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Effect of Various Organic Fertilisers on Phosphorus Mineralisation, Use Efficiency and Maize Yield

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Abstract: When soils are phosphorus (P) deficient, external sources in the form of fertilisers have to be applied to increase crop yields. The world depends on mined sources for P fertilisers, and recent reports indicate that an increase in the human population has led to rising demand for P fertilisers, making its future supply uncertain. A low supply of chemical P fertilisers may lead to food insecurity. Although the efficacy of organic sources of P is unclear, organic waste materials containing P can potentially replace inorganic P sources. Previously, organic fertilisers have been used to supply N and even P, but the application rates were mostly N based, resulting in inconsistent and comparable results. This research was conducted to understand P mineralisation and the availability of the P-based organic fertilisers. The results 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 yield. The organic P sources maintained soil available P above the threshold available P value in Malawi. The P sources did not affect the maize P use efficiency (PUE). The results indicate that organic P sources could be used as an alternative fertiliser for maize production in Malawi.

Keywords: organic waste; faecal sludge; organic phosphorus; phosphorus use efficiency; Malawi

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1. Introduction

The bioavailability and concentration of soil phosphorus (P) are both significant for plant growth [1]. Among other factors, soil pH controls the bioavailability of phosphorus: in low pH/acidic soils (pH < 5.5), P forms stable compounds after reacting with aluminium and iron oxides, while in high pH/alkaline soils (pH > 8.5), P reacts with calcium. These reactions remove P from the solution (the aqueous phase) and make it difficult for the plant to access [2]. 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 level 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 [3]. If not replenished, the P would be depleted when the crop still needs it. P can be replaced using inorganic fertiliser or organic sources such as animal manure, faecal sludge, or compost.

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 [4–7]. Morocco-controlled Western Sahara is home to 75% of the world's phosphate reserves; the rest are in the United States of America, Jordan, China, and South Africa [8]. Between 2009 and 2019, phosphate mining increased by 51% [8,9]. Over 90% of mined phosphate rock is used to make fertilisers. Phosphate rock is necessary for food security and there is no replacement for P in agriculture [8,10]. For an adequate future food supply, the world needs to sustainably manage the current phosphate reserves and explore alternative sources of P, one of which could be made from organic waste materials.

Plants do not absorb all P that is applied. The amount of P taken absorbed by the plant depends on several factors such as soil pH, crop variety and the P source [11]. Knowing how much the plants take up helps to decide to increase or reduce the application rate to maximise plant yield and protect the environment. P 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 by the plant is either fixed in the soil or carried away by erosion, contaminating the water.

The P content and bioavailability in recycled sources such as organic waste, poultry litter, faecal sludge, urine, cattle, and pig manure varies. 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 [12]. However, the application of recycled P sources has been shown to increase both plant-available P and plant P uptake [1,13–15].

The effect of organic P sources on PUE has been reported to be equal to or 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, crop performance should 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 [16,17]. However, there is no consistency in the results [18,19]. 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.

Although previous studies evaluated organic fertilisers' impact on P availability, few studies used P-based application rates [18,20]; and they measured available P in the soil after harvesting the crops. The other studies' application rates were based on N requirements [21,22] and farmers' practice [23]. Sometimes, organic fertilisers were applied to evaluate their potential to supply plant nutrients, so the application rates were not based on nutrient requirements [15,24]. 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.

Furthermore, previous studies have demonstrated that organic P improve available P in soils and encourages P uptake by plants, but 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 [11]. In addition, the P organic sources were not P-based applications resulting in more or less than the required P being 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 need P during the early growth stages, e.g., wheat [25]. Previous studies show that the use of organic sources of P improves PUE [11]. 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 of P can improve it.

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 a 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 a positive impact on maize yield, and available P concentrations in the soil are affected by the P sources which influence the PUE of maize.

2. Methodology

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). Both sites are run by the Department of Agricultural Research Services in the Ministry of Agriculture, Irrigation, and Water Development.

Bvumbwe and Makoka research stations both have acidic, dark red Lixisols [26]. Sandy loam soils dominate Makoka with patches of heavy clays. The temperature ranges from 15.6 to 25 degrees Celsius, receives 1044 mm of rainfall annually and is located on the latitude 15° 32′ South and longitude 35° 11′ East at an altitude 1029 m above sea level. Bvumbwe gets 1219 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 1228 and 1174 m above sea level, latitude 15° 55′ South and longitude 35° 04′ East.

2.2. Experimental Design

The experiments were designed using a 5 × 4 factorial approach: five P sources, each with 4 levels (application rates, 0, 15, 30 and 45 kg P/ha), laid out in a complete randomized block design (CRBD) with four replicates. The treatments were market waste compost (MW), faecal sludge mixed with market waste compost (FSMW), market waste + NPK fertilizer (MW + NPK), faecal sludge mixed with market compost + NPK (FSMW + NPK) and NPK fertilizer, each with four application rates (0, 15, 30 and 45 kg P/ha) based on total P content of the fertilizers. The compost was sourced from Waste Advisors in Blantyre, Malawi. The faecal sludge mixed with market waste compost treatment was produced by mixing faecal sludge and market waste (1:1 on weight basis) when the compost pile was made. The NPK + organic fertilizers treatment was made up of half chemical P and half organic P source with reference to its P content. For example, 30 kg P/ha of FSMW+NPK was made up of 15 kg P/ha from FSMW and 15 kg P/ha from NPK.

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 × 6 m × 0.75 m); planting stations were 0.75 m apart with three maize plants per planting station. The recycled P materials were manually placed on the planting stations 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 treatments.

2.3. Soil and Compost Characterization

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 1). 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 2). The following chemical and physical properties were determined: pH [27], soil texture [28], organic carbon [29], total P [30,31], available P using a Mehlich 3 solution [30]. The metal (Fe, Al, Cd, etc.) concentrations were analysed after Aqua regia digestion and quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Table 1. 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.

Table 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
Zn (mg/kg)	447.61 ± 35.7	335.72 ± 59.48
Cd (mg/kg)	0.31 ± 0.03	0.23 ± 0.07

The numbers after ± are standard errors.

2.4. Data Collection, Calculations, and Analysis

Changes in available soil P were monitored by taking soil samples at weeks 3, 6, and 9 after planting from all the plots. Then, the average (from all the application rates) soil available P from all the treatments was compared. 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 (%).

$$\text{PUE} = \frac{\text{P in grains } \times 100}{\text{P added}} \tag{1}$$

PUE was determined after harvesting since the 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, which is why this study ignored other crop properties during the early growth stages and just focused on PUE and maize yield.

In Malawi, chemical fertilisers are imported. Basal fertilisers for maize are composed of 23 % N, 10% P, 5% K, and 6% S as macronutrients, and 0.1% Zn as micronutrients. In this study a recommended rate of N (92 kg N) was applied to all the treatments through Urea (46%N) in addition to the N applied through basal application. 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 1) 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 were 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 on 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 identify means which were different or the same.

3. Results

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) showed that available P at 3, 6, and 9 weeks after planting significantly impacted maize grain yield. The constant was high and significant (Table 3). 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. 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). The columns 1, 2, and 3 are regression results for available P at 3, 6, and 9 weeks after planting.

Parameters	Column 1	Column 2	Column 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 numbers in parentheses are standard errors.

The effect of the site on maize yield may be due to local environmental conditions such as 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). 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 each week is always a significant predictor of yield.

3.2. 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 as all the treatments in the first seasons (Figure 1). However, at nine weeks available P was different only in NPK treatment (Figure 1). The trend was the same in the second season.

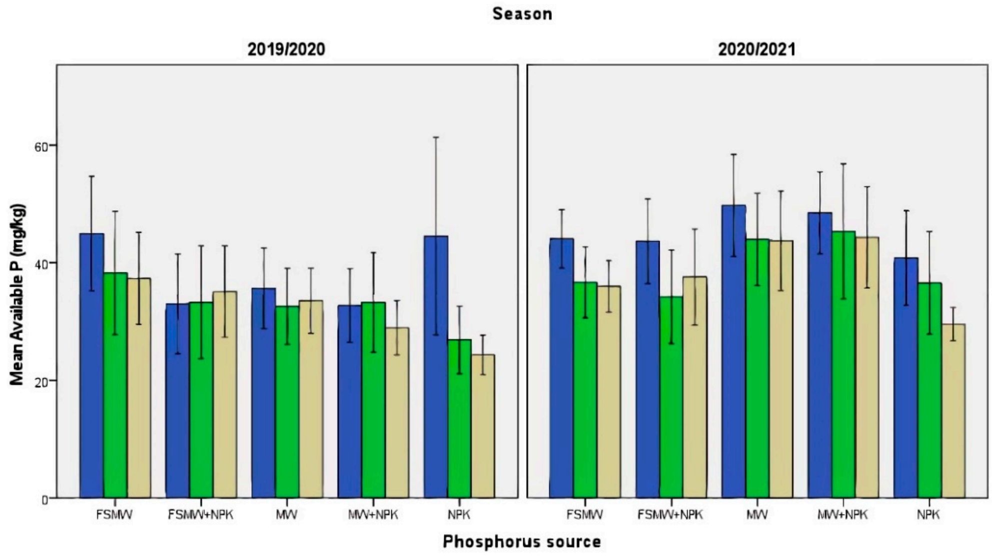

Figure 1. Soil available P three, six and nine weeks after planting at Makoka. The whiskers on the bar graphs indicate standard errors (n = 4). Key: blue = 3 weeks after planting, green = 6 weeks after planting, gold = 9 weeks after planting.

At Bvumbwe (Figure 2), ANOVA results showed that the available P concentration in the soil was the same regardless of the P source at three and nine weeks after planting in the first season, but it was different at six weeks.

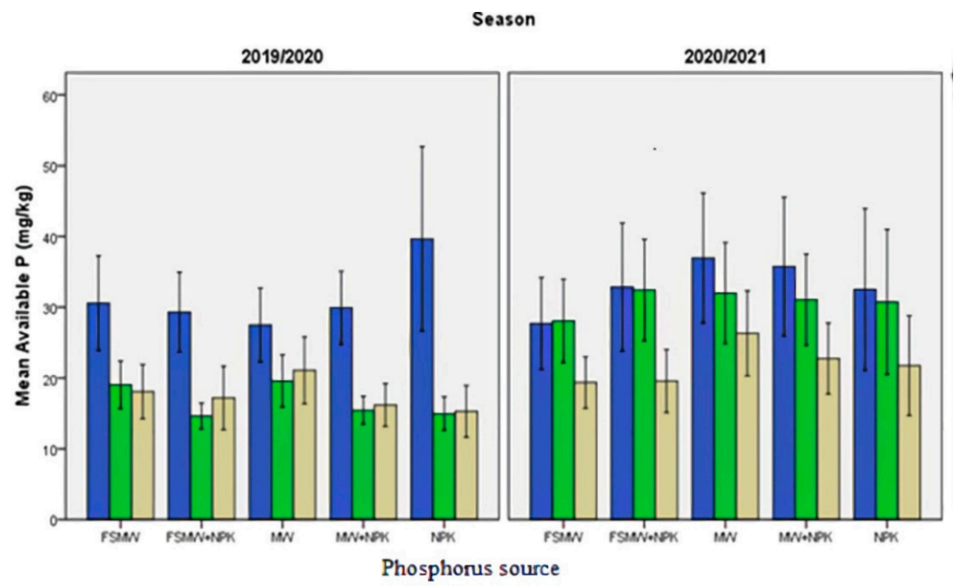

Figure 2. Soil available P three, six and nine weeks after planting at Bvumbwe. The whiskers on the bar graphs indicate standard errors (n = 4). Key: blue = 3 weeks after planting, green = 6 weeks after planting, gold = 9 weeks after planting.

In the second season (Figure 2), there were no differences in available P concentration at three, six, and nine weeks after planting. All the treatments had statistically the same concentration of P in the soil.

3.3. 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). 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 a 15 kg P/ha application rate in the second season.

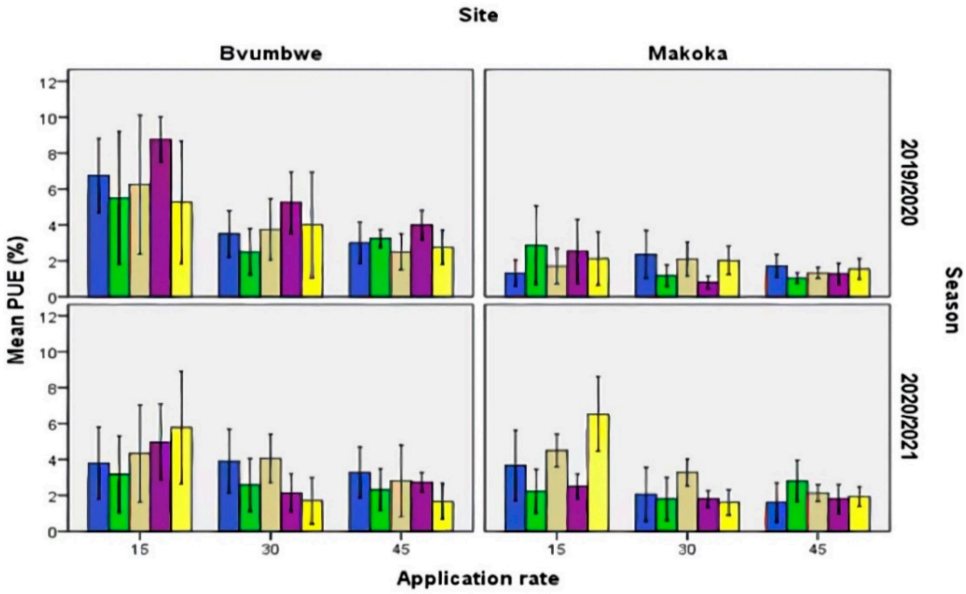

Figure 3. Maize PUE after application of different P sources at application rates in two seasons. The whiskers on the bar graphs indicate standard errors (n = 4). Key: blue = FSMW, green = FSMW + NPK gold = MW, purple = MW + NPK yellow = NPK.

4. Discussion

4.1. Effects of Available P on Maize 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 these nutrients are used for seed development [32]. 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 [33]. 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.

4.2. Effects of P Sources on Soil Available P

The results showed that both organic and inorganic fertilisers maintained the same concentration of available P in the soil in both seasons at Bvumbwe. Unlike inorganic fertilisers, only a small percentage of the P in organic fertilisers is readily available. The P becomes available as the organic fertilisers are mineralising, thereby increasing the available P in the soil. In soils dominated by iron and aluminium ions, as in this study (Table 2), P is easily fixed. However, organic molecules such as humic acid from the organic matter can chelate these metal oxide ions, thereby leaving P in solution [33,34]. 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). 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 in the NPK-treated plots. Organic fertilisers release nutrients slowly, which means that, unlike inorganic fertilisers, the P is available throughout the growth period of the crop and even the crops in the following year will utilise nutrients from the previous seasons [35,36]. The slow release of P from organic fertilisers reduces the chances of water contamination, since the released P is likely to be taken up by the growing crops, and not becoming leached or eroded. The P inorganic fertiliser, is readily available, increasing the chances of water contamination since the growing plants may not utilise it before it becomes leached or eroded. The results also show that organic fertiliser, which is relatively cheaper and locally available, can be used for maize production without fear of low output due to P deficiency. Chemical sources of P also come with heavy metals that threaten human health [10]. On the other hand, the organic fertilisers in Malawi made from organic waste and faecal sludge have a negligible concentration of heavy metals, e.g., Cd (Table 2).

4.3. Effects of P Sources on PUE

Although others have reported that P sources affect the PUE [18,19], 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 stems) is relocated to the grains [37]. P deficiency does not necessarily reduce P portioning to different parts of the plant but reduces yield [37]. 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. [38] found that different maize cultivars partition P differently at maturity. Some accumulate more P in the leaves and stems than in the seeds.

The results agree with the results of Xin et al. (2017) 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. (2017) 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 (SC 2403) was one of the hybrid maize varieties cultivated in Malawi. However, PUE is cultivar specific as P uptake by maize cultivars varies [37,38], suggesting that different cultivars will have different PUE values.

5. 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 been shown to be associated with increased maize yield. Therefore, the hypothesis that available P in the soil during the early growth stages of maize has an 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, identical to 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 the PUE of maize is influenced by P source were rejected.

Although P is necessary for plant growth, it is also dangerous for water bodies; excessive P may cause eutrophication. 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, and P transfer to water bodies can also be studied. Studies on the modelling of P mineralisation and crop uptake from organic fertilisers can also utilise data from long-term trials.

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