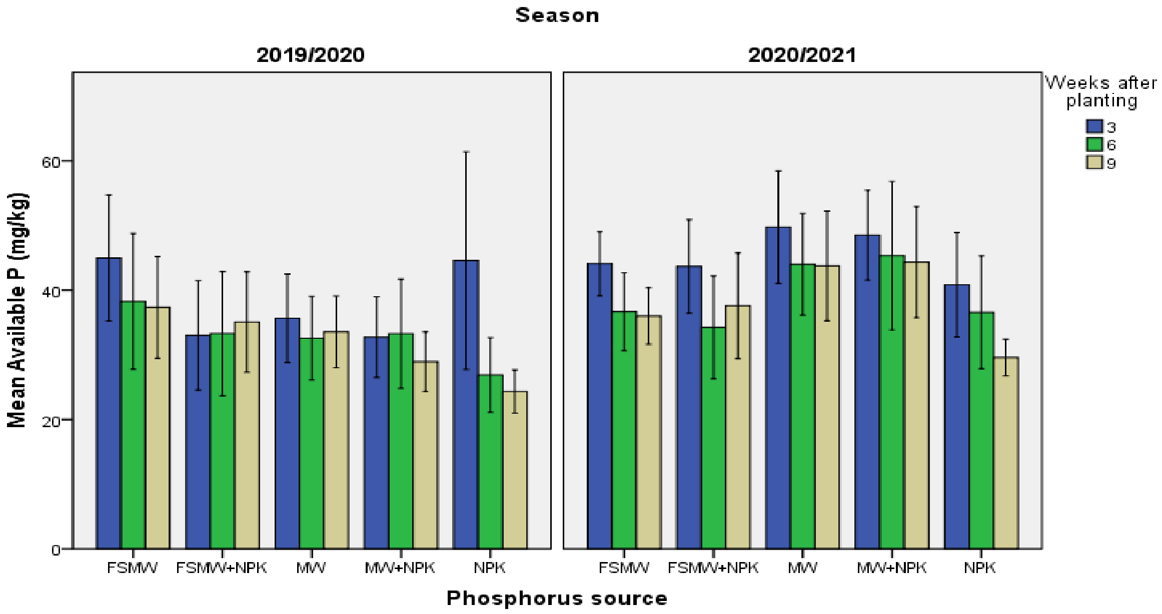

Figure 3.3. Soil available P three, six and nine weeks after planting at Makoka. The whiskers on the bar graphs indicate standard errors

At Bvumbwe (Figure 3.4), ANOVA results showed that the available P concentration in the soil was the same regardless of P source at three and nine weeks after planting in the first season. However, at six weeks, NPK, FSMW+NPK and MW+NPK resulted in 15 mg/kg available P. The available P concentrations in NPK, MW+NPK, and FSMW+MPK treatments were statistically lower than 19 mg/kg in FSMW and 20 mg/kg in MW treatments (Table 3.7).

Table 3.7. Differences between available P (mg/kg) means and pairwise comparison at 6 weeks after planting in the first season at Bvumbwe. Differences larger than LSD (3.6) are significant at p-value = 0.05

P sources	**P content (mg/kg)**	**FSMW**	**FSMW+NPK**	**MW**	**MW+NPK**	**NPK**
FSMW	19		4*	1	4*	4*
FSMW+NPK	15			5*	0	0
MW	20				5*	5*
MW+NPK	15					0
NPK	15					

NA = Not applicable, NS = Not significant, S = Significant

In the second season, there was no differences in available P concentration at three, six, and nice weeks after planting. All the treatments had statistically the same concentration of P in the soil. The results agreed with Horrocks et al., (2016) and Giannakis et al., (2014), who reported increased available P concentration in the soil at the end of the crops' growing season after applying organic fertilisers. However, the current study measured available P in the soil during the crops' growing period to understand the capability of the organic fertilisers to supply P to the crops when P is needed.

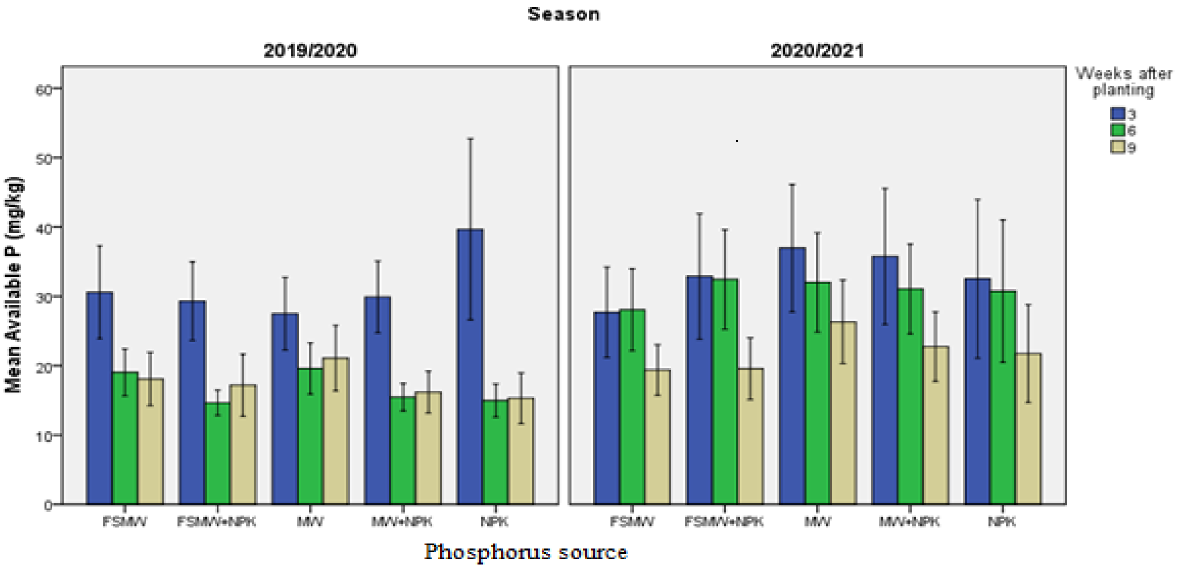

Figure 3.4. Soil available P three, six and nine weeks after planting at Bvumbwe. The whiskers on the bar graphs indicate standard errors

The results showed that both organic and inorganic fertilisers maintained the same concentration of available P in the soil in both seasons at Bvumbwe. Generally, only a small percentage of the P in these organic fertilisers is readily available. As the organic fertilisers were mineralising, P was released, thereby increasing the available P in the soil. In soils dominated with iron and aluminium ions, like this study (Table 3.2), P is easily fixed. However, organic molecules like humic acid from the organic matter can chelate these metal oxide ions, thereby leaving P in solution (Kahiluoto et al., 2015; Shen et al., 2011). Although P from the inorganic fertiliser was readily available, the P was easily fixed as the soils have low organic matter and high metal oxides content at both sites (Table 3.2). The ability of the organic molecules in organic fertilisers to react with metal oxides could be why organic P sources maintained the same concertation of P in solution as inorganic fertilisers. Furthermore, at Makoka at nine weeks after planting, there was still more P in the solution where organic sources of P were applied than the NPK treated plots. Organic fertilisers release nutrients slowly, which means that, unlike inorganic fertilisers, even the crops in the following year will utilise nutrients from the previous seasons (Gagnon et al., 2012; Prasad, 2013). The slow release of P from organic fertilisers reduces chances water contamination, since the released P is likely to be taken up by the growing crops, and not getting leachedor eroded. The P inorganic fertiliser, is readily available, increasing the chances of water contamination since the growing plants may not utilise before it gets leached or eroded. Approximately 35000 Mg of P, which is two times the annual P demand for Malawi, accumulate in organic materials each year (Mnthambala et al., 2021), meaning Malawi could rely on the organic source of P performing the same as NPK and are locally available

3.3.3 Effects of P source on PUE

The ANOVA results for PUE showed that there were no differences in the PUE values of maize in either season at Bvumbwe regardless of P source and application rates (Figure 3.5). At Makoka, neither P source, regardless of application rate, affected PUE in the first season. However, applications of NPK and MW resulted in statistically higher PUE than the other P sources at 15 AR in the second season (Table 3.8)

Table 3.8. Differences between PUE (%) means and pairwise comparison at 15AR at Makoka. Differences larger than LSD (2.62) are significant at p-value = 0.05

P sources	PUE (%)	FSMW	FSMW+NPK	MW	MW+NPK	NPK
FSMW	3.7		1.5	0.9	1.	2.8*
FSMW+NPK	2.2			2.4	0.3	4.5*
MW	4.6				2.1	1.9
MW+NPK	2.5					4*
NPK	6.5					

* = Significant

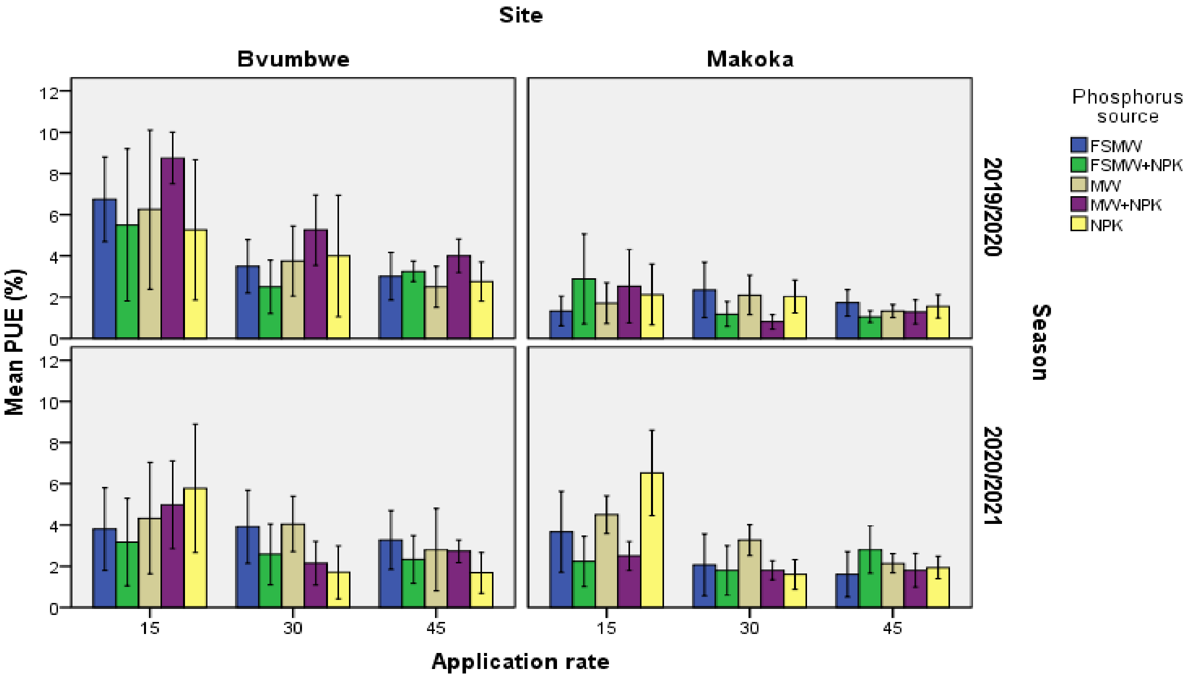

Figure 3.5. Maize PUE after application of different P sources at application rates in two seasons. The whiskers on the bar graphs indicate standard errors

At 15AR, NPK resulted in 6.5% PUE and MW resulted in 4.5% PUE. The results agree with the results of Xin et al., (2017b) and Komiyama et al., (2014), who found no significant differences between the PUE of maize applied with inorganic fertiliser and maize applied with organic fertilisers. Komiyama et al., (2014), calculated the maize PUE using data from three years of experiments, while Xin et al., (2017b) used data from twenty years of experimentation. On the other hand, Ademba et al., (2015) found that farmyard compost resulted in a higher PUE than inorganic sources of P in one site and a lower PUE in another area, which was attributed to differences in internal crop P requirement in those two sites. In this project, at both locations, inorganic and organic fertilisers had the same PUE. The maize cultivar used was one of the hybrid maize varieties used in Malawi. However, PUE is cultivar specific as P uptake by maize cultivars vary (Ray et al., 2020; Zhang et al., 2021), suggesting that different cultivars will have different PUE values. Although others have reported that P sources affect the PUE, our results show that all the P sources had the same effect on available P in the soil through the plant vegetative and reproductive stages. The same available P in the soil means the maize could take up almost the same amount of P from all the treatments.

We can also suggest that the results showed no significant difference in PUE because the only P in the grains was considered, not any other parts of the plants; when the soil P does not meet grain P demand, P from other parts (leaves and steams) is relocated to the grains (Zhang et al., 2021). P deficiency does not necessarily reduce P portioning to different parts of the plant but reduces yield (Zhang et al., 2021). For example, at Makoka nine weeks after planting, there was lower available P in NPK treatments than the other P sources. Still, the maize may have relocated P from different parts to the grains. When P is sufficient and meets the grain P demand, the P in the other parts of the plant may stay there, increasing the total P in the plant. Ray et al., (2020) found that different maize cultivars partition P differently at maturity. Some accumulate more P in the leaves and stems than in the seeds.

3.3.4 Comparison of PUE of maize at Makoka and Bvumbwe

Since MW and FSMW had the same PUE at both sites (Figure 3.5), the comparison of PUE between Makoka and Bvumbwe was for MW (organic fertiliser) and NPK. The comparison of PUE of maize at Makoka and Bvumbwe showed that organic fertiliser at 15 AR resulted in a PUE value of 5.9% at Bvumbwe and 2.3% at Makoka in the first season (Table 3.9). In the second season, the PUE at Bvumbwe was 4.9% and 4.1% at Makoka, which were not statistically different. In the first season (Table 8), the NPK fertiliser at 15 AR resulted in the same PUE at Bvumbwe and Makoka, but at 30 AR and 45 AR, there was a higher PUE at Bvumbwe than Makoka. At both 30AR and 45AR, in the first season, the organic fertilisers resulted in higher PUE at Bvumbwe than Makoka

Table 3.9. A T-test between PUE (%) values for maize after application of P based organic fertilisers and inorganic P at Makoka and Bvumbwe in 2019/2020 season

Site	15AR		30AR		45AR	
	Organic	NPK	Organic	NPK	Organic	NPK
Bvumbwe	5.9	4.0	4.3	3.0	3.0	3.0
Makoka	2.3	3.0	2.4	2.0	2.0	2.0
Sig.	*		*	*	*	*

*Significant at $p<0.05$

In the second season, NPK at 15AR, 30AR and 45AR, there were no differences between PUE at Bvumbwe and Makoka (Table 3.9). Organic fertilisers at 30AR and 45AR in the second season at Bvumbwe had a significantly higher PUE than at Makoka (Table 3.10).

Table 3.10. A T-test between PUE values of maize after application of P based organic fertilisers and inorganic P at Makoka and Bvumbwe in season 2020/2021

Site	15AR		30AR		45AR	
	Organic	NPK	Organic	NPK	Organic	NPK
Bvumbwe	4.9	4.3	4.2	2.2	3.8	2.2
Makoka	4.1	5.2	2.2	1.6	1.8	1.6
Sig.			*		*	

*Significant at $p<0.05$

The results show that in the first season, at both sites, maize utilised an equal percentage of the applied P at 15AR of NPK. However, at 30AR and 45AR, there was more PUE at Bvumbwe than at Makoka. In the second year, all the application rates of NPK had the same PUE at Bvumbwe and Makoka. Before these experiments, the experimental plots were three years on fallow, and Bvumbwe had a higher organic matter content than Makoka (Table3.2). The organic matter may have promoted P uptake at Bvumbwe in the first season, resulting in higher PUE values. In the second season, the organic matter may have degraded, increasing the sorption potential of the soil, and lowering P uptake. Koocheki and Seyyedi (2015) suggested that organic matter promotes P uptake. The presence of organic acids in the organic matter that chelates the metal ions that bind P promotes P uptake (Adamtey et al., 2010; Amoah et al., 2017). Therefore, it can be suggested that the difference in the first season between the PUE at the two sites when NPK was applied was due to soil organic matter content.

In the first season, the organic fertilisers at all the application rates had higher PUE at Bvumbwe than at Makoka. However, in the second season, the 15AR resulted in the same PUE at both sites, suggesting that the soil condition (e.g., organic matter) improved, promoting P uptake at Makoka. At 30AR and 40AR in both years, maize at Bvumbwe had higher PUE than at Makoka, suggesting that the additional P resulted in less yield increase at Makoka than at Bvumbwe. The results also indicate that with 15 AR of organic fertilisers application, maize will yield the same at both sites. However, increased application rates will result in more maize yield at Bvumbwe than at Makoka.

3.4 Conclusions

The availability of P at 3, 6 and 9 weeks after planting has been shown to impact the maize yield. The availability of P in these weeks has shown to be associated with increased maize yield. P must be available in the soil at these times for optimum maize growth and productivity. Therefore, the hypothesis that available P in the soil during the early growth stages of maize has impact on maize yield was supported.

Earlier, it was also hypothesised that available P concentration in the soil is affected by the P source. This study has demonstrated that the application of organic fertilisers, either alone or in combination with inorganic P fertiliser, can maintain the soil available P just like NPK, from the early plant growth stages (3 weeks) when plant nutrients are needed for plant growth and production. Therefore, replacing inorganic sources of P with organic sources will not reduce maize yield due to the inability of the organic source to supply P for maize uptake. So, the hypothesis was rejected.

None of the P sources at any of the application rates resulted in higher PUE values than the others. The organic fertilisers did not influence maize to uptake more P than the inorganic fertilisers. Therefore according to these results the hypotheses that PUE of maize is influenced by P source were rejected. Although it has been reported that organic fertilisers improve PUE in maize, but differences in soil, cultivar and years of organic fertiliser application also influence PUE.

Although P is necessary for plant growth, it is also dangerous for water bodies; excessive P may cause eutrophication. Organic fertilisers improve the soils chemical, physical, and biological properties, which affect crops nutrients uptake and utilisation, and reduce soil erosion. However, continued application of organic sources of P in excess of crop requirement would lead to the accumulation of P in the soil over time, ending up in water bodies. Therefore, there is a need for long term experiments on these organic fertilisers. The long-term experiments will offer a platform where the long-term trends in crop yield, P transfer to water bodies can be studied. Studies on modelling of P mineralisation and crop uptake from the organic fertilisers can also utilise data from long term trials.

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Chapter 4 . The impact of phosphorus-based organic fertilisers on soil health: a maize study in Malawi

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Abstract

The soil's health needs to be maintained or restored if the soil is to remain productive and produce enough food for future generations. However, human activities like conventional tillage, continuous cropping, and burning of crop residues have led to soil organic matter loss, nutrients leaching, increased soil acidity, reduced water holding capacity, and increased soil erosion. The use of organic fertilisers has been strongly connected to improvements in soil health. Recently, due to the dwindling of world phosphorus reserves, there has been strong emphasis on recycling phosphorus from organic waste materials and human excreta. Previously, organic fertilisers have been applied to crops based on nitrogen requirement, not phosphorus requirement. Therefore, field trials laid out in randomised complete block design were conducted at Bvumbwe and Makoka to evaluate field scale evidence of the effects of organic P sources derived from organic market waste and faecal sludge on soil health in Malawi. The results showed that soil organic matter increased by 60% in two seasons at Bvumbwe and 80% at Makoka. On average soil pH increase from 4.75 to 5.82 in two seasons. There were almost 6 times more earthworms in the soil at Bvumbwe and 4 times more earthworms in the soil at Makoka when organic fertiliser was applied than when inorganic fertiliser was applied. It was only at Bvumbwe where a decrease in soil bulk density was observed. The results have shown that P based application of organic fertilisers can improve/restore soil health in Malawi. However, the results are site-specific, which means more research is needed on the long-term effect of these P based organic fertilisers on soil health and environment and research on area-specific recommendations of these organic fertilisers.

Keywords: Organic fertilisers, phosphorus, human excreta, soil health, Malawi

4.1 Introduction

4.1.1 Background

Uncertainty surrounding the future of phosphorus (P) has triggered researchers to start exploring ways of recapturing P from organic waste materials (household waste, municipal wastewater, livestock manure, etc.) to be used in agriculture as fertiliser. Nutrient recycling is not a new practice in agriculture as incorporating plant residues and applying animal manure to crops have been practised for millennia. The use of human excreta as a fertiliser dates back to ancient times in Britain, China, Greece and, Rome (Buckwell and Nadeu, 2016; Smet and Sudgen, 2006; Shiming, 2002). People are still using human excreta for fertiliser either from composting toilets or wastewater treatment plants, either after composting or in the raw form (Nyirenda and Holm, 2015). The use of organic fertilisers has been strongly connected to improvements in soil health (Acharya & Ghimire, 2019; Khorram et al., 2018; Meena et al., 2019; Parker et al., 2018; Singh et al., 2019)

Soil health is defined as “the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans” (USDA-NRCS, 2012) as reported by Cornell University -Soil Health Laboratory (2016). Soil health is adversely affected by human activities like conventional tillage, continuous cropping, and burning of crop residues, among others leading to loss of soil organic matter, increased soil acidity, reduced water holding capacity, and increased soil erosion. The soil should be managed in a way that does not cause it to lose its main functions (Cornell University, 2016), which include retaining and cycling nutrients, sequestering carbon, and supporting food and feed production, among other functions. Soil health encompasses chemical, physical, and biological aspects of soils, and when assessing it, all three aspects must be included (Gugino et al., 2009).

In different studies when organic fertilisers were used, available P increased ranging from 125% to 1650% and ranging from 27% to 162% (Acharya & Ghimire, 2019; Girma et al., 2019; Liu et al., 2019; Parker et al., 2018; Singh et al., 2019). Adalberto et al., (2018) reported a nearly 90% increase in earthworm numbers after the incorporation of crop residues. Girma et al., (2019) found that the total number of soil bacteria and fungi increased from 1 x 10^7 to 6.5 x 10^7 and from 1 x 10^5 to 3 x 10^5 bacteria/gram of soil after adding compost to the soils. Soil bulk density, water holding capacity, and porosity are some of the physical soil properties that improve upon the application of organic fertilisers (Girma et al., 2019; Parker et al., 2018). Retention of crop residues caused soil bulk density to change from 1.37 Mg/m^3 to 1.27 Mg/$m^{3,}$

and micro-porosity changed from 0.17m^3/m^3 to 0.19m^3/m^3 while water holding capacity increased from 11.5% to 14% upon the application of compost (Girma et al., 2019). In all these studies, the authors attributed the chemical, physical, and biological improvements to nutrients released slowly into the soil as the organic materials are mineralised and the organic matter present in the organic fertiliser

Rickson et al., (2018) recommended that soil depth, soil water retention, soil bulk density, visual soil assessment/evaluation, erosion rate, soil sealing, and soil aggregate stability should be the main soil physical attributes to be evaluated when assessing soil health. Gugino et al (2009) proposed root health, organic matter content, microbial respiration, active carbon content, decomposition rate, and beneficial nematodes population as the parameters to be considered as the biological part of soil health. P, N, K, pH, Mg, Fe, Al, Mn, Zn, Cu, and exchangeable acidity were proposed as the chemical parameters for the evaluation of soil health. The extensive list of proposed parameters indicates how complex soil health is. Although soil health should include chemical, physical, and biological assessments (Gugino et al., 2009; Cornell University-Soil Health Laboratory, 2016), few studies have assessed all of them, and most studies only address on one or two components and not all of the proposed parameters under each component are assessed. The most assessed soil health component is the chemical component, and soil pH, organic carbon, nitrogen, phosphorus, and potassium are the most frequent chemical parameters analysed (Table 4.1).

Table 4.1. Soil health parameters measured in organic material application studies

Organic Material used	**Parameters measured**	**Crop grown**	**Source**
Sugarcane leaves and tops (Brazil)	Bulk density, micro, and macro-porosity, soil resistance to penetration and earthworm count	Sugarcane	Adalberto et al., 2018
Cow manure (New Mexico, USA)	Soil organic carbon. Total N, available P, K, Ca, Mg, S, pH, EC, and CEC	Sorghum	Acharya & Ghimire, 2019
Organic market waste (Italy)	pH, organic carbon, available P, heavy metals (Pb, Zn, etc.)	*Brassica carinata* A. (Braun)	Debiase et al., 2018
Crop residues and animal manure compost (China)	P, pH, total carbon, total N, organic matter, maize root length, and fungal mycorrhiza	Maize	Liu et al., 2019
Farmyard manure and crop residues (India)	Bulky density, total N, P, K, S, and Zn	Rice and wheat	Singh et al., 2019
Raw/composted cow manure (Texas, USA)	N, P, K, Zn, EC, pH, organic carbon	Corn	Parker et al., 2018
Agro-organic waste compost (Ethiopia)	pH, EC, N, P, K, Ca, Na, Mg, bacterial biomass, fungal numbers, and water holding capacity.	Onion	Girma et al., 2019
Hardwood chips and vegetable waste (Iran)	Bulky density, total N, P, K, CE, organic carbon, and water holding capacity	Apple	Khorram et al., 2018
Vermicompost, farmyard manure, and leaf compost (India)	N, P, K, organic carbon, bulk density, bacteria, and fungi	Corn and potato	Meena, 2019
Sewage sludge compost (India)	Organic carbon, N, P, K	Rice	Gosal et al., 2018

Although much has been written on the benefits of organic fertilisers to soil health, the organic fertiliser application rates were rarely based on P requirements of the crops, which means even the amount of the organic fertilisers applied per unit area should be different. The majority of the studies based the application rates on the nitrogen content of the organic fertiliser, while some just followed the farmers' practices (Acharya & Ghimire, 2019; Debiase et al., 2018; Girma et al., 2019; Gosal et al., 2018; Khorram et al., 2018; Liu et al., 2019; Meena et al., 2019) and the few that use P as the basis for organic fertiliser application rates just evaluated the chemical component of soil health (Parker et al., 2018; Singh et al., 2019) leaving out two other aspects (biological and physical components). It is also evident that few studies have assessed the impact of faecal-based organic fertilisers on soil health as most of the assessed the crop quality and performance (Moya et al, 2017; Torgbo et al, 2018)

4.1.2 Visual soil assessment (VSA)

The chemical component (N, P, K, pH, etc.) of soil health is primarily determined in the laboratory using methodologies and protocols which are sometimes technologically advanced and chemically intensive. On the other hand, some of the biological and physical soil health components can be determined in the field using VSA (Ball et al., 2012; Houšková, 2007; Shepherd et al., 2008). Properties like soil structure, soil texture, earthworm counts, and soil porosity can be determined by VSA, a simple procedure to assess a soil's response to management or use (Shepherd et al., 2008). Studies have proved that VSA results of parameters like root count, rooting depth, and soil structure correlate well with results got from using standard field or lab measurements (Leeuwen et al., 2018)

According to Shepherd et al., (2008) and Väderstad (2016), soil structure is classified based on the size, shape, firmness, porosity, and abundance of soil aggregates and clods. The soil structure score ranges from 0 to 2, with 0 being "poor condition" and 2 being "good condition". A soil dominated with friable and fine aggregates with sub-round clods and often porous is given a score of 2, while a soil dominated with sub angular/angular coarse clods with few fine aggregates is given a 0 score. Ball et al., (2012) developed a scale of 1 to 5 for visual soil structure assessment. The score of 1, termed structure quality 1 (sq1), corresponds to friable soils, while sq 5 is for very compacted soils. Similarly, to Shepherd et al., (2008) and Väderstad (2016), Ball et al., (2012) based structure their quality assessment on the size, shape, firmness, and the porosity of the soil aggregates. When the soil shows properties of two different structural qualities, e.g., sq1 and sq2, a 1.5 sq can be used (Ball et al., 2012; Shepherd et al., 2008).

Just like soil structure, Shepherd et al., (2008) gave a score of 0 to 2 for soil texture, porosity, and earthworm count, with 0 being “poor” and 2 being “good”. Sand is a poor soil structure (score=0); it is gritty and cannot be moulded into a ball, while an example of soil with a good structure (score = 2) would be silt loam. The scores for earthworm counts correspond to the number and species abundance in a 20 cm cube of soil. The 0 score is for less than 15 earthworms dominated by one species, 1 stands for 15 to 30 earthworms with two or more species, and above 30 earthworms, its score is 2. Amongst the soil health parameters, soil structure is the one that is most commonly assessed using a visual soil structure assessment (VSSA) tool (Leeuwen et al., 2018; Sadegh et al., 2013).

4.1.3 Soil health efforts in Malawi

The need to feed the growing population in Malawi has put pressure on soils to produce more food. However, soil fertility has declined in Malawi (Njoloma et al., 2016). Continuous cropping without rotation, burning of crop residues, and application of acidifying fertilisers has resulted in soil fertility decline (Snapp, 1998). Still, farmers must apply fertiliser to achieve an adequate harvest. However, the over-reliance on inorganic fertiliser has promoted acidification of the soil which further reduces the soil’s capacity to supply essential nutrients for plant growth (Omuto & Ronald, 2018). Several authors have reported on soil degradation in Malawi. Soils in Malawi have low levels of available P, nitrogen, organic matter and pH (Maida, 2013; Njoloma et al., 2016; Snapp, 1998), among other paraments. In addition, there is almost 20 tonne/ha of (Omuto & Ronald, 2018) soil removed every year by soil erosion. Most people in Malawi depend on agriculture for their well-being. It is against this background that efforts to restore soil health in Malawi got its momentum.

The term soil health became common in Malawi around 2010 when the Soil Health Consortium of Malawi (SoHCoM) was formed. SoHCoM was created by Lilongwe University of Agriculture and Natural Resources, Ministry of Agriculture and other organisations involved in the agricultural sector. SoHCoM aimed to restore soil fertility and reduce soil degradation through Integrated Soil Fertility Management (ISFM). The SoHCoM projected that agricultural productivity would improve by 15 percent by the year 2050 through ISFM, which would address poor and declining soil fertility in Malawi. Some of the consortium projects include compost and manure, intercropping of legumes and cereals, crop rotation, and conservation agriculture (CA) (SoHCoM, 2013). The legume-cereal (maize) intercropping system and compost use projects dominated the ISFM under the SoHCoM and the work funded by McKnight Foundation. The projects aimed at increasing maize yield through the biological nitrogen fixation from the legumes and also the incorporation of leaf biomass from the legumes and compost application in combination with inorganic nitrogen (Kalasa et al., 2018; Ngwira et al., 2012; Njira et al., 2013; Njira et al., 2012).

However, the formation of SoHCoM was not the genesis of the efforts to restore or maintain the soil health status of soils in Malawi. CA was practised and promoted before the formation of the consortium. Some of the benefits of CA include an increase in soil organic matter, improved soil water retention, improved soil biology, among others which are the attributes of soil health. A literature review shows that research on CA in Malawi focused on crop yield rather than soil (Ngwira et al., 2012; Ngwira et al., 2013; Nyagumbo et al., 2016; Steward et al., 2019; TerAvest et al., 2019). Ngwira et al., (2013) used the term soil quality when assessing the effects of CA on soil organic carbon, water infiltration, soil aggregate stability, and below-ground fauna after five years of CA. Mloza-Banda, Makwiza, & Mloza-Banda, (2016) assessed physical (bulk density, soil texture, and stable aggregates) and chemical (pH, NPK, CEC, SOC) properties after two and five years under CA. The legume-legume intercrop (double up legume) followed by maize applied with a reduced dose of inorganic nitrogen or compost resulted in increased maize yield compared to maize yield from plots that previously were not grown with legumes (Kalasa et al., 2018; Njira et al., 2012, 2013). Although increased maize yield indicates improvement in soil health, no other changes in the chemical, physical or biological aspect was assessed apart from the nitrogen fixed in different legume-legume intercrops (Njira et al., 2012, 2013). Kalasa et al., (2018) also evaluated the changes in soil chemical properties in two locations affected by legume technologies but only one location showed improvement in soil pH, SOC, and available phosphorus. These experiments were conducted over one growing season, which is not enough to notice changes in soil parameters as most changes are seen after 3 years (Clark et al,., 1998) and also observed by Ngwira, et al., (2013), Mloza-Banda et al., (2016), Ngwira et al., (2012; 2013), Steward et al., (2019).

Although the efforts to restore, improve or maintain soil health through legume-cereal intercropping, compost, manure, and CA in Malawi have shown improvement. No previous study assessed parameters in all the three components of soil health and no faecal sludge or organic market waste compost was used. Therefore, the use of organic P sources (organic waste and faecal sludge) offers an opportunity to improve soil health. Elsewhere, organic fertiliser has resulted in improvements in soil health, but those previous studies were not done in the context of sustainable P management with emphasis on recycling of solid organic waste materials. Even the organic fertiliser application was not P based; most of the application rates were based on nitrogen content. There is low nitrogen content in organic fertilisers compared to P content, which means P based application will result in less quantities of organic fertiliser applied than nitrogen-based application.

Furthermore, as world struggle to produce more food for a growing population, maintaining and improving soil health should be a priority; only a healthy soil can produce more food sustainably. However, application of organic fertilisers based on P maize requirement may result in reduced amounts of organic materials applied compared to application rates based on N maize requirement. Only a few studies assessed the maize yield response to P-based application of faecal and organic market waste and their effect on soil health. Therefore, this project evaluates field scale evidence of the effects of organic P sources derived from market waste and faecal sludge on soil health in Malawi. It was hypothesised that maize yield would not reduce significantly if organic fertilisers were applied based on P application rates, P based application of organic fertilisers would improve soil health, and improved soil health parameters would positively influence maize yield.

4.2 Materials and methodology

4.2.1 Sites

The field experiments were conducted at Bvumbwe (Figure 4.1) (15.9233° S, 35.0709° E) and Makoka (Figure 4.2) (15°31'10.1"S 35°13'20.7"E) agricultural research stations in Thyolo and Zomba districts, respectively, during the 2019/2020 and 2020/2021 growing seasons. These two research stations belong to the Department of Agricultural Research Services under the Ministry of Agriculture, Irrigation and Water Development.

Although both Bvumbwe and Makoka research stations have acidic dark red Lixisols (Dijkshoorn et al*.,* 2016), Makoka soils are dominated by sandy loam soils with patches of heavy clays. On average, Makoka temperature ranges from 15.6 to 25 degrees Celsius, receives 1,044 mm of rainfall annually and is located at an altitude of 1,029 m above sea level. On the other hand, Bvumbwe gets 1,219 mm of rain annually, and the soils are primarily sandy clay. Bvumbwe is located at the southern end of the Blantyre escarpment between 1,228 and 1,174 m above sea level (http://www.sdnp.org.mw/darts/research/index.htm retrived on 3/1/2019). Maize was the test crop at both stations.

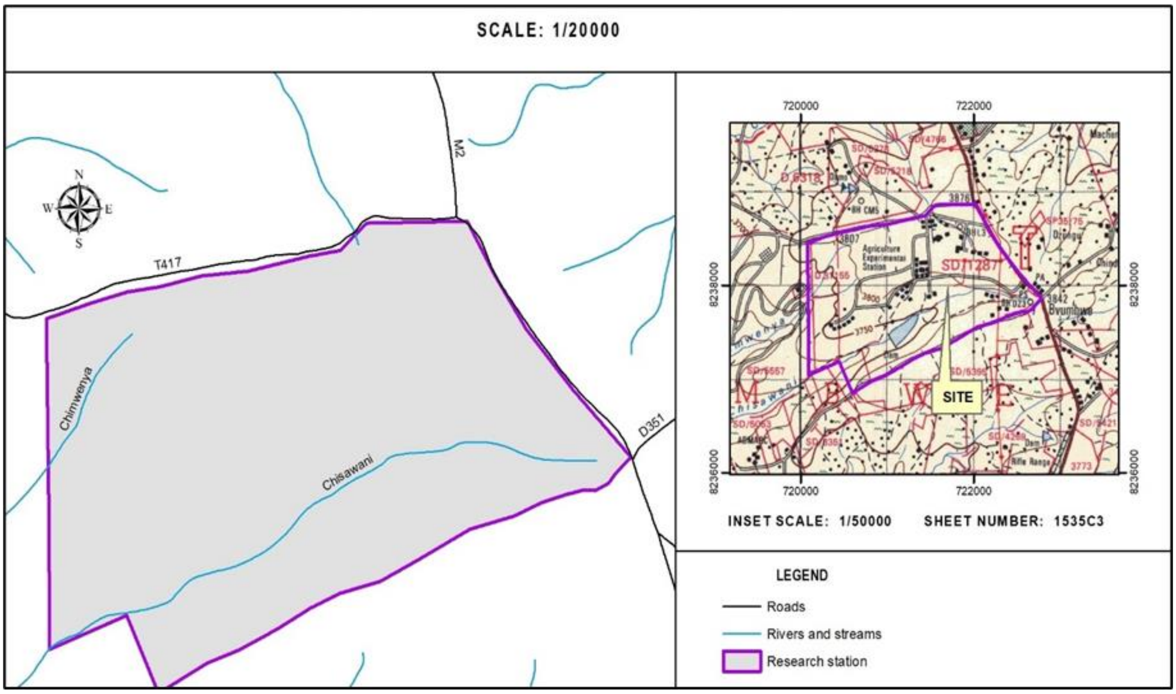


Figure 4.1. Bvumbwe research station in Thyolo district

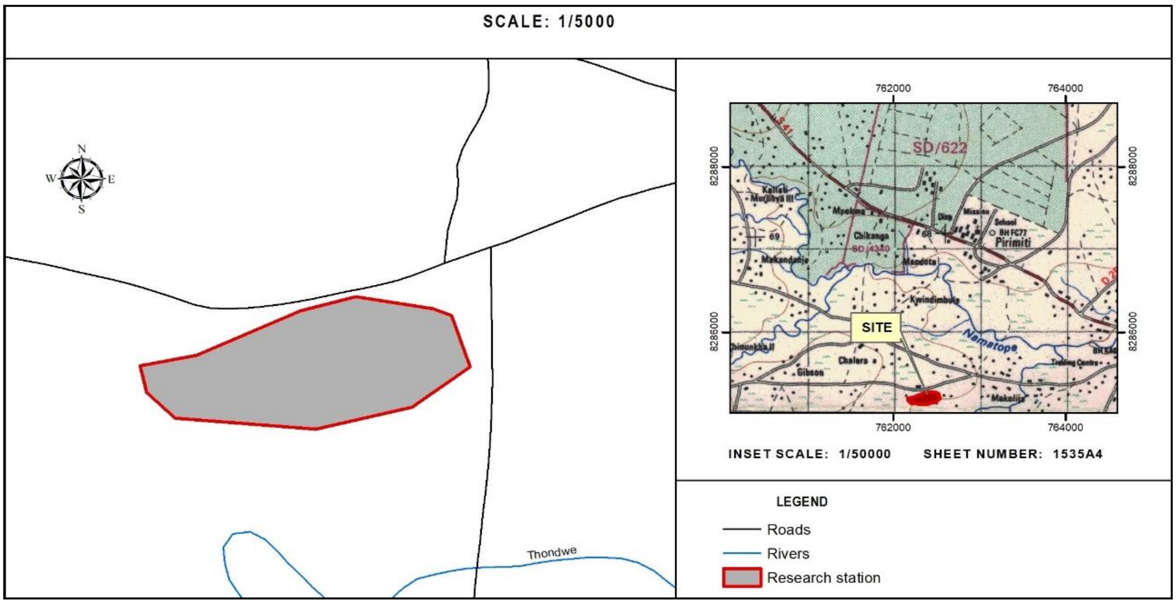


Figure 4.2. Makoka research station in Zomba district

4.2.2 Experimental design and management

The experiments were designed using a 5x4 factorial approach: five P sources, each with 4 levels (application rates), laid out in a complete randomised block design with four replicates. The treatments were market waste compost (MW), faecal sludge-market waste compost (FSMW), market waste + NPK fertilizer (MW+NPK), faecal sludge-market compost + NPK (FSMW+NPK) and NPK fertiliser, each with four application rates (0, 15, 30 and 45 kg P/ha) based on total P in the organic fertilisers. The experiment was established on land which was on fallow for three years. The fields were ploughed and ridged before plots were demarcated. The treatment plots contained 3 ridges, each 6 m long and spaced 0.75 m apart (3 x 6 m x 0.75 m); planting stations were 0.75 m apart with three maize plants per planting station. The recycled P materials were placed on the planting stations manually and mixed with soil to a depth of 20 cm one month before planting. The crop was grown under a rainfed system, and to make sure that nitrogen was not a limiting nutrient, a recommended rate of 92 kg N per hectare was applied. All crop husbandry practices (weeding, disease control, etc.) were followed so that the only source of variation would be from the P treatments.

4.2.3 Soil and compost characterisation

Before starting the experiments, soil samples were collected from both sites using a random zigzag pattern at a constant depth of 0 -20 cm for chemical and physical analysis (Table 4.2). The field was divided into four blocks (replicates), and from each block, 4 composite soil samples were collected, air-dried, and passed through a 2 mm sieve. Compost samples were also collected, milled, and sieved before analysis (Table 4.3). The following chemical and physical properties were determined: pH (Blakemore et al., 1987), soil texture (Ashworth et al., 2007), organic carbon (GLOSOLAN, 2019), total P (Murphy & Riley, 1962; Okalebo et al., 2002), available P using a Mehlich 3 solution (Murphy & Riley, 1962). The metal (Fe, Al, Cd, etc) concentration were analysed after Aqua regia digestion and read on Inductively Coupled Plasma Mass Spectrometry (ICP-MS)Table 4.2. Chemical characteristics of the faecal sludge-market waste and market waste compost

Parameter	Market waste-faecal sludge compost	Market waste compost
$pH_{(water)}$	7.20 ± 0.07	8.82 ± 0.09
Organic matter (%)	14.86 ± 0.87	13.17 ± 1.23
Total P(mg/kg)	4906.76 ± 384.80	3522.22 ± 430.10
Available P(mg/kg)	132.69 ± 9.85	113.68 ± 7.62
Ca (g/kg)	11.60 ±0.46	15.20 ± 2.49
K (g/kg)	4.64 ± 0.62	5.24 ±0.61
Mg (g/kg)	4.21 ±0.52	3.80 ±0.18

The numbers after ± are standard errors

Table 4.3. Chemical and physical properties of soils at Bvumbwe and Makoka research stations

Parameter	Makoka	Bvumbwe
Available P (mg/kg)	23.86 ±4.20	15.92 ±3.35
pH(water)	4.97±0.12	4.73 ±0.35
Al (g/kg)	43.66 ±4.48	68.45 ±5.44
Fe (g/kg)	43.5 ±10.80	81.81 ±4.72

Organic matter (%)	0.92 ±0.11	1.17± 0.06
Ca (mg/kg)	597.97 ±112.0	545.45 ±81.23
K (mg/kg)	692.94 ±155.5	659.18 ±65.67
Mg (mg/kg)	930.52 ±88.64	1002.49 ±111.3
Silt (%)	7.33 ±1.03	10.00 ±1.27
Clay (%)	21.33 ±3.72	42.00 ±2.83
Sand (%)	71.30 ±3.27	48.00 ±3.35

The numbers after ± are standard errors

4.2.4 Soil health assessment

Soil bulk density, pH, earthworm count, and organic matter were assessed. Soil pH, and organic matter were analysed as explained in the soil characterisation section. Soil bulk density was determined by collecting undisturbed soil samples at 0 – 10 cm depth using cores of known volume. The weights of the cores were taken before soil sampling, and after sampling, they were put in the oven for 48 hrs at 105 degrees Celsius. Then the final weights were used to calculate the bulk density (g/cm$^{3)}$ (Adalberto et al., 2018; Meena et al., 2019; Singh et al., 2019).

Earthworm count was determined using visual soil assessment methods by Ball et al., (2012), Väderstad Ltd (2016) and Shepherd et al (2008). A 20 cm cube of soil was taken from every treatment plot using a spade and transferred to a plastic sheet. The block was broken up, and the earthworms were counted, recorded, and reported.

Soil health has three components, that is chemical, physical and biological. Due to the complexity of soil health, there is no single measurement to be used as an indicator of soil health. The variables chosen in this study represent the chemical (e.g. pH), biological (e.g. earthworm abundance) and physical (e.g., bulk density) components of soil health. Soil pH controls nutrient availability and microbial activity in the soil, while bulk density is an indicator of soil compaction, which affect air and water and plant root movement in the soil and soil erosion. On the other hand, soil organic matter influences soil water holding capacity, soil erodibility, and nutrient supply. Earthworms are considered to be an indicator of healthy soil. The work of earthworms affects water, air, plant roots movement in the soil, decomposition of organic compounds, and nutrient recycling, among others. Therefore, the parameters chosen are important indicators of soil health. The methodologies used in assessing the parameters are widely used (Ball et al., 2012; Väderstad Ltd, 2016; Shepherd et al., 2008; Adalberto et al., 2018; Meena et al., 2019; Singh et al., 2019).The results were analysed using One-way and Two-way ANOVA. Two-way ANOVA was used to assess the effects of P sources and application rates on the tested parameters. One-way ANOVA was used to evaluate the impact of the application rates of each individual P source on the tested parameters. Also, note that when comparing application rates, 0 kg P/ha is the control. Whenever the means were different, they were separated using Fisher's protected LSD. All the analyses were run using Genstat statistical software 20th edition.

4.3 Results and discussion

4.3.1 Effects of some of the soil health parameters on maize yield

A regression analysis was performed to understand the contribution of site, season (time), earthworms, soil pH, soil organic matter to maize yield after two seasons of organic fertiliser application in two locations. Soil pH, Earthworms, and organic matter are indicators of soil health. The results (Table 4.4) showed that the organic matter, soil pH, earthworms, and season all positively contributed to maize yield. On the season, it means that maize yield will likely improve as the application of organic fertiliser continues. It is important to note that the results are site-specific. Makoka site was not responding in the same way as Bvumbwe. This could be due to initial soil conditions when the project started and the areas' local environmental conditions.

Earthworms, pH, and organic matter affect other soil properties like nutrients availability, water infiltration, water holding capacity, aeration, and microbial activities in the soil, thereby improving the productivity of the maize.

Table 4.4. regression analysis results of some soil health parameters with maize yield.

Parameters	**Coefficients**
Intercept	-1430
	(773)
Site (Makoka)	-1946**
	(242)
Season (second season)	325*

	(141)
Earthworms (numbers/m^2)	2*
	(1)
pH	821**
	(169)
OM (%)	661*
	(239)

**p- value < 0.001, *p- value < 0.05. The figures in parenthesis are standard errors

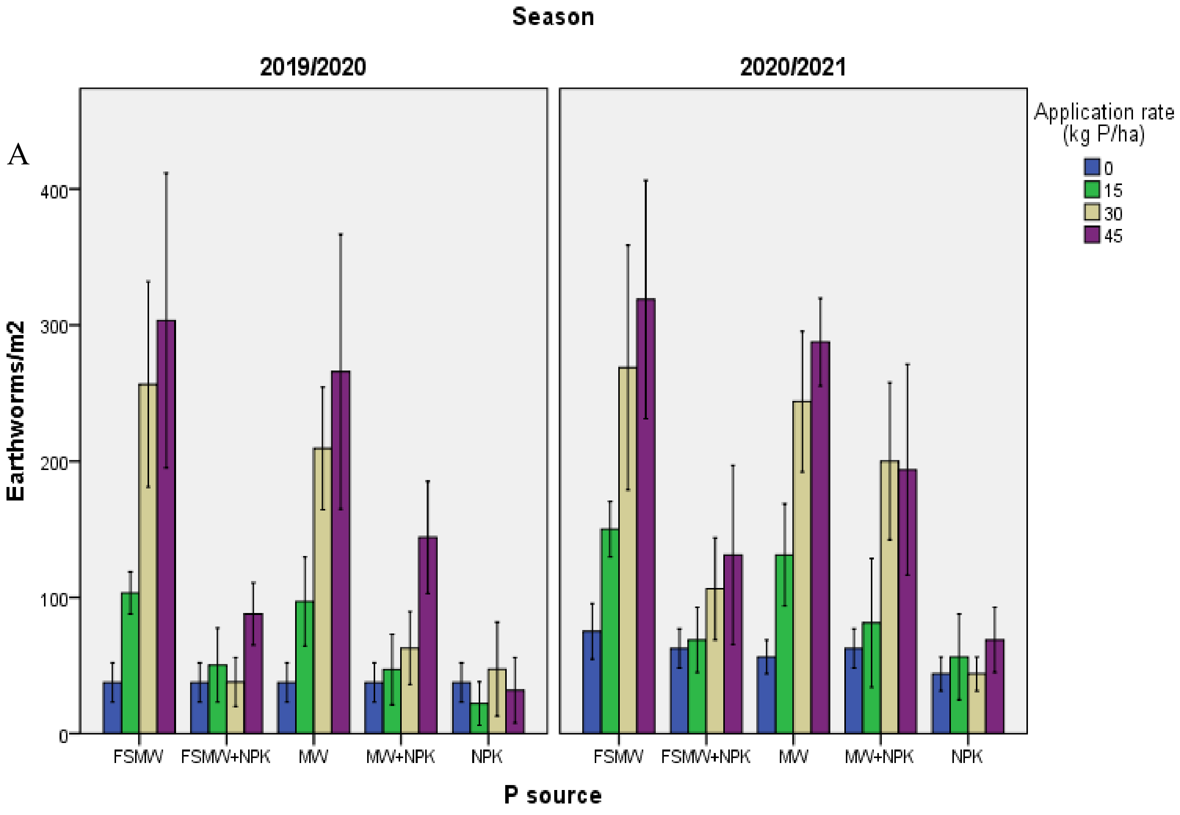
Further analysis was conducted to understand the contribution of organic fertilisers to soil health parameters compared to inorganic fertilisers.

4.3.2 Effects of P sources on earthworm abundance in the soil

At Bvumbwe field (Figure 4.3), P source affected the earthworm numbers in the soil significantly (p-value < 0.05) in both growing seasons. In both seasons, NPK had the significantly lowest numbers of earthworms of 34 earthworms/m^{-2} in the first season and 53 earthworm/m^{-2} in the second season. In the first season, MW+NPK had 72 and FSMW+NPK had 53 earthworms/m$^{-2,}$ which were statistically not different but different from the NPK. In the second season, MW+NPK produced more earthworms (134) compared to FSMW+NPK (92). In both seasons, MW and FSMW recorded the highest numbers of earthworms. In the first season, MW had 152 and 179 earthworm/m^2 in the second season, while FSMW had 175 in the first season and 203 earthworms/m^2 in the second season.

The application rate of some P sources also affected the presence of earthworms in the soil. During both growing seasons, application rates did not affect the earthworm numbers in NPK treatments; all application rates recorded equal numbers of earthworms. On the other hand, MW, FSMW, NPK+MW, and NPK+FSMW application rates affected the earthworm numbers in the soils. In the FSMW treatment, 45 kg P/ha had 303 earthworms/m^{2,} and 30 kg P/ha application had 256 earthworms/m^{2,} significantly different from 103 earthworms/m^2 from 15 kg P/ha and 37 earthworms/m^2 from 0 kg P/ha. The MW treatment, 45 kg P/ha, had 265 earthworms/m2 and 30 kg P/ha application with 209 earthworms/m^2, which were significantly different from 96 earthworms/m^2 from 15 kg P/ha and 37 earthworms/m^2 from 0 kg P/ha. On the other hand, FSMW+NPK and MW+NPK, only 45 kg/ha, had significantly more earthworms than the other application rates. It was 87 earthworms/m^2 in FSMW+NPK and 143 earthworms/m^2 in MW+NPK

In the 2020/2021 growing season, FSMW produced the results like the previous year, but MW, MW+NPK, and FSMW+NPK had different results. In MW, 0 kg P/ha application recorded the lowest number of earthworms, which were 56/m2, followed by a 15 kg P/ha application rate with 131 earthworms/m^2. The 30 and 45 kg P/ha had the same highest number of earthworms which were 243/m^2 and 287/m^{2,} respectively and were different to the rest of the application rates in MW. In MW+NPK, 0 kg P/ha had 62 earthworms/m^2 and 15 had 81 earthworms/m^2; these were not significantly different but were lower than the earthworms recorded in 30 kg P/ha (192 earworms/m^2) and 45 kg P/ha (200 earthworms/m^2). Unlike in the previous season, application rates did not affect the earthworm numbers in FSMW+NPK in the 2020/2021 season



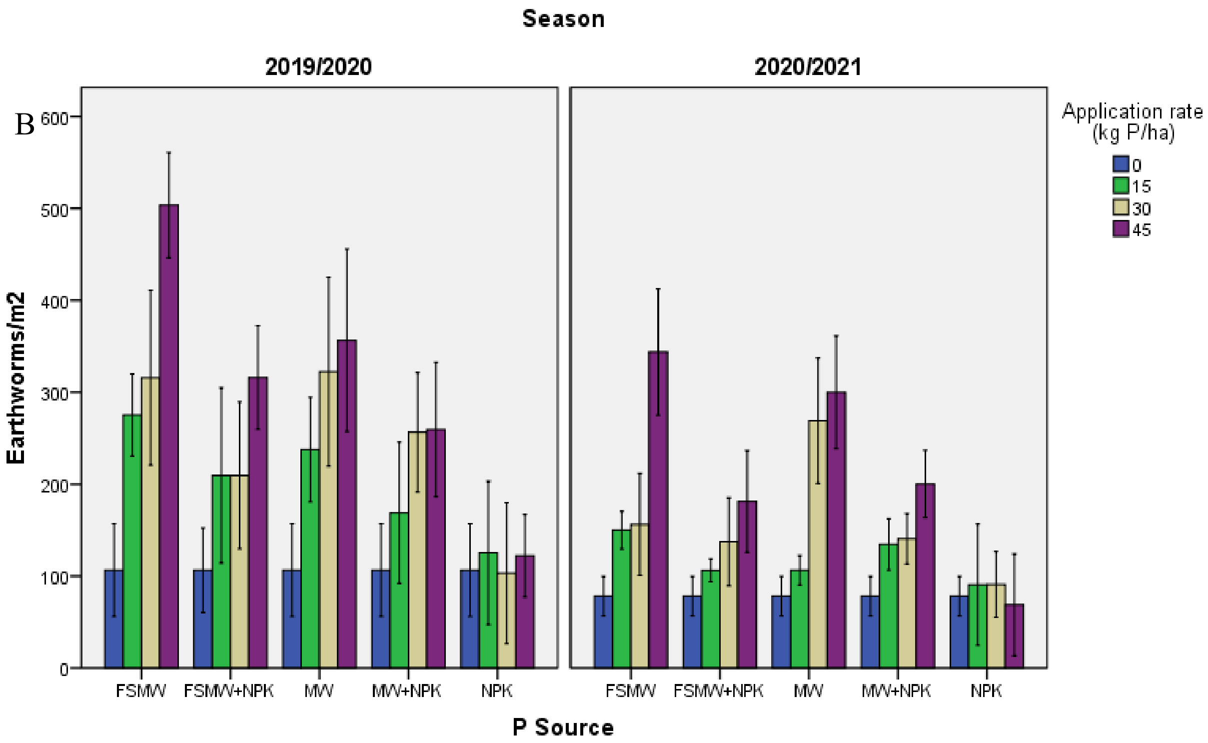


Figure 4.3. Earthworms abundance at Bvumbwe (A) and Makoka (B) research stations as affected by organic P sources. The whiskers on the bar graphs indicate standard error.

At Makoka field (Figure 4.3), just like at Bvumbwe P source affected (P-value < 0.001) the presence of earthworms in the soil in both seasons. The NPK treatment recorded the lesser number of earthworms, 114 earthworms/m^2 in the first season and 82 earthworms/m^2 in the second season. MW+NPK had 197 in the first season and 137 earthworms/m^2 in the second season. FSMW+NPK had 210 in the first season and 137 in the second season. Statistically, MW+NPK and FSMW+NPK recorded the same numbers of earthworms in both seasons. MW and FSMW treatments also recorded the same numbers of earthworms in both seasons, which were the highest of all the P sources. In the first season, MW had 255 earthworms/m^{2,} and FSMW had 300 earthworms/m^2. In the second season, FSMW had 194 earthworms/m^{2,} and MW had 196 earthworms/m^2.

Similar to Bvumbwe results, at Makoka, NPK application rates did not affect earthworm numbers in both seasons. On the contrary, in both seasons, FSMW and MW application rates influenced (p-value <0.001) the earthworm numbers, in the same way, FSMW, 0 kg P/ha gave 102 earthworms/m^2 in the first season and 87 earthworms/m^2 in the second season. The 15 kg/ha and 30 kg P/ha had the same numbers of earthworms in both seasons. In the first season, 15 kg P/ha had 275 earthworms/m^{2,} and 30 kg P/ha had 315 earthworms/m^2. In the second season, they were 158 and 167 earthworms/m^{2}respectively. The 45 P/ha had the highest number of earthworms. In the first season, there were 501 earthworms/m^2 and 366 in the second season. In MW treatments, 30 kg P/ha recorded 321 earthworms/m^2 in the first season and 283 earthworms/m^2 in the second, and 45 kg P/ha recorded 356 earthworms/m^2 in the first season and 308 earthworms/m^{2,} which were higher than earthworms from 0 and 15 kg P/ha. The 0 and 15 kg P/ha recorded the same numbers of earthworms.

In the first season, FSMW+NPK, 0, 15, and 30 kg P/ha had 106, 209, and 209 earthworms/m^2, respectively were lower than earthworms from 45 kg p/ha (315 earthworms/m^2). In the second season, it was 0 and 15 kg P/ha that produced the lowest (87 and 108 earthworms/m^2) numbers while 45 kg P/ha recorded 200 earthworms/m^{2,} which was highest, followed by 30 kg P/ha which had 150 earthworms/m^2. The MW+NPK treatment in the first season, 0 and 15 kg P/ha recorded 106 and 168 earthworms/m^{2,} respectively lower number than 30 and 45 kg P/ha which recorded 256 and 259 earthworms/m^2 respectively, but in the second season, the 15 and 30 kg P/ha recorded the same number of earthworms (129 and 145 earthworms/m^2) which were higher than the 0 kg P/ha (87 earthworms/m^2). The 45 kg P/ha recorded the highest number of earthworms which was 183 earthworms/m^2.

The results showed the importance of organic P fertilisers to soil health concerning earthworm abundance. Unlike the NPK, which only supply P for crop's use, organic P fertilisers, in addition to supplying P, also add organic matter to the soil. It is the added organic matter that supports the presence of earthworms in the soil. The results corroborate with the finding of (Adalberto et al., 2018; Fonte & Six, 2009; Madar´asz et al., 2021), which recorded more earthworms in soils with higher organic matter content than in soils with lower organic matter.

However, when inorganic fertiliser is mixed with organic fertiliser (1:1) there are fewer earthworms than just applying the organic P fertilisers alone. When organic fertiliser is mixed with inorganic fertiliser, the amount of organic matter that comes together with the P is reduced, thereby reducing the substrate for earthworms. The earthworms utilise the carbon in the organic matter for growth and reproduction. Earthworms are essential to soil health. As they move in the soil, they create temporary and permanent burrows, thereby improving water infiltration, aeration, and water holding capacity of the soil and root growth too. Earthworms also stimulate microbial activities in the soil by shredding organic residues into smaller parts and inoculating microbes as the organic matter passes through the intestines, promoting nutrient recycling.

The results also showed the site and accumulative effect of the performance of the organic fertilisers. In the first season, 15 kg P/ha FSMW at Bvumbwe recorded results similar to the control, but at Makoka, it recorded more earthworms than the control. Also, 30 kg P/ha MW+NPK in the first season at Bvumbwe performed the same as control, but at Makoka, it performed better than the control. On accumulative effect, in the first season, 15 kg P/ha MW at Bvumbwe, 30 FSMW+NPK, and 15 MW+NPK at Makoka did not outperform the control in the first season, but in the second season, these treatments recorded more earthworms than the control. This suggests that after two applications of the organic P fertilisers, these treatments accumulated more organic matter that was able to support more earthworms.

4.3.3 Effects of P sources on soil bulk density

The soil bulk density (Figure 4.4) was measured in the second year of the study, and only the 45 kg P/ha treatment was assessed. The 45 kg P/ha treatment level was chosen at this level the treatment effect was most likely to be seen. At Makoka, the P sources did not affect soil bulk density. It was at Bvumbwe that P sources had an impact on soil bulk density. The MW treatment had the lowest bulk density of 1.064 g/cm^3. Singh et al., (2019), Khorram et al., (2018), Meena, (2019) also observed decreased bulk density after organic fertiliser application. The decrease in bulk decrease was attributed to increased organic matter, which has lower particle density itself and prevents close soil packing. The organic matter also improves aeration and improved soil aggregation thereby impacting on soil bulk density. Although all the P sources had the same level of P only MW affected the soil bulk density and Bvumbwe. MW had lowest P content amongst the P sources, meaning more organic materials were applied to match the application rates of other P sources. Therefore, if the organic P source has lower P content it would require large volume of it to be applied to meet P plant requirement, affecting soil health faster than an organic P source with higher P concentration..

Although MW at Bvumbwe improved the soil bulk density, at Makoka it did not affect bulk density. This can be attributed to the fact that the organic matter accumulation in the soil was insufficient to bring about changes to the soils' bulk density. The soil at Makoka had a lower base organic matter content (Table 4.3). In addition to lower base organic matter content, the soil at Makoka had higher sand content, encouraging organic matter degradation and limiting building up. Clark et al., (1998), Ngwira et al., (2012), Ngwira et al., (2013), Steward et al., (2019) and Mloza-Banda et al., (2016) reported that changes in some soil properties are likely to be noticed after 3 to 5 years of organic fertilisers application. It is also worth noting that

MW+NPK and FSMW+NPK add half the amount of organic matter that MW and FSMW treatments add to the soil, which means their effects are likely to take longer than that of MW and FSMW.

Although the effect was only observed in MW and at Bvumbwe only, continued application of the organic fertiliser still will lead to improvement of soil bulky density. Healthy soils have an ideal soil density for crop productivity. Bulk density is an indicator of soil compaction. The application of organic fertiliser makes the soil less compacted, allowing easy water infiltration, easy aeration, root growth, more water holding capacity, and increased microbial activities in the soil.

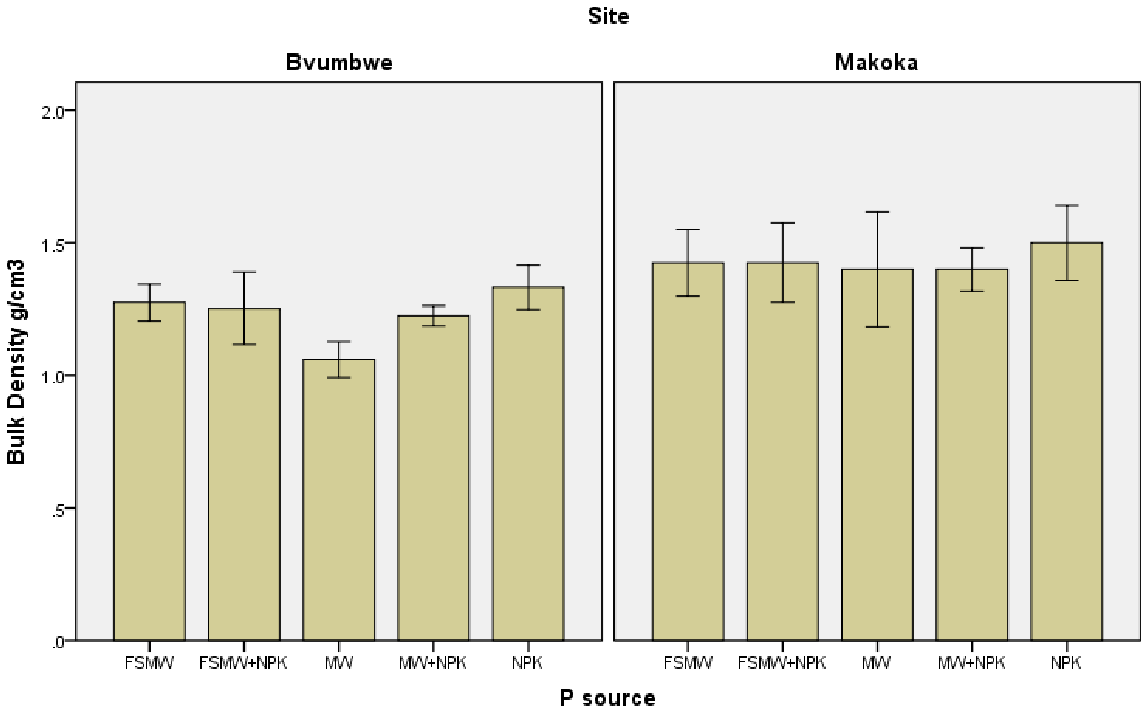


Figure 4.4. Soil bulk density at Bvumbwe (A) and Makoka (B) research stations as affected by organic P sources. The whiskers on the bar graphs indicate standard error.

4.3.4 Effects of P sources on soil pH

The soil pH at Bvumbwe was affected by both the P source and the application rates (Figure 4.5). In both seasons, NPK had the lowest pH values of 4.67 in the first season and 4.92 in the second season. In 2019/2020 season, MW+NPK had 4.98 pH, and FSMW+NPK had 4.95 pH, which was higher (p-value < 0.001) pH values than pH values from NPK. On the other hand, MW recorded 5.23 pH and FSM recorded 5.12 pH, which was the highest pH value. In the 2020/2021 season, MW+NPK, FSMW+NPK, MW, and FSMW all had the same pH values, which were higher (p-value < 0.001) than pH values found from NPK treatment was 4.92.

Although application rates affected the soil pH, it was only organic fertiliser application rates that affected pH. In both seasons, NPK application rates did not affect pH values. The 15, 30, and 45 kg P/ha recorded the same pH values as the 0 kg P/ha application rate. The FSMW treatment, in the first season, the 0 and 15 kg P/ha had the same pH of 4.73 and 4.99 respectively followed by 30 kg P/ha with pH 5.12 and then 45 kg P/ha application rates with pH 5.65 which was highest (p-value < 0.001) almost all the application rates. During the second season, the 15 kg P/ha had pH of 5.55, 30 kg P/ha had pH of 5.45, and 45 kg P/ha had pH of 5.60 which were statistically the same but higher (p-value <0.001) than the pH 4.80 from 0 kg P/ha application rate.

In the MW treatment, in the first season, the 0 kg P/ha had pH 4.73, and 15 kg P/ha had pH 5.07, which were lower (p-value < 0.001) than the pH 5.43 recorded in 30 kg P/ha and pH 5.67 recorded in 45 kg P/ha application rates. During the second season, the 0 kg P/ha had pH 4.80 and 15 kg P/ha had pH 5.31 lower (p-value < 0.001) than the pH 5.68 recorded in 30 kg P/ha and pH 5.85 recorded in 45 kg P/ha application rates. The 0 kg P/ha of FSMW+NPK recorded 4.733 pH in the first season, which was lower than pH values 4.97 from 15 kg P/ha, 5.04 from 30 kg P/ha and 5.07 from 40 kg P/ha. Again, in the second season, the 0 kg P/ha had the lowest pH of 4.80 while 15 kg P/ha had pH of 5.28, 30 kg P/ha had pH of 5.38, and 40 kg P/ha had a pH of 5.51. The MW+NPK, in 2091/2020 season 0 and 15 kg P/ha application rate had the same lower pH of 4.73 and 4.81 respectively (p-value < 0.001) than pH values 5.03 from 30 kg P/ha and pH 5.37 from 45 kg P/ha which were also the same. In the second season, only the 0 kg P/ha had the lower pH values of 4.80 than the rest of the application rates.

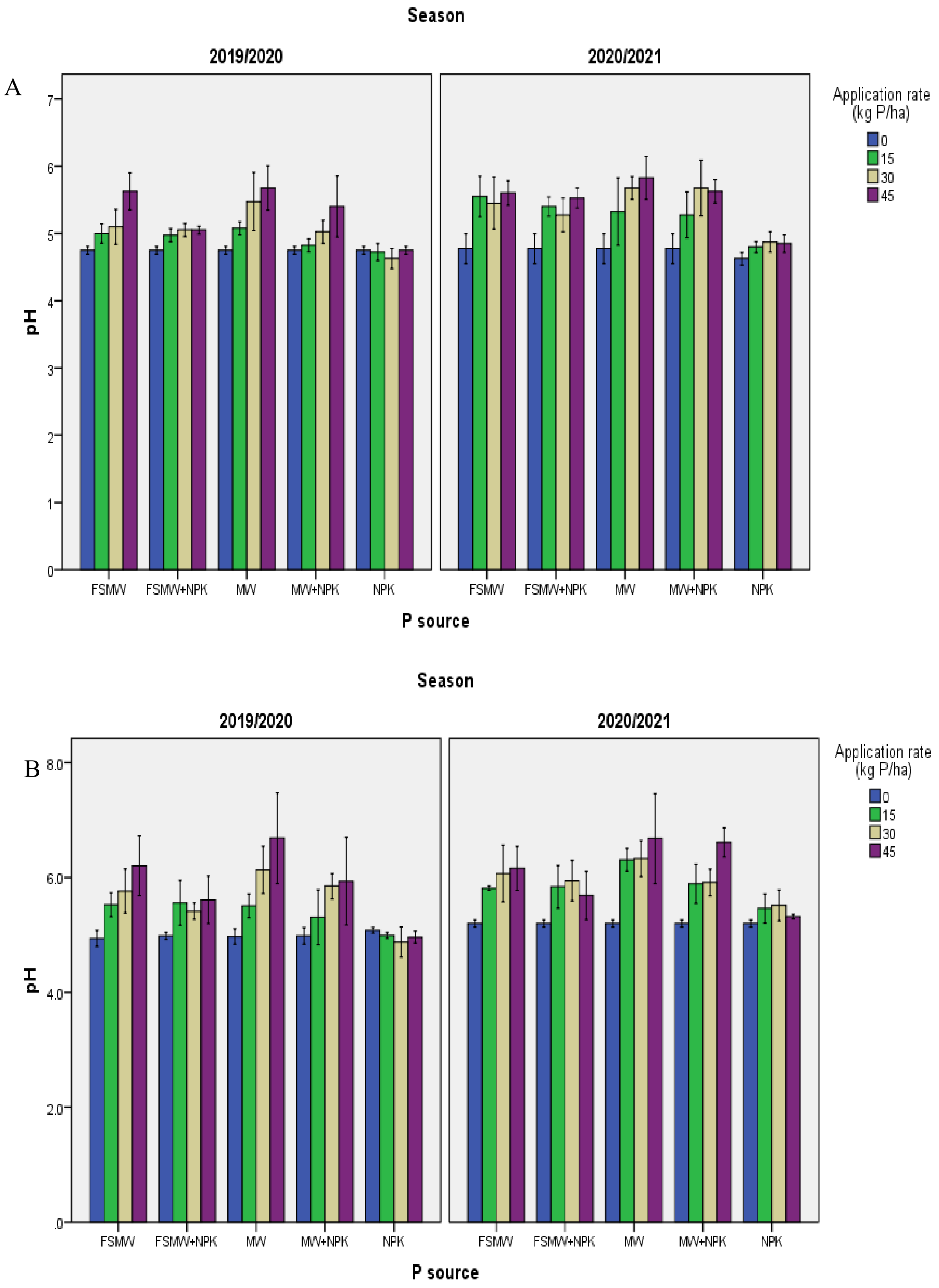


Figure 4.5. Soil pH at Bvumbwe (A) and Makoka (B) research stations as affected by organic P sources. The whiskers on the bar graphs indicate standard error

Just like at Bvumbwe, at Makoka, the soil pH was also affected by P source and application rates too (Figure 4.5). In both seasons, NPK treatment had the lowest pH values, 4.95 in the first season and 5.37 in the second season. In the 2019/2020 season, MW+NPK had pH 5.52 and FSMW+NPK had pH 5.39, which were statistically the same but lower than pH values 5.82 from MW and 5.62 FSMW treatments (p-value <0.001). In the 2020/2021 season, MW had pH 6.13, FSMW had pH 5.81, MW+NPK had pH 5.90, and FSMW+NPK had pH 5.67. However, the MW treatment had the highest (p-value < 0.001) pH value amongst the P sources.

The detailed analysis of the effect of P sources' application rates on soil pH revealed that NPK and FSMW+NPK application rates had no impact on pH in both seasons. However, the application rates of the FSMW, MW, and MW+NPK affected the soil pH.

In the first season, FSMW treatment, the 0 kg P/ha and 15 kg P/ha application rates had pH 4.87 and 5.52 respectively and were statistically the same but lower than pH 5.77 from 30 kg P/ha and pH 6.20 from 45 kg P/ha application rate. Like FSMW, the 0 kg P/ha and 15 kg P/ha application rates of MW had the same and lower pH than 30 kg P/ha and 45 kg P/ha application rates. The 0 kg P/ha had pH 4.97, 15 kg P/ha, 5.51, 30 kg P/ha, 6.13, and 45 kg P/ha, 6.69 pH. In MW+NPK treatment, too, 0 kg P/ha and 15 kg P/ha application rates had the same pH value but lower than pH 5.85 recorded in 30 kg P/ha and pH 5.94 from 45 kg P/ha.

In the second season, the 15 kg P/ha, 30 kg P/ha, and 45 kg P/ha application rates of FSMW had the pH values 5.81, 6.07, and 6.16, respectively. These pH values were statistically the same but higher than 5.20 pH from 0 kg P/ha. In MW, all application rates have the same pH values except the 0 kg P/ha which had lower pH of 5.20. The 15 kg P/ha in MW+NPK had pH 5.89, which was the same as pH 5.91 from 30 kg P/ha but higher than pH 5.20 from 0 kg P/ha. It was the 45 ka P/ha gave the highest (p-value <0.001) pH value of 6.61.

The results revealed the importance of organic P fertilisers in increasing pH. The organic matter that comes with the P was responsible for raising the soil pH due to the buffering capacity of calcium carbonates from the organic fertilisers. There was no increase in soil pH when NPK was applied. Within two seasons of organic P fertiliser application, the pH at Bvumbwe went up from 4.73 to 5.24 with FSMW+NPK application, to 5.34 with MW+NPK application, to 5.35 with FSMW and to 5.41 with MW application. On the other at Makoka pH rose from 4.97 to 5.81 in FSMW treatment, to 5.67 in FSMW+NPK treatment, to 5.90 in MW+NPK treatment, and to 6.13 in MW treatment. Similar results were reported by Acharya & Ghimire, (2019), although they did not mix organic and inorganic fertilisers. The soil of Malawi has low pH

(<5.5) (Njoloma et al.,, 2016) and the use of the organic sources of P can help in increasing soil pH. The impact of organic fertiliser on soil pH was also reported by Eghball, 1(999), Girma et al., (2019), and Whalen, Chang et al.,, (2000) which reported an increase in pH of acidic soils after application of manure and the pH increased with increasing application rate. The pH increase may be due to the buffering effect of calcium carbonate from the organic fertilisers and the release of K^+, Ca^{2+}, $Mg^{2+,}$ and OH^- into the soil after organic matter decomposition.

However, the current results disagree with the finding of Parker et al., (2018) and Eghball, (1999) who reported no pH change after applying P based organic fertilisers. The resistance in pH change was due to the alkalinity and high buffering capacity of the soils (Parker et al., 2018). Eghball, (1999) pointed out that the pH increase was proportional to the amount of organic fertiliser applied and N based application resulted in almost two times more organic fertiliser application than the P based application. The N based application increased the pH. So, it can be suggested that the P based application did not increase the pH because of less amount of organic fertiliser applied and due to the already slightly high original pH (6.2).

Most soil in Malawi has low available P (Maida, 2013) and pH less than 5.5 (Njoloma et al., 2016). Low pH has largely been attributed to low soil P availability. Low pH (pH <5.5) favours the solubility of aluminium and iron. The aluminium and iron ions react with phosphate ions, making the P unavailable to crops (Penn & Camberato, 2019). Soil pH also affects the reproduction and activities of soil microbes, which in turn affects soil microbial functions like biological nitrogen fixation and decomposition (Sullivan et al., 2017). In general, pH range of 6.5 to 7.5 tends to favour the availability of most plant nutrients (Jensen, 2010). So, this research demonstrated that the application of organic fertiliser results in an increase of pH. This means, organic fertilisers are one the factors to be consider when maintaining or restoring soil health.

4.3.5 Effects of P sources on soil organic matter

The soil organic matter was determined at the end of each season. At the end of both seasons at Bvumbwe (Figure 4.6) the soil organic matter was affected by both P sources and their application rates. In the first season, NPK (control) had 1.21%, FSMW+NPK had 1.32%, and MW+NPK had 1.31% organic matter values, which were statistically not different and lower (p-value < 0.001) than 1.48% got from MW and 1. 55 got from FSMW. In the second season, NPK recorded the lowest (p-value <0.001) organic matter content of 1.22%, while MW had 1.83%, MW+NPK has, 1.78%, FSMW had 1.76%, and FSMW+NPK had 1.84%.

NPK application rates did not affect the organic matter content in the soil in both seasons. All the application rates hard the same organic matter content as the 0 kg P/ha. In the first season, the application rates of MW+NPK and FSMW+NPK did not affect organic matter content in the soil. In the second season, the 15, 30, and 45 kg P/ha of FSMW+NPK had 1.95%, 2.16% and 2.1% organic matter higher than the organic matter content from the 0 kg P/ha application rate. The MW+NPK, the 0 kg P/ha, had the lowest organic matter content of 1.23%, which was statistically lower than then rest of the application rates. The 15 kg P/ha application rate recorded 1.91%, 30 kg P/ha had 1.97%, and the 45 kg P/ha had 2.01% organic matter.

The MW and FSMW treatments, their application rates affected the organic matter content in the soil too during both seasons. In the first season, the MW, 0 kg P/had the lowest organic matter of 1,17%. The 15 kg P/ha had 1.51%, the 30 kg P/ha had 1.57% and the 40 kg P/ha had 1.69% and these were not significantly different. In the second, the 0 kg P/ha still had the lowest organic matter content of 1.21. The 15 kg P/ha had 1.87% higher than the organic matter in 0 kg P/ha but lower than the organic matter content of 2.09% from 30 kg P/ha and 2.11% from 45 kg P/ha. In the first year, for MW the 0 kg P/ha and 15 kg P/ha hard the same organic matter content of 1.17% and 1.52 respectively which were lower than organic matter content of 1.72% from 30 kg P/ha and 1.8% form 45 kg P/ha application rates. The second season was only 0 kg P/ha application rate with the lowest organic matter content of 1.23%. The rest of the application rates had the equal content of organic matter.

At Makoka (Figure 4.6), the organic matter content in the soil was also affected by both P source and application rates. In the first season, NPK had 0.89%, MW+NPK had 0.92%, and FSMW+NPK had 0.94%, which were significantly different from 1.2% from MW and 1.2% FSMW. The NPK, FSMW+NPK, and MW+NPK gave the lowest organic matter content in the second season compared to MW and FSMW.

Further analysis on the effect of application rates showed that NPK, MW+NPK, and FSMW+NPK application rates did not affect the organic matter content in the soil in both seasons. It was the application rates of MW and FSMW that affected the organic matter in the soil. However, it was only the 45 kg P/ha application rate that produced significantly higher (P-value < 0.001) organic matter content than the rest (0, 15 and 30) in both seasons. In the first the 45 kg P/ha of MW had 1.83 % and 1.58% organic matter in the second season. On the other had the 45 kg P/ha of FSMW recorded 1.89% organic matter in the first season and 1.35% organic matter in the second season.

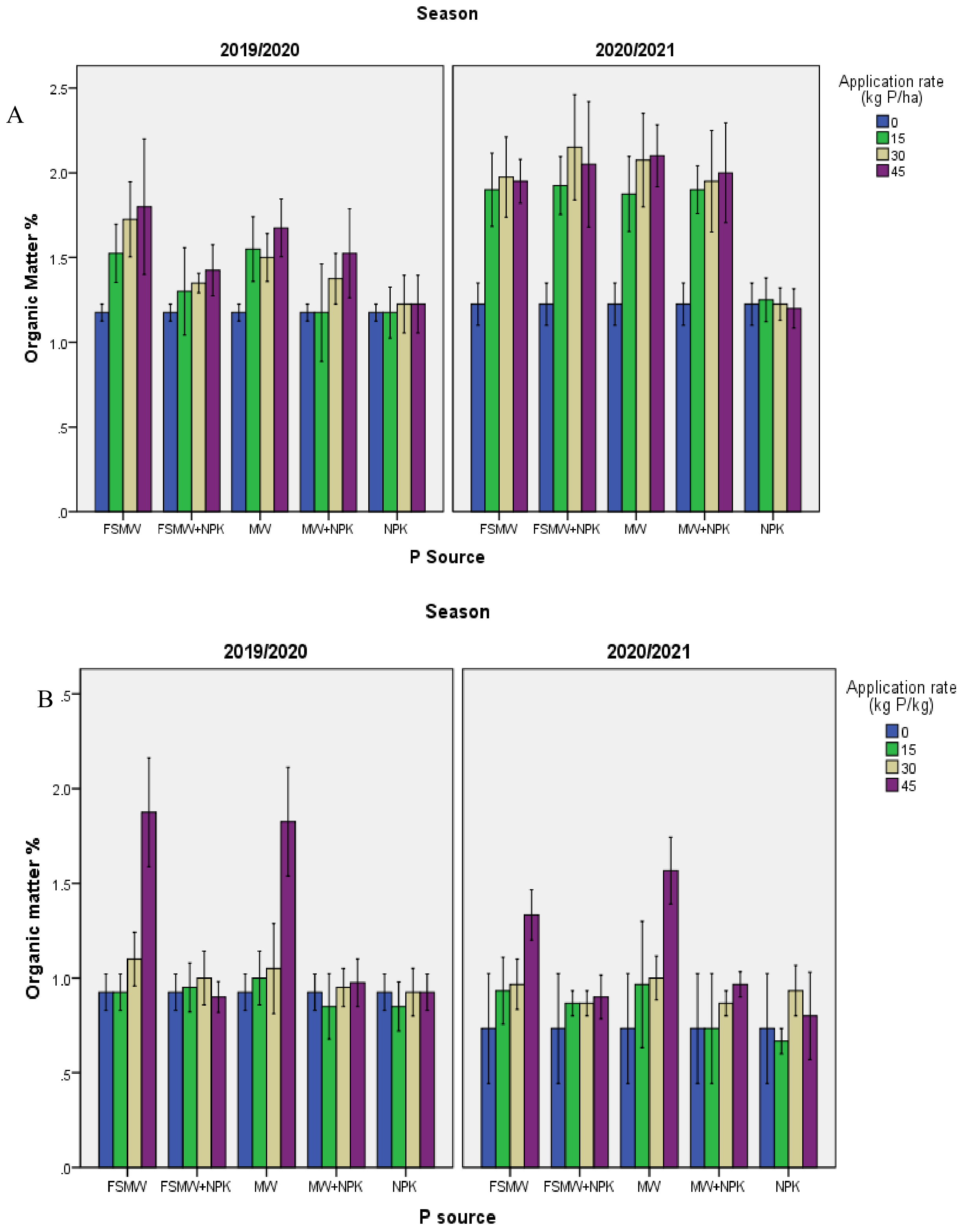


Figure 4.6. Soil organic matter content at Bvumbwe (A) and Makoka (B) research stations as affected by organic P sources. The whiskers on the bar graphs indicate standard error.

The results revealed the importance of organic P fertilisers in restoring soil organic matter. In addition to supplying P for plant growth, organic P fertilisers also add organic matter to the soil. However, the initial soil organic matter status and the application rates affect the soil's response. In the current study the combination of organic and inorganic fertilisers (1:1), which reduces the amount of organic matter that comes with the P, required two seasons to change the organic matter content of the soil at Bvumbwe, but at Makoka, even two seasons were not enough to bring about a noticeable change to soil organic matter content. This result agrees with the finding of Ngwira, et al., (2013) The organic fertilisers, even at the lowest rates (15 kg P/ha) was able to raise the organic matter content of the soil at Bvumbwe, but at Makoka, it was only at 45 kg P/ha. This shows that soil's response is site-specific and not generalisable. The increase in soil organic matter after compost application was also reported by Acharya & Ghimire, (2019), Khorram et al., (2018), Meena et al., (2019) and Parker et al., (2018).

Njoloma et al., (2016) stated that most smallholder fields in Malawi have low organic matter. Soil organic matter promotes water infiltration and retention. Therefore, the increase in organic matter will increase the soil's water-holding capacity and vice versa (Huntington, 2007). This means the application of organic fertiliser is one of the ways of adapting to the droughts that are becoming frequent now due to climate change. Soil organic matter also boosts the soil cation exchange capacity, thereby increasing the soils' ability to hold and supply plant nutrients. Soil organic matter also promotes availability of P in the soil solution by chelating aluminium and iron ions which are responsible for precipitating P from the soil solution.

4.3.6 Effects of P sources on maize grain yield

The maize grain yield at both sites and in both seasons was not affected by the P source, but it was affected by the application rates (Figure 4.7). At Bvumbwe, in the first season, the FSMW treatment produced the highest maize yield of 5285 kg when 45 kg P/ha application. The 30 kg P/ha had 4798 kg of maize, and 4286 kg was realised from the 15 kg P/ha application rate. The lowest yield was from the 0 kg P/ha which dad 2348 kg of maize. In the second year, 0 kg P/ha recorded the lowest yield too. The 15 kg P/ha rate had 4670 kg, 30 kg P/ha had 4747 kg and 45 kg P/ha had 5664 kg.

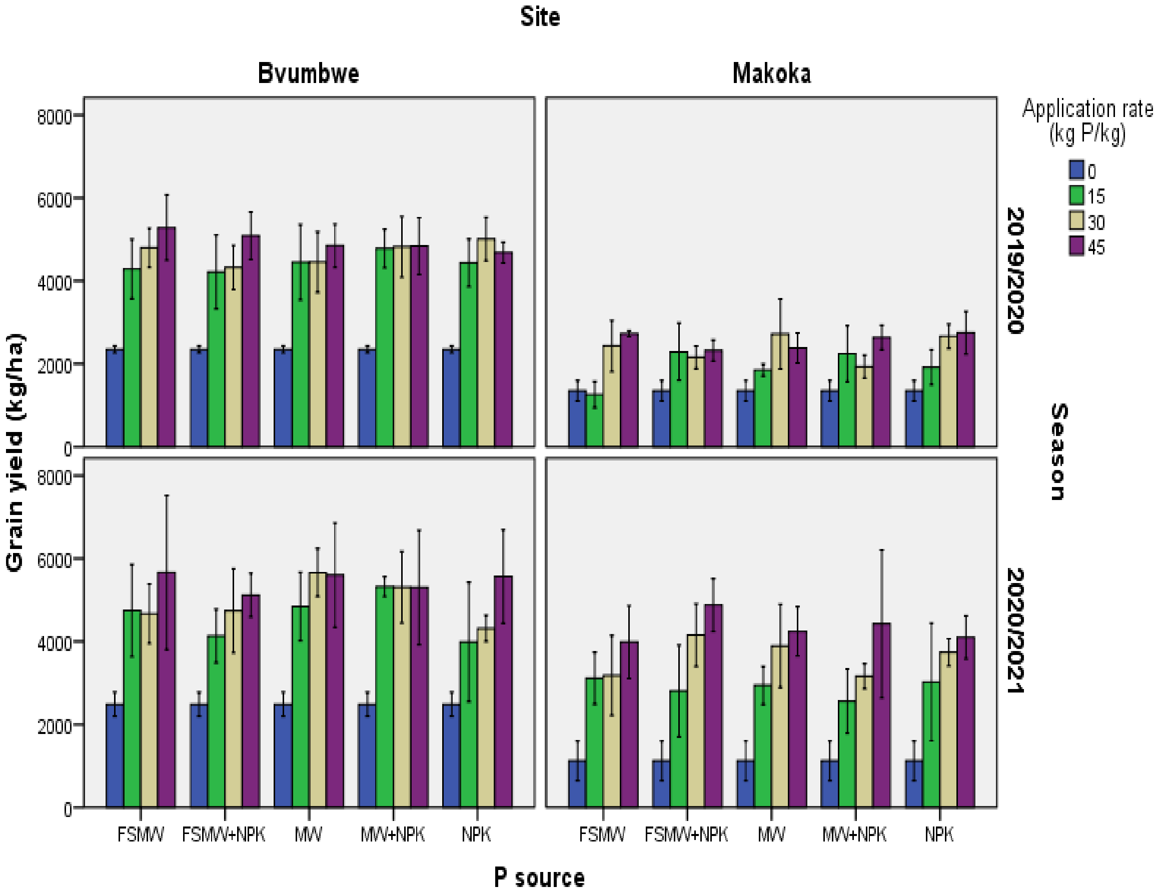


Figure 4.7. Maize grain yield at Bvumbwe and Makoka research stations. The whiskers on the bar graphs indicate standard error.

The MW application rate of 0 kg P/ha produced the lowest maize yield in both seasons. It was 2348 kg in the first season and 2485 kg in the second season. The yields got from 15, 30 and 45 kg P/ha of MW were not significantly different. The MW+NPK's application rates gave results similar to MW. The 0 kg P/ha had lowest yield of 2348 kg in the first season and 2485 kg in the second season. The other three application rates had statistically the same yield in both seasons. Just like MW+NPK, the trend was the same for FSMW+NPK and NPK.

At Makoka (Figure 7), in the first season, the 0 and 15 kg P/ha application rates of FSMW had equal yields of 1350 kg, and 1260 kg, which was lower than 2430 kg got from 30 kg P/ha and 2726 kg got from 45 kg P/ha. In the second season, the 0 kg P/ha had 1126 kg which was lower yield than the yield got from the rest of the application rates. The same trend was also observed in NPK treatment. FSMW+NPK, in the first season, all its application rates had the equal yield except 0 kg P/ha which had the lowest yield of 1350 kg. In the second season, 30 kg P/ha had 4156 kg and 45 kg P/ha had 4881 kg, followed by 15 kg P/ha which had 2810 kg. The 0 kg P/ha application rate had the lowest yield of 1126 kg.

Regarding the MW treatment, in the first season, the 30 kg P/ha had 2382 kg and 45 kg P/ha had 2722 kg, which was the highest yields followed by 15 kg P/ha which had 1852 kg and the 0 kg P/ha application rate had 1350, which was the lowest yield. However, in the second season, the 45 kg P/ha had 4243, which was the highest yield, while the 15 and 30 kg P/ha rate had the same yield. Still, the 0 kg P/ha had the lowest yield of 1126 kg. The MW+NPK performed the same during both seasons. The 45 kg P/ha had the highest yield of 2634 kg in the first season and 4423 kg in the second season, followed by 15 and 30 kg P/ha which had equal grain yield. The 0 kg/ha had the lowest grain yield of 1350 kg in the first and 1126 kg in the second season.

In addition to improving soil parameters like pH, organic matter, and bulk density, organic sources of P can also match inorganic fertilisers on maize yield. The results showed that either organic or inorganic source of P, the maize yield was the same. However, inorganic fertilisers contribute nothing to soil health. Inorganic fertilisers are expensive in Malawi for poor smallholder farmers (Government of Malawi, 2010; Government of Malawi, 2007). Therefore, the use of organic P sources which are locally available offers a cheaper alternative. The use of organic fertilisers has shown that the yield improves with time. In the first season, the 15 kg P/ha application rate performed the same as control, but in the second season, the yield improved. Parker et al., (2018) Meena et al., (2019) reported similar results, although their organic fertiliser application rates were not P based. If the use of organic sources of P is promoted more farmers will access the fertiliser, and Malawi will be moving towards achieving food security which is part of the sustainable development goal two.

4.4 Conclusions

It is only healthy soil that can sustainably remain productive for a long time. After two seasons, on average, the tested parameters showed improvements. Soil pH increased from 4.75 to 5.82 in two seasons, soil organic matter increased by 60% at Bvumbwe, and at Makoka, it increased by 82%. Earthworm numbers in the soil also increase and there was even more when 45 kg P/ha of organic fertilisers was used. There was four times more earthworms at Makoka and six times more earthworms at Bvumbwe when organic fertilisers were applied compared to applying inorganic fertiliser. The organic fertilisers did not have big impact on soil bulk density. Improvement in soil bulk density was only observed at Bvumbwe. Furthermore, the regression analysis showed that organic matter and pH have a positive impact on maize yield. Therefore, with these results, the hypothesises which stated that P based application of organic fertilisers would improve soil health, and improved soil health parameters would influence maize yield were supported.

This study has also shown that using organic sources of P will not result in reduced maize yield. Pure organic P fertiliser or a combination of organic and inorganic fertiliser yielded the same as inorganic fertiliser. Likewise, the hypotheses that Maize yield would not adversely affected if organic fertilisers are applied based on P application rates was supported. However, without P fertiliser (inorganic or organic) application, there was an almost 157% decrease in maize at Makoka and an 85% maize yield drop at Bvumbwe compared to maize yield realised when 15 kg P/ha was applied. It was 284% maize yield drop at Makoka and 119% at Bvumbwe when no P was applied compared to yield harvested after applying 45 kg P/ha.

Organic fertilisers are locally available and cheaper compared to inorganic fertilisers. It means the farmer will reduce the cost of production, and even the resource-poor farmers will produce enough food for their families.

However, it is important to note that these trials were conducted after three years of fallow. The fallowing may promote the building up of organic matter, influencing other soil parameters like soil pH. This means that a field owned by a smallholder farmer that has continuously been worked on should have completely different conditions to the control in this experiment, thereby making the response time to the application of organic fertilisers different.

It is important to note that the soil's response to organic fertiliser is site-specific as the case in the current study regarding some soil parameters. This means that more research is needed mainly on long term effect of these P based organic fertilisers on soil health and research of area-specific recommendations of these organic fertilisers.

4.5 References

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Chapter 5 . Discussion

5.1 Introduction

The overall aim of this research was to evaluate the amount/stocks of organic P sources and their potential for use in agriculture in Malawi. The literature review established that there was insufficient knowledge on P use and flows in Malawi. Specifically, there was limited information on the amount and the sources (organic waste, manure, faecal matter, etc.) of organic P ; P mineralisation from organic fertilisers; or the the ability of organic P sources to meet P demand during vegetative and reproductive stages when applied based on P application rates. In addition, previous work has not addressed the impact of applied organic P sources on soil health, specifically the biological component of soil health and rather focused on the chemical and physical components. This chapter discusses results from the three papers and highlights their linkages to achieve the overall aim of the study.

5.2 Quantities of organic P in Malawi

Poverty, infertile soils, and a high population density (UN, 2020), exacerbated by climate change which causes frequent droughts, have led to household food insecurity in Malawi. In 2020, 10% to 15% of the population were food insecure (IPC, 2020). For farmers in Malawi to harvest enough maize, they need to apply fertilisers. One of the deficient soil nutrients in Malawi is P which has to be applied to crops to maintain yield and ensure people have enough food. Like other countries that do not have phosphorus mines, Malawi depends on imported inorganic P fertilisers for crop production, which accounts for almost 66% of the P used in agriculture for crop production. Malawi would be severely food insecure if it could not access inorganic P.

Inorganic fertilisers represent the biggest flow of P (14000 Mg of P) into Malawi, followed by imported food and washing products (2300 Mg). There are other flows that move P within the countries, and other flows export P out of the country. For example, crops that take P from the soil are transported to homes or processing units; livestock convert P from the grazing lands into meat and milk; P from humans is excreted into pit latrines, septic tanks and WWTPs; and P-rich organic waste from homes and markets is stockpiled in landfills and others dumping areas all of which remain within the borders of Malawi. On the other hand, P in river water flows out of the country, as does the P within the crops that are exported abroad

Approximately 66% of the P used in Malawi for crop production is imported inorganic P, which is higher than the values for the UK (27%) (Cooper & Carliell-marquet, 2013), the Netherlands (24%) (Smit et al., 2010), and Spain (48%) (Álvarez et al., 2018). It is important to note that, although the country relies on imported inorganic P, this study found that less P is applied to crops than the P removed from the soil through crop biomass. In 2016, almost 21000 Mg of P (inorganic and organic) was used, but there was 25000 Mg of P in crops, representing nearly one kilogramme of P mined per hectare. The negative P balance is a result of the fact that farmers cannot use sufficient inorganic P fertilisers to maintain soil P reserves. The current recommended application rate is 20 kg P/ha (Ministry of Agriculture and Food Security, 2012), but farmers are applying approximately 6 kg P/ha (FAOSTAT, 2021). In this way, the soils are mined of P, depleting the soil reserves, and slowly the capacity to support crop growth is slowly reduced further, requiring even higher doses of P to produce food.

If Malawi could recycle the P, it may significantly reduce the use of inorganic P in agriculture. This study found that approximately 35000 Mg of P in organic materials each year can be used for crop production. Out of this, 10000 Mg are in faecal matter, 13000 in animal manure, and 5500 Mg in solid organic waste. However, only 16% of the P in organic materials was recycled. P in animal manure is the most recycled, with 38% of it used for crop production. Malawi is not yet recycling P from faecal sludge and organic waste in landfills. Non recycling of faecal sludge in Malawi may be due to lack of efforts by government to incentisive on the benefits of recycling faecal sludge. On the other hand, most of the faecal sludge are in pit latrines which are scattered, sometimes in hard to reach locations and not designed for emptying, therefore recycling becomes expensive. From 2000 to 2019, the Netherlands reduced its inorganic P use in agriculture by almost 80%, the UK declined by 33%, and Spain reduced it by 15% (FAOSTAT, 2021). The P that is used in agriculture for crop production is 73% from organic sources in the UK, 77% in the Netherlands, and 52% in Spain. P from manure takes a more considerable percentage of the recycled P: 62% in the UK, 39% in Spain and 72% in the Netherlands. The remaining recycled P comes from faecal sludge and compost (Álvarez et al., 2018; Cooper & Carliell-Marquet, 2013; Smit et al., 2010).

In Malawi, manure is the most used source of P (38%), and should therefore be promoted along with the use of composted market waste and faecal sludge which represent the most extensive P stocks and are not recycled for crop production. Therefore, this study evaluated faecal sludge and organic waste in field crop trials. The ability of these organic sources of P to improve soil health, improve PUE and maintain available P concentrations in the soil for plant uptake was evaluated.

As the human population increases and the demand for animal products rises, faecal sludge and manure production will rise accordingly. In this study, the P flow analysis showed that animal manure and faecal sludge are the most important but under-utilised P sources in Malawi.

The reduction of inorganic P dependency is not needed in Malawi only. As a developing country with no P mines, Malawi's situation is similar to other countries, both regional and international. Between 2009 to 2019, inorganic P imports for other Sub Saharan African countries like Botswana, Namibia, Tanzania, Zambia, and Zimbabwe increased (FAOSTAT, 2022). In this period, P imports for Botswana increased by 87%, Namibia by 235%, Tanzania by 238%, Zambia by 659%, and Zimbabwe by137%. Likewise, countries like Austria, Austria, Brazil, and Canada also experienced a rise in P imports, with Brazil increasing their imports by 202%. In order to ensure a sustainable and continued food supply, all countries must reduce the use of inorganic P and turn to organic P, which is locally available.

5.3 Impact of organic P fertilisers on physical, chemical, and biological soil properties

This study found that applying P-based organic fertilisers increased soil pH from 4.75 to 5.82 in two seasons. Soil organic matter content increased by almost 82%, and earthworm numbers rose by 500%. On the other hand, there was reduced soil bulk density.

5.3.1 The implication of increased organic matter

Soil organic matter plays different essential roles in making the soil productive. Soil organic matter improves the soil's water-holding capacity and binds the soil particles together into stable aggregates that resist soil erosion (Cao et al., 2021; Mloza-Banda et al., 2016; Parhizkar et al., 2021). In addition, the soil organic matter supplies plants nutrients like potassium (K), calcium (Ca), N, etc., as the organic matter is decomposing. One of the effects of climate change is the frequency of droughts which affects crop growth, resulting in reduced crop yields. Since the soils in Malawi have low organic matter (<1.5%) (Njoloma et al., 2016; Snapp, 1998), the soils have a decreased capacity to hold water for crop uptake. Currently, Malawi is losing around 20 Mg of soil per hectare per year (Omuto and Ronald, 2018) due to soil erosion. Soil erosion removes the fertile topsoil while transporting the soil and nutrients into water bodies causing siltation and eutrophication. The drinking water supply and electricity generation in Malawi is affected by the siltation of the water bodies (Kadewere, 2007; Mzuza et al., 2019; Taulo et al., 2015; USAID, 2018). Eutrophication of Lake Malawi is also ongoing (Otu et al., 2011). Siltation will result in the decreased capacity of the water bodies to hold enough water for power generation, supply potable water, and provide habitat for fish.

Currently, only 11% of the households in Malawi are connected to power, while 18.1% drink piped water (National Statistical Office, 2019). Fish provides 28% of the dietary animal protein and contributes 4% to the GDP of Malawi (USAID, 2016). Therefore, if Malawi were to increase its use of organic fertilisers, the increase in organic matter would reduce soil erosion, which would lessen its impact on water bodies. Water, power and fish are all critical to Malawi. The low percentage of households connected to the national power grid has always been the significant cause of deforestation as people search for alternative energy sources. Deforestation contributes to climate change, makes people vulnerable to flooding, and further increases soil erosion. There are reports of decreased fish populations in Lake Malawi, which is projected to continue declining due to habitat destruction caused by siltation (Hara and Njaya, 2015; USAID, 2016).

Increased organic matter will also improve the water-holding capacity of the soil. Climate change has resulted in frequent occurrences of droughts which significantly reduce crop yields. Therefore, with more organic matter, the soil would be able to keep water for a longer time, thereby reducing the impact of drought on crop production,

The organic materials containing P also have other plant nutrients (N, Ca, K, Mg, etc.). Therefore, applying organic fertilisers adds these plant nutrients to the soil for plant use. The soils in Malawi and other tropical regions are highly weathered dominated with Fe and Al ions which have high affinity for P ions, making P unavailable for plant use. However, the organic acids from organic matter react with Fe and Al ions, which would have reacted with P, making P available for plant uptake. The carbon in the organic fertilisers also improves the cation exchange capacity (CEC) of the soil. The soil can retain nutrients in exchange sites that plants efficiently absorb. The improved CEC also reduces the leaching of plant nutrients, which may contaminate groundwater.

As much as Malawi would benefit from applying organic fertilisers, the impacts would also be felt in neighbouring countries as less P-rich water would cross their borders. Overall, if the switch to more P based organic fertilisers, would improve water quality and power generation, while ensuring food security and adapting to climate change.

5.3.2 The implication of increased soil pH

The pH of the soil affects the availability of essential plant nutrients. In acidic soils (pH<5.5), K, Ca and Mg are unavailable for plant uptake since they are easily leached because the Fe and Al ions dominate the exchangeable sites. In addition, Fe and Al precipitate P from the soil solution. Al and Mn toxicity damage plant roots, restricting nutrients uptake in acidic soil. In alkaline soils, micronutrients precipitate, making them unavailable for plant use (Miller, 2016). A pH between 5.5 to 8.0 is ideal for the availability of plant nutrients (Lake, 2000; Läuchli and Grattan, 2012; USDA, 1994). However, most of the soils in Malawi, just like other tropical countries where the soils are highly weathered and dominated by 1:1 clay and metal oxides, have low pH (<5.5) (Maida, 2013; Njoloma et al., 2016; Snapp, 1998), which affects plant nutrient availability and plant growth.

However, in this study, the application of organic fertilisers increased soil pH. Therefore, if Malawi and countries which have similar soils apply organic fertiliser, the soil pH would likely rise to levels where plant nutrients are available for plant utilisation. If plants can access nutrients from the soil, crop yield would be expected to increase, ideally leading to food-secure households.

5.3.3 Impact of improved soil biology (earthworms)

Soil biology deals with soil organisms and how their activities affect soil functions and properties. These organisms include bacteria, fungi, nematodes, and earthworms, amongst others. Soil biology is one of the components that determine the soil's health and compared to physical and chemical components of soil health, is least understood (Johns, 2017). Soil microbes are essential as they are involved in critical soil processes: nutrient recycling, nutrient retention, infiltration and water holding capacity, carbon sequestration, etc. The presence of earthworms especially, mirrors healthy soil (Lloyd and Crotty, 2017). The burrowing done by earthworms increases soil aeration, water infiltration, the number of channels through which plant roots grow down with less resistance, and improve soil structure (Bhadauria & Saxena, 2010; Lloyd & Crotty, 2017; Pfiffner, 2014; Zhang et al., 2021). When more water infiltrates into the soil, the chances of runoff are reduced, and water holding capacity is increased. As the plant roots grow freely through the burrows, they can access nutrients for their growth and production, and soil particles are held together, increasing resistance to soil erosion. Earthworms also secrete larger organic molecules into smaller materials for further decomposition by other microbes like bacteria.

In this study, we measured the abundance of earthworms in the soil, and found that organic fertilisers boost the earthworm numbers. Therefore, if Malawi farmers were to use more organic sources of P, the earthworm numbers in soil could increase. The earthworms increase would result in reduced soil erosion as well as help with nutrient recycling and allow plant roots to access water and nutrients for optimum plant growth and production. Therefore, the use of organic fertiliser would improve the soil's productivity and contribute to making Malawi more food secure.

5.3.4 The implication of reduced bulk density

Bulk density is an indicator of soil compaction. It occurs when soil particles have been compressed into a smaller volume, reducing pore spaces that hold water and air (McKenzie, 2010). The use of heavy machinery and conventional farming practices e.g ridging (when soil is too wet or too dry), breaks soil structure, and causes soil compaction. Compacted soils restrict water infiltration as well as air and root movement, which lead to reduced soil productivity. When the soil is compacted, the microbial population and crop yield decrease (Li et al., 2002) partly because roots cannot move freely to access water and nutrients for plant growth. Due to lack of water and reduced aeration, microbial populations are also affected. Compacted soil also encourages runoff, leading to soil erosion. Organic matter has been reported to reduce soil compaction by Adalberto et al., (2018), Meena et al., (2019), and Singh et al., (2019).

This study found that organic fertilizer application reduced soil bulk density by almost 25% after two seasons of application. Reducing bulk density would increase crop production as plants would access enough water and nutrients, and the soil would also allow water to sink in better. Soil biology, which is also negatively affected by compacted soils, flourishes when soil is uncompacted.

5.4 Impact of organic fertilisers on maize yield, P availability and PUE

The organic fertilisers were also assessed on their ability to maintain P in soil solution for plant uptake, PUE and crop productivity.

This study showed that maize yield from both organic fertiliser and inorganic fertilisers was statistically the same at both sites in both years. On average, both inorganic and organic sources of P resulted in around 5000 kg grain yield per hactare. Therefore, if farmers adopted organic sources of P, they could have the same amount of maize they have been harvesting using NPK fertilisers. Maize is the main food crop for people in Malawi (Government of Malawi, 2016), and for Malawi to remain food secure, it imports fertilisers for crop production. One of the nutrients in the imported fertilisers is P, but the cost of importing is increasing. For example, in the past ten years (2010 to 2019), the cost of importing fertiliser has risen by 420% (Government of Malawi, 2020b). The yield of maize in this study means that the country could still be food secure using organic P fertilisers. Since there is over 35000 Mg of P in organic waste materials every year, the cost of P importation could be reduced by using locally available organic P fertilisers.

In this study, maize had the same P use efficiency regardless of the P source at both sites. The P amount utilised by the maize was the same from both sources. The P not taken up by crops either remains in the soil or is washed away. It is essential to know that P in inorganic fertiliser is readily available. If P is not absorbed by the crops and not fixed by other soil minerals, it can easily contaminate water bodies.

On the other hand, P in organic fertilisers is mostly in organic forms and is released slowly, reducing the chances of P from the organic fertilisers contaminating water bodies. However, continued application of the organic fertiliser would lead to the accumulation of P in the soil to the point that it may threaten water quality (Wang et al., 2019). The PUE determines how much of the added P has been used by the crop. If increased application rates do not improve PUE, the extra P applied is not used by the crop.

Sometimes the PUE is affected by the P source (Ademba et al., 2015). However, Bvumbwe had higher PUEs than Makoka, which shows that the maize at Bvumbwe utilised more of the applied P than at Makoka. Since it was the same variety of maize used, the difference in PUE may be due to the soil conditions of the two sites. Bvumbwe had higher organic matter content than Makoka, which might have reduced the soil's affinity for P, encouraging P uptake. On the other hand, Makoka had a higher initial available P concentration which might reduce the uptake of the applied P by the maize, since there was already P in the soil for utilisation.

So as Malawi and other countries that depend on inorganic sources of P adopt organic sources of P, precaution on water contamination has to be exercised. Recommended application rates of different organic P sources in various areas have to be established to efficiently utilise the nutrient and protect the world water bodies.

In Malawi, less than 18 mg/kg soil available P concentration is considered low and significantly reduces maize yield (Chilimba, n.d.). Extra P is applied to ensure the available P concentration in the soil is above 18 mg/kg for optimal crop (maize) growth and reproduction. In this study, inorganic and organic sources had the same P concentration from vegetative to reproductive stages which was 25 mg/kg on average. So, the organic fertiliser would not lead to reduced crop yield because P in the soil will be enough for crops just as after applying inorganic fertiliser. Malawi and other nations, as mentioned earlier, can use organic sources for maize production without fear of food insecurity. The maize could be cheaply produced as the organic sources are local and easily accessed, unlike inorganic fertiliser imports.

5.5 Site-specific performance of organic fertilisers

Lastly, although it has been observed that organic fertilisers improved soil health at both sites and resulted in the same yield as the inorganic fertilisers, the response of soil health parameters was site-specific. For example, a reduction in bulk density was only observed at Bvumbwe, and pH increased from 4.95 to 5.82 Makoka and from 4.75 to 5.23 at Bvumbwe. Therefore, Malawi needs to do multi-locational experiments to establish recommended practices for different areas because the variability in soil. Establishing a site-specific recommended application rate is important because the applied organic P fertiliser would need to be enough to achieve optimal maize yield and improve soil health in that area without threatening water quality. Establishing site-specific recommendations would also mean efficient resource allocation as the quantities needed in different regions would be foreknown, and production would much that.

5.6 Heterogeneity of P fertilisers

The content of P in the organic P fertilisers depends on the content of P in the organic materials used in the production (Table 5.1). Different feedstocks would lead to organic P fertilisers with different P content. Therefore, as countries encourage the production and use of organic fertilisers, standards have to be established for the producers to follow. The standards would ensure that all the organic P fertilisers on the market are of a consistent and predictable quality.

Table 5.1. P content in different organic materials

Source of recycled P	**P content (total P)**	**Reference**
Poultry droppings	19400 mg/kg	Amoah et al., 2017
Cattle manure	169.7- 2430 mg/kg	Anwar et al., 2017; Soma et al., 2018
Faecal sludge	7500 – 28170	Coutinho et al., 1997; Adamtey et al., 2010; Moya et al, 2017; Amoah et al, 2017

Municipal wastewater sludge	5000 mg/kg	Tomócsik et al., 2016
Urine	300 – 1070 mg/kg	Amoah et al, 2017
Municipal/market waste	3619 – 4600 mg/kg	Adamtey et al., 2010; Horrocks et al., 2016; Grau et al, 2017

For example, in Malawi, currently, there is no policy that guides and regulates the production of organic fertilisers. In the absence of such a policy, farmers are obtaining organic P fertilisers with different P content even from the same supplier. Varying P content would also affect application rate and crop performance.

As much as individual farmers should be encouraged to produce their own organic fertiliser, government should encourage the setting up of small scale organic fertilisers production plants. Just as the government subsides inorganic fertilisers, organic fertilisers should also be subsided and producers should be given soft loans, so that poor smallholder farmers should afford to buy. Setting up these plants would make it easier for governments to guide, monitor, and control the quality of organic fertilisers.

5.7 The cost of organic fertiliser production

Although materials for organic fertiliser production are locally found, sometimes organic fertiliser tends to be more expensive than inorganic fertilisers. The machinery costs, both production and transportation, make the organic fertilisers expensive. However, when the organic fertiliser is made on the farm, organic fertilisers are 40% cheaper than inorganic fertilisers (Loncaric et al., 2013).

In a situation where no waste separation is made at the source, waste sorting is another process that makes organic fertilisers production costly. Therefore, sorting waste at the source should be enforced to encourage organic fertiliser production and reduce production costs. If proper composting methods are followed, where the temperature goes up to 60 ^{0}C, pathogens are destroyed , the resulting product is safe for people to use. Also to make sure that the cost of production is reasonable, the organic fertiliser producing facilities should be in locations/cities where pit or septic tanks and organic waste collection services are available to get the feedstock easily. Furthermore, as the cities are growing, councils should include waste recycling issues in their plans. Issues of access roads, design of pit latrines and septic tanks, sawer system development and waste collection, are important in the production of organic fertilisers. In

Malawi, pit latrines are currently scattered, inaccessible and not designed for emptying. Few people use septic tanks, the sewer system is damaged, and there is no proper waste collection system. The current situation is likely to make organic fertiliser production business not viable.

5.8 Academic contributions

There are numerous P flow analyses for a number of European countries, e.g., the UK, Spain, and the Netherlands. However, previous to this study, there was no complete P flow analysis for any African country. There was a P flow assessment at the district/regional level in both Uganda and Tanzania (Lederer et al., 2015; Xiong et al., 2020). However, considering the unique soil, climate, waste, and crops of Malawi, was an obvious need for a country-specific analysis. In Malawi, P in faecal matter accumulates in pit latrines, whereas in countries with sewer systems, P in faecal matter collects at WWTPs from where the faecal sludge can be collected.

In Malawi, animals are let out to graze without any extra artificial feed given to them. The grass and shrubs they feed on are not applied with external fertilisers: animals mine P the soil through grazing and bring it to homes in manure and animal products. In industrialized countries, animals are mostly fed on manufactured feed, and the pasture is fertilised with inorganic fertilisers, so the P in manure is rarely from the soil only. For the first time in P flow analysis, this study reported that the P in animal manure is from the wild grazing areas that plants get from the natural soil's reserves.

Although it is well established that organic fertilisers improve soil health, previous crop studies did not base the organic fertilizer application on P, but rather on nitrogen (Abubaker et al., 2012; Amoah et al., 2017; Cavalli et al., 2016). Few studies have evaluated all three components of soil health when faecal and market-based organic fertilisers were used (Debiase et al., 2018; Gosal et al., 2018). It was important to establish if the P-based application of organic fertilisers would improve soil health since it is only a healthy soil that can sustainably produce food. By measuring all three components of soil health, the study has established that P based applications improve soil health as indicated by the increase in earthworms of almost 500% (biological indicator), increased of around 100 times in soil pH, 82% increase in organic matter (chemical indicators) and a reduction of 25% in bulk density (physical indicator).

P mineralisation from organic fertiliser has been studied; however, like soil health, the application was not based on P but on N which likely means that more P was applied (Giannakis et al., 2014; Grau et al., 2017; Moya et al., 2017). Furthermore, the amount of P in the soil was measured at the beginning and at the end of the experiments, which may not necessarily explain if P was available and meeting crop requirements during the growth of the crops (Tolofari et al., 2021). By measuring P every three weeks from planting until the physiological maturity of maize, this study monitored the transformation during both vegetative and reproductive stages of the maize crop. This work is the first to report that P from organic sources could maintain P concentration levels in the soil from vegetative to reproductive stages of maize growth just as the inorganic fertiliser. In Malawi, the P concentration in the soil for optimal maize growth and reproduction needs to be above 18 mg/kg. The P concentration was above the threshold in both inorganic and treated organic plots.

The new knowledge generated in this project would contribute to the specific approaches needed for P recycling in developing countries since the outlook is different from the developed nations. Furthermore, this study justifies the need for organic P recyclingas yield and soil health improve by using organic P sources..

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Chapter 6 . Conclusion

6.1 Introduction

This chapter summarises this study's successes and limitations; suggestions for future work are also presented.

6.2 Success

Overall, the study achieved the goals set. Through the use of STAN software and data from national and international databases, literature, reports, and expert judgement on food and fertilisers export and imports, human, population, P content in different organic materials, and sanitation facilities among other things, the study identified and quantified the sources and stocks of organic P in Malawi. Collectively, the sources of organic P add up to 35000 Mg of P annually, which is two times the inorganic P that Malawi imports (14000 Mg) annually for crop production. The major sources are faecal matter in pit latrines, accounting for 10000 Mg P, animal manure, with 6000 Mg of P in stock annually, and organic solid, which contributes about 5500 Mg of P each year.

Despite having two times its annual P demand in organic P sources, Malawi uses 66% inorganic P and 34% organic P for crop production. Still, the applied P is not enough because there is a negative P balance in the soil. Malawi should encourage the production and use of organic fertilisers to reduce dependency on inorganic P.

The study also found the importance of livestock and fish for the P flow in Malawi. The livestock gathers P from natural soil reserves by grazing natural pasture and bringing the P to households in the form of manure and animal products. The P that is lost to water bodies and P from natural minerals dissolving in water supports life in water. Some of the P from the water bodies is utilised by the fish that the human population consumes. The consumption of the fish recycles some of the P from water bodies. If fish waste (bones and intestines) and human excreta are used as fertilisers, then the some of the P lost to water bodies can be recycled.

The other success is that this study showed that in Malawi, the P in faecal sludge is concentrated in pit latrines and not at WWTPs as is the case in developed countries. This finding may also apply to other developing countries that do not have a well-developed sewer system, and where the citizens rely on on-site sanitation facilities.

The research also demonstrated that soil health indicators selected in this study: soil organic matter, pH, earthworm abundance, and bulk density, improved when organic fertilisers based on P recommendations were applied. Specifically, the soil pH went up by 23%, organic matter content in the soil increased by 82%, there were 500% more earthworms in plots treated with organic fertilisers compared to the NPK plots, and bulk density was reduced by 25%.

Apart from improving soil health, the organic P sources also did not reduce maize yield. The organic and inorganic P resulted in the same maize yield. On average, the maize yield was 5000 kg/ha.

soil available P of less than 18mg/kg is considered inadequate and reduce maize yield in Malawi. However, the application of organic and inorganic sources of P maintained the available P concentration in the soil at 25mg/kg (on average) throughout the maize growth period. By maintaining soil available P at 25 mg/kg means that the organic fertilisers are as good as NPK and can meet crop demand.

Another success was that the maize PUE was the same from both, inorganic and organic P sources. A similar PUE means that maize was able to absorb and utilise P from the organic source just as it was getting P from the inorganic sources.

6.3 Limitations and future studies

Although the implications of this work are novel and far-reaching, there are some limitations. Firstly, although the organic P sources were identified and quantified, the P flow analysis produced does not show the actual locations of the P sources (i.e., their distribution within the country). The next step should be to identify the precise locations and concentrations to aid decision-makers in developing recycling strategies to minimise transport to farming areas where the P can be utilised.

Secondly, much of the data used in the P flow analysis was from external databases and not based on locally available values. In order to produce nutrient flow analyses with minimal uncertainties and a true reflection of the Malawi situation, an organised database of all the nutrients contents of all the food products consumed and produced in the country must be put in one place. To deal with data uncertainty, the P analysis in this project employed a methodology developed by Hedbrant & Sorme (2001), which is a widely used approach in P flow analysis (Álvarez et al., 2018; Cooper & Carliell-Marquet, 2013; Klinglmair, Lemming, Jensen, et al., 2015; Laner et al., 2015).

Although the field trials were able to show the size-specific effects, the results are limited to two locations in the Southern Region. They are not generalisable to the whole country. Therefore, the study should be replicated in more locations to understand site-specific effects and develop site-specific recommendations. With a few more sites, it could be possible to use geospatial technology and geostatistics to extrapolate the results to a larger scale. It would also be beneficial to conduct these trials for longer (> 10 years) to establish the long-term benefits of applying the organic P sources to the soil. The long-term experiments can also be used to study the long-term adverse effects of organic P sources on water bodies and microplastic accumulation in the soil.

Future work should further investigate the earthworm species present in the treated and control plots: work beyond this study's scope. Over time, it may also be interesting to assess earthworm species succession in the organic fertiliser plots and whether each species plays different soil roles.

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