Aluminum phosphate sludge as a phosphorus source for maize production under low soil phosphorus availability

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Background. With increasing food demand as a consequence of the growing world population, there is a corresponding demand for additional sources of phosphorus (P). Alum-phosphate (Al-P) sludge is a by-product of wastewater treatment and can be a good source of P. In this study, the response of maize (*Zea mays* L.) to Al-P sludge was tested. Maize was chosen as the test crop due to its prevalent use as human and animal food and as a source of biofuel. The objective of the study was to investigate Al-P sludge as a source of P compared to a commercial fertilizer (monoammonium phosphate, MAP).

Methods. A growth chamber assay was conducted over four cropping cycles (45 d each). The application rate was 9.7, 19.4, 29.1 and 38.8 mg P kg^{-1} dry soil. Amendments were applied once at the start of the first cropping cycle. Plants were harvested after each cycle and pots were re-seeded. Dry matter yield (DMY), total P uptake, Al-P uptake, soil total P and Olsen-P concentrations, pH, and EC were measured.

Results. DMY was significantly greater in pots amended with Al-P sludge than in pots treated with MAP. There was a significant rate × cropping cycle interaction effect on DMY with the differences among rates in cycle 1 different from those in cycle 4. Phosphorus uptake depended on cropping cycle, P source and P application rate. With sludge uptake higher than MAP in all cycles, the highest P uptake was observed at the highest application rate except for cycle 2 where this was observed at the rate 29.1 mg kg^{-1}. For MAP, Phosphorus recovery efficiency (PRE) at the highest rate was significantly greater than that at the lowest rate whereas PRE in cycle 1 was significantly higher than that in cycle 4. In the first two cycles, aluminum uptake was negligible in both MAP and Al-P sludge treatments; however, in cycles 3 and 4, there was significantly more Al in maize from sludge amended pots. Our results show that Al-P sludge was as effective as MAP in supplying enough P for biomass yield. We, therefore, conclude that Al-P sludge could be an alternative source of P, especially for growing maize as feedstock for bioenergy.

Aluminum Phosphate Sludge as a Phosphorus Source for Maize Production under Low Soil Phosphorus Availability

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Abstract

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29   **Results.** DMY was significantly greater in pots amended with Al-P sludge than in pots treated

30   with MAP. There was a significant rate × cropping cycle interaction effect on DMY with the

31   differences among rates in cycle 1 different from those in cycle 4. Phosphorus uptake depended

32   on cropping cycle, P source and P application rate. With sludge uptake higher than MAP in all

33   cycles, the highest P uptake was observed at the highest application rate except for cycle 2 where

34   this was observed at the rate 29.1 mg kg^{-1}. For MAP, Phosphorus recovery efficiency (PRE) at

35   the highest rate was significantly greater than that at the lowest rate whereas PRE in cycle 1 was

36   significantly higher than that in cycle 4. In the first two cycles, aluminum uptake was negligible

37   in both MAP and Al-P sludge treatments; however, in cycles 3 and 4, there was significantly

38   more Al in maize from sludge amended pots. Our results show that Al-P sludge was as effective

39   as MAP in supplying enough P for biomass yield. We, therefore, conclude that Al-P sludge could

40   be an alternative source of P, especially for growing maize as feedstock for bioenergy.

41   Introduction

42   To sustain future economic growth, fertilizer usage will continue to increase due to increasing

43   population and corresponding food demand (Schroder et al., 2011). With several speculations of

44   pure phosphate rock extinction, there may be a looming crisis in the nearest future (Liu et al.,

45   2020). Improved agronomic practices and soil fertilization are expedient to alleviate phosphorus

46   (P) pressured demands. With over-reliance on mineral fertilizers, the agronomic sector face a

47   near global-P challenge and increasing environmental concerns as global P usage efficiency is

48   reported to be about 25% on average (MacDonald et al., 2011; Dhillon et al., 2017; Liu et al.

49   2020; Sattari et al. 2012). In the face of this scarcity, with the agricultural sector accounting for

50   about 90% of P demand (Maghsoodi et al., 2020; Childers et al., 2011), focus on P recovery from

51   Al-P sludge should be prioritized.

52 P is abundantly found in wastewater sludge, and depending on the treatment method applied, it

53 could be chemically or biologically bound (Ojo and Ifelebuegu, 2018). With the abundance of

54 chemical sludge (aluminum phosphate) in Manitoba Canada, aluminum-phosphate (Al-P) sludge

55 is mostly landfilled. This disposal method is quite expensive (Keeley et al., 2012; Babatunde and

56 Zhao, 2007). P recovery from chemical sludge is one of the ways to ensure a cleaner and more

57 sustainable environment as well as ensure that all sludge P are put to beneficial use (Tolofari et

58 al., 2021; Alvarenga et al., 2016; Mazen et al., 2010).

59 As a widely studied crop, maize is mostly known for its feed generation for humans and animals.

60 It is the third-ranking cereal and a very critical staple for the world's growing population

61 (FAOSTAT 2010; Ranum et al., 2014). In recent times, it is a widely sought-after feed for

62 ethanol production. Maize generates more ethanol due to cellulose conversion technology

63 (Schwietzkey et al., 2009). With an increasing demand for maize in bioethanol production, there

64 will be intensifying competition and a surge in demand for all first users (man and animal).

65 Maize cultivation and production should be intensified to secure its availability through a rising

66 global demand scenario. Rosegrant et al. (2009) reports a shortage in current production

67 compared to demand, which is most likely to double by 2050 in developing countries (Shiferaw

68 et al., 2011). A significant challenge to achieving this surplus production is hinged on the reports

69 of depleted P reserves (Cordell et al., 2009), with fertilization cost seen as a major contributor

70 making maize less affordable (Omenda et al., 2021; Pereira et al., 2020; Metson et al., 2016). P

71 usage for maize is crucial at the initial growing season and can primarily affect yield and uptake

72 (Cadot et al., 2018; Lino et al., 2018; Grant et al., 2001). Root development and distribution

73 relative to the P in soil solution determine the extent of P uptake by maize (Klamer et al., 2019;

74 Mollier and Pellerin, 1999). With a higher initial P concentration in soil solution, plants have a

75 better initial root development and subsequent yield increase (Dhillon et al., 2017; Wu et al.,

76 2015).

77 Therefore, reuse options for Al-P sludge are viable to enhance the reduction of GHG emissions;

78 this can be achieved by the cropping of maize solely to produce ethanol as a biofuel (Tolofari et

79 al., 2021; Maghsoodi et al., 2020). This would reduce cost competition against first users better

80 the environment and prevent groundwater contamination (Hoekman et al., 2018; Chiodo et al.,

81 2018).

82 Al-P sludge is rich in organic carbon and major nutrients such as N, P and K, which are

83 beneficial to crops (Kluzcka et al., 2017; Kim et al., 2002). The use of Al-P sludge for growing

84 crops is a cost-effective way of recovering P as well as a means to improve overall soil

85 properties that facilitate plant growth (Kim et al., 2002). This amendment can fill some gaps in

86 the P industry and also foster growth in the agricultural industry. The risk of Al toxicity has been

87 highlighted as a limitation to the use of Al-P sludge (Kluzcka et al., 2017; Kim et al., 2002);

88 however, creating the right balance in terms of soil conditions and application rate could allow

89 for the safe use of Al-P sludge as a nutrient source for crop plants. The reuse of Al-P sludge as a

90 P recovery option is a crucial step in addressing some of the challenges with the forecasted

91 depletion of global P reserves and to reduce the dependence on inorganic fertilizers. Phosphorus

92 availability in Al-P sludge could be dependent on the organic matter content and pH of the soil

93 (Chowdhury et al., 2020; Tolofari et al., 2021).

94 The objective of this study was, therefore, to investigate the effectiveness of Al-P sludge as a

95 source of P compared to a commercial fertilizer (monoammonium phosphate) at 9.7, 19.4, 29.1

96 and 38.8 mg P kg^{-1} dry soil. We hypothesize that (i) P uptake by maize is greater in MAP-

97 amended soil than in soil amended with Al-P sludge, (ii) maize biomass yield increases with P

98   application rate and (iii) maize biomass yield decreases as the number of cropping cycles

99   increases.

Materials & Methods

Phosphorus Sources

102   Dewatered sludge with 18% solids content was sourced from Headingley wastewater treatment

103   plant in Manitoba, Canada (49°52' 25.4" N; 97°26'16.1" W), while monoammonium phosphate

104   (MAP, 11-52-0; a soluble inorganic commercial fertilizer containing 11% nitrogen and 52%

105   phosphate) was obtained from a local distributor in Canada. Application of P to potted soil was

106   based on the available P concentration in the Al-P sludge to enable comparison between sludge

107   and MAP treatments. Since a large percentage of total P in the sludge is organic and unlikely to

108   be readily available for plant uptake, applying P on the basis of bicarbonate-extractable P (Olsen-

109   P; Olsen et al., 1954) content in Al-P sludge was more appropriate. Application of sludge based

110   on available P (Olsen-P) should be carefully considered as a part of the non-labile P pool could

111   mineralize during the cropping period. Thus, sludge application based solely on available P

112   could lead to the addition of excess available P than intended (Tolofari et al., 2021). Chemical

113   properties of the Headingly sludge have previously been reported (Tolofari et al., 2021) with a

114   moisture content of 82% and total phosphorus (TP) concentration of 11,560 mg kg^{-1}.

Soil

116   Topsoil (0-15 cm) from Roseisle, Manitoba, Canada (49°33.577' N; 98°24.824' W) was used for

117   this study. The soil was a well-drained Entisol (dark-grey Gleyed Regosolic sand) with an initial

118   pH of 8.2 and a Olsen P concentration of 3 mg kg^{-1} (Tolofari et al., 2021).

119   Chemical properties of the soil have been previously published (Tolofari et al., 2021) and are

120   summarized in Table 1.

121
122
123 **Experimental Set-up**
124 The investigation was conducted in a growth chamber where the temperature regime was

125 maintained at 25/15°C for day/night respectively, with a relative humidity of 60%, and a

126 proportionate photoperiod of 16 h. The experimental design was completely randomized; the set-

127 up was with a factorial treatment structure involving two P sources (MAP and Al-P sludge), four

128 P application rates (9.7, 19.4, 27.1 and 38.8 mg P kg^{-1} dry soil) and four cropping cycles. Sludge

129 P application was based on Olsen P concentration. The sludge application rates were 12, 24, 36

130 and 48 g kg^{-1} dry soil to achieve the above stated P application rates. All treatments, including

131 the control, were replicated three times. On a dry weight basis, P application rates corresponded

132 to 9.8, 19.7, 29.5 and 40 kg ha^{-1} P. Typical agronomic rates for corn in Manitoba are within the

133 range 20 to 25 kg ha^{-1} P (Manitoba Agriculture, 2007).

134 The soil was meticulously mixed and passed through a 4 mm sieve to remove stones and roots,

135 after which it was air-dried and properly stored for analysis. Approximately 1.5 kg of air-dried

136 soil sample was put into each 14.9 cm diameter by 16.5 cm height plastic pots. Reverse osmosis

137 (RO) water and a full-strength nutrient solution without P (Zvomuya et al., 2006) were added to

138 all pots to bring the soil moisture content to field capacity. The pots were then stored in a growth

139 room for 24 h prior to the commencement of planting.

140 Three maize seeds were planted into each pot; the seedlings were later thinned down to one 5 d

141 after germination. The pots received two applications of essential macronutrient solutions (P

142 excluded) in each growth cycle (Zvomuya et al., 2006). All pots were weighed and watered

143 every other day to replace moisture lost via evapotranspiration. A total of four cropping (seeding

144 to harvest) cycles were completed, with each cycle lasting 45 d in duration. Plants were

145 harvested on Day 45 by clipping at 2 cm height above the surface of the soil. The contents of

146   each pot were emptied into a clean tray and thoroughly mixed. A 20-g soil subsample was

147   collected at the end of every growth cycle for analysis. Plant roots were recovered, cut into small

148   pieces, and mixed with the soil, which was re-potted for the next cropping cycle. The soil was

149   stored in the growth room for 5 d before planting. Harvested biomass was weighed and oven-

150   dried for 72 h at approximately 60°C. Oven-dried biomass samples were later weighed, chopped

151   into tiny pieces, and fine-ground in a mill grinder (< 0.2mm, Model 8000D Spex Sample Prep,

152   Metuchen, NJ). At the completion of the fourth cycle, plant roots were retrieved, washed with

153   RO water, dried, and ground for analysis.

154   **Laboratory Analysis**

155   Preliminary analysis before bioassay, the plant available (Olsen) P was analyzed for the soil

156   using the ascorbic acid-molybdate method (Murphy and Riley, 1962) with a Skalar SAN++

157   segmented flow analyzer (Skalar Analytical B.V., Breda, Netherlands)] after extraction with 0.5

158   M concentration of $NaHCO_3$ at pH 8.5 (Olsen et al., 1954); concentration of nitrate (using Cd

159   reduction method; Mulvaney, 1996); pH of the soil and electrical conductivity (1:1 soil to water

160   suspension); exchangeable K, Mg, Ca, and other cations [using atomic absorption spectroscopy

161   after extraction of 5 g of soil with 33 mL of 1 M concentration NH_4OAc at a pH of 7

162   (Hendershot et al., 2008)]; concentration of aluminum (Al) in the soil was measured with an

163   inductively coupled plasma optical spectrophotometer (ICP-OES, Thermo Electron ICAP 6300

164   Radial) after the digestion of the samples in block digester using sulfuric acid (99.7% H_2SO_4) and

165   hydrogen peroxide (30% H_2O_2) (Parkinson and Allen, 1975); cation exchange capacity (sum of

166   exchangeable Na, K, Ca and Mg) (Hendershot et al., 2008); concentration of soil organic matter

167   (SOM) [using loss on ignition method (Nelson and Sommers, 1996)]; and carbonates were

168   analyzed using the pressure calcimeter method (Loeppert and Suarez, 1996), represented as

169   calcium carbonate equivalent (CCE). Soil organic carbon (SOC) concentration was obtained by

170   multiplying SOM by 0.58.

171   Total P (TP) and aluminum (Al) concentrations in the plant tissue were measured with an

172   inductively coupled plasma optical spectrophotometer (ICP-OES, Thermo Electron ICAP 6300

173   Radial) after the digestion of the plant tissue samples in a block digester using sulfuric acid

174   (99.7% H_2SO_4) and hydrogen peroxide (30% H_2O_2) (Parkinson and Allen, 1975). Concentration

175   of Olsen-P in the soil was determined by the $NaHCO_3$ (99.7%) extraction method (Olsen et al.

176   1954; Olsen and Sommers 1982) at pH 8.5. Phosphorus concentration in the extract was

177   determined colorimetrically using the ascorbic acid-molybdate method (Murphy and Riley,

178   1962).

179   **Statistical Analysis**

180   To determine treatment and interaction effects, analysis of variance (ANOVA) was carried out

181   on P concentration in the soil, dry matter yield, P uptake and PRE data using PROC GLIMMIX

182   for repeated measures (with cycle as the repeated measures factor) in SAS 9.4 (SAS Institute,

183   2013). Phosphorus recovery efficiency (PRE) was computed as [(P uptake in each amended pot –

184   P uptake in control pot)/ P application rate] for each harvest. Phosphorus source and P rate were

185   modeled as fixed effects. Data for all variables were normally-distributed, except for Olsen P

186   data which were analyzed as a lognormal distribution and PRE as a beta distribution. Treatment

187   means were compared using the Tukey multiple comparison procedure at $\alpha = 0.05$.

188   # Results and Discussion

189

190   **Dry Matter Yield**

191   We observed a significant effect of P source on maize DMY (Table 2). Averaged across all rates

192   and cycles, pots amended with sludge had a significantly higher DMY than MAP amended

193   treatments. Ramphisa and Davenport (2020) reported a different result as no significant effect of

194   P source (MAP and organic manure) was observed on corn yield in their study. The authors

195   attributed the lack of P source effect on maize yield to the short time (2 years) of the study. The

196   same was true for the study on maize using alum sludge where there was no recorded significant

197   DMY although this was attributed to the type of seed used (Lin and Green, 1990). The higher

198   yield observed in our study for sludge amended soils could be due to the increase in inorganic P

199   from sludge total P, as organic P can be transformed to inorganic P with time (Shen et al., 2011).

200   Another reason could be that the sludge addition increased the organic matter content present in

201   the soil coupled with the plant residue/root incorporated after each cycle. This could have

202   increased microbial activities hence the overall increase of DMY (Gatiboni et al., 2008).

203

204   Regardless of the amendment applied, the rate effect on DMY varied with the cropping cycle

205   (Table 2; Fig. 1). For cycle 1, as the rate increased from 9.7 to 19.4 mg P kg^{-1} soil, we observed a

206   significant increase in DMY. Between 19.4 and 29.1 mg P kg^{-1} soil, there was no significant

207   difference between DMY. However, a significant increase in DMY was identified between 29.1

208   mg P kg^{-1} soil and 38.8 mg P kg^{-1} soil. For cycles 2 and 3, DMY was similar across all rates, no

209   significant effect of rate on DMY. For cycle 4, DMY was similar for rates 9.7, 19.4 and 29.1 mg

210   P kg^{-1} soil. DMY was significantly higher at 38.8 mg P kg^{-1} soil in contrast to the lowest rate, 9.7

211   mg P kg^{-1} soil. However, the DMY at 38.8 mg P kg^{-1} soil was similar to DMY at 19.4 and 29.1

212   mg P kg^{-1} soil. Similar to what was observed in cycle 1, Lino et al. (2018) observed an increasing

213   rate effect on corn yield. Ortas and Islam (2018) observed a non-linear increase in corn yield

214   with respect to increasing P application rate. They attributed the increased yield to higher soil P

215   availability due to mycorrhizal root interactions and mineralization of soil organic material

216 (Ortas and Islam, 2018). For our study, a low-P soil was used; however, since some P was

217 supplied in the first cycle, it could be that this increased the available P pool thus removing any

218 rate effect in cycles 2 and 3 (Lopes et al., 2007). The increase in DMY for the highest rate in

219 cycle 4 could be because of an interaction effect between soil processes and mineralization of

220 incorporated roots (Ortas and Islam, 2018, Martinazzo et al., 2007; Santos et al., 2008).

221 Sludge, which is rich in organic matter and major nutrients, can improve soil physical and

222 chemical properties which are important for plant growth (Rodríguez-Berbel et al., 2022), and

223 therefore yield. The increase in DMY must have been improved by soil properties such as CEC,

224 organic carbon, carbonates etc. The addition of Al-P sludge to the soil resulted in an increase in

225 SOM, which then improved the fertility and properties of the soil (Chowdhury et al., 2020). For

226 example, Chowdhury et al. (2020) explained that CEC above 10 $cmol_c$ kg^{-1} soil would improve

227 plant growth as well increase biomass yield. This would also improve uptake of micronutrients

228 and prevent deficiency. The presence of organic carbon improves the availability of nutrients by

229 the continuous decomposition and breaking down of bound nutrients into readily usable forms

230 which would improve crop growth and invariably the dry matter yield of the plant. Organic

231 matter decomposition facilitates nutrient availability and uptake by roots, thus increasing DMY

232 (Chowdhury et al., 2020; King et al., 2020).

233 **Phosphorus Uptake**

234 Phosphorus uptake showed a significant amendment by rate by cycle interaction (p< 0.002)

235 (Table 2, Fig. 2). For cycle 1, as the rate increased from 9.7 mg P kg^{-1} soil to 38.8 mg P kg^{-1} soil,

236 we observed a significant increment in P uptake by maize in both MAP and sludge amended

237 soils. Interestingly, P uptake by maize was significantly higher in sludge amended soils than in

238 MAP at all application rates. For both P sources, the highest P uptake by maize occurred at the

239 highest application rate. This report collaborates what Pizzeghello et al. (2019) and Yossif and

240   Gezgin (2019) observed. The authors reported an increased P uptake as the application rate of

241   MAP/single superphosphate and MAP/DAP increased (Pizzeghello et al., 2019; Yossif &

242   Gezgin, 2019). Silva et al. (2012) also reported that the highest P uptake was at the highest P

243   application rate.

244   For cycle 2, P uptake in sludge amended pots was significantly higher at each rate compared to

245   MAP amended pots, this observation is similar to cycle 1. As the rate increased for MAP, there

246   was no significant increase in P uptake. For sludge amended soils, there was no significant

247   difference in P uptake at these application rates (9.7, 19.4, and 38.8 mg P kg^{-1} soil). The highest

248   P uptake from sludge amended soils occurred at rate of 29.1 mg P kg^{-1} soil and was significantly

249   higher than P uptake in pots amended with rate 9.7 mg P kg^{-1} soil. However, in cycle 3, there

250   was a significant increase in P uptake between rate 9.7 and 38.8 mg P kg^{-1} soil for sludge

251   amended soils. As the application rate increased, no significant increase in P uptake from MAP

252   amended soils was observed for cycle 3. For cycle 4, similar to what we observed in cycle 3,

253   there was no significant increase in P uptake with increasing P rate in MAP amended soils.

254   However, P uptake increased between rate 9.7 and 29.1 mg P kg^{-1} soil. P uptake in pots amended

255   at rate 29.1 mg P kg^{-1} soil was not significantly different to P uptake at 38.8 mg P kg^{-1} soil, for

256   sludge amended soils.

257   For MAP and sludge amended soils, the highest P uptake was observed for cycle 1. This was not

258   surprising for MAP as it is an inorganic source of P, and all its P is in the readily available form.

259   Readily available P in MAP may have been precipitated by calcium and magnesium in the soil,

260   thus reducing its availability to plants (Tolofari et al., 2021). Sludge, being an organic source of

261   nutrients has both organic and inorganic pools of P, with the organic pool being a long-term

262   source of available P with a gradual release pattern for other growth cycles (Ahmed et al., 2010;

263   Kiehl, 2008). This provides an explanation of the differing trends we observed in the different

264   cycles as the organic P becomes more available. In cycles 1, 2 and 3, at each P rate, P uptake in

265   sludge amended soils was significantly greater than MAP amended pots. However, in cycle 4, at

266   9.7 mg P kg^{-1} soil amendment application rate, there was no observed significant difference in P

267   uptake between sludge and MAP amended pots. At other rates, the trend was similar to those

268   observed in previous cycles where P uptake for sludge treatments was higher. The similar P

269   uptake in cycle 4 for both MAP and sludge at the lowest rate (9.7 mg kg^{-1} soil) could be

270   explained by the complete mineralization of all the organic P in the sludge as a consequence of

271   the lower P supplied at this rate (9.7 mg kg^{-1} soil) (Santos et al., 2008; Martinazzo et al., 2007). It

272   is also possible that newly developing roots do not have good contact with soil solution, hence

273   reducing P uptake from the pot (Rehim et al., 2016).

274   **Phosphorus Recovery Efficiency**

275   There was a significant P source × cycle interaction and P source × rate interaction. For sludge,

276   there was no significant effect of rate on PRE, while for MAP, there was a numerical increase in

277   PRE with increasing P application rate (Fig. 3). PRE for MAP amended soils was significantly

278   higher at 38.8 mg kg^{-1} soil compared to 9.7 mg kg^{-1} soil. Similar to our Al-P sludge treatment, Sa

279   et al. (2017) reported no significant change in PRE across all rates of P application for both

280   organic and inorganic P sources (50-400 mg P kg^{-1} soil). The authors also observed no

281   significant difference between PRE of MAP and OMF (Sa et al., 2017). This was not the case in

282   our study as at every application rate, sludge had a significantly greater PRE than MAP.

283   Although, Sa et al. (2017) expected differences due to the different formulations of the fertilizers

284   and the uniqueness of the contact surfaces, which could affect P availability, they observed none.

285   They however concluded that the recovery efficiency with the high DMY makes poultry litter a

286   competitive source of P. In our study, the higher PRE for sludge compared to MAP might be due

287   to an increase in the bioavailability of the P in Al-P sludge when in contact with the calcareous

288   soil (Von Wandruszka, 2006). Since P in MAP is in the readily available form, its P

289   bioavailability in calcareous soils could be limited due to the formation of less soluble forms

290   through its interaction with Ca and Mg hence leading to precipitation (Weeks and Hettiarachchi

291   2019; Naeem et al., 2013; Syers et al., 2008).

292   Tolofari et al. (2021) reported that PRE for sludge amended pots had shown the highest recovery

293   efficiency at the lowest P application rate (9.7 mg kg^{-1}). At the other P rates in their study, no

294   significant difference in PRE at was observed (Tolofari et al., 2021); this is similar to our

295   observation. Yossif and Gezgin (2019), who worked on maize, observed that P recovery for

296   calcareous soils is low, with the highest recovery observed at 30 mg kg^{-1} P_2O_5 (13.77%) and the

297   least recovery at 90 mg kg^{-1} P_2O_5 (9.36%). Low PRE observed at higher P application rates could

298   mean that maize used just a small fraction of the applied rate (Rehim et al., 2012a).

299   There was also a significant P source by cycle interaction (Fig. 4). In all cycles, PRE of sludge

300   was significantly higher than MAP. For MAP, PRE decreased with cycle. This is mostly due to

301   the possible fixation of available P due to the calcareous nature of the soil, and this is also

302   aggravated by the one-time P source addition which was prior to the first cycle. In contrast, no

303   increasing or decreasing trend was observed for sludge amended soils in all four cycles. The

304   varying PRE for sludge is similar to the trend we observed for P uptake and could be attributed

305   to the slow release of available P from the organic P pool in sludge (Iyamuremye et al., 1996).

306   The lowest P uptake was observed in cycle 4, which explains the PRE in cycle 4. Tolofari et al.

307   (2021) observed an increase in PRE with cycle which was dissimilar to our study, as we

308   observed decreasing PRE with cycle (for MAP) and no trend for sludge. This difference could be

309   due to the effect of the plant/organic residue which was re-introduced into the pots, and which

310   must have increased biological activities in the soil (Smith et al., 1993; Nziguheba et al., 1998).

311   **Aluminum Uptake**

312   There was a significant P source × cycle interaction on aluminum uptake, indicating that

313   aluminum uptake in each cycle was dependent on the P source (Fig. 5). In cycle 1 and 2, Al

314   uptake by MAP and sludge was similar (Fig 5). It is important to state that the Al uptake was

315   very close to zero in cycle 1 and 2 (Table 2). In cycles 3 and 4, there was significantly more Al

316   uptake in sludge amended soils compared to MAP amended soils, with the uptake in cycle 4,

317   higher than uptake in cycle 3. This suggests an effect of time as well as P source on Al release

318   from soil. Unfortunately, Al in soil was not quantified at the start of the study. The Al in sludge

319   could have contributed to the increased Al uptake from sludge amended pots. The mineralization

320   of organic matter may have caused an increase in the uptake of Al by the plants (Meriño-

321   Gergichevich et al., 2010; Hede et al., 2001).

322   Maize is reportedly a very sensitive crop to Al and high levels of Al limits biomass production

323   and P uptake, even at very low Al application rates and short exposure intervals (Giannakaola et

324   al., 2008; Yossif and Gezgin, 2019; Tandzi et al., 2018). The effect of Al in alkaline and acidic

325   soils negatively impact root growth, however acidic soils have much more severe impact on root

326   reduction (Stass et al., 2006; Lidon & Barreiro, 2002). In this work, the effect of Al was not

327   noticeable as Al uptake did not occur in the first two cycles. This could be due to the pH of the

328   soil which was at 8.2 at the start of the experiment. Mimmo et al. 2009 explained that prominent

329   levels of Al in soil may affect nutrient uptake; however, their experiment on beans showed that P

330   uptake was not significantly limited by Al in soil even at a pH of 4.50. Although the species of

331   Al in the soil were not assessed, Al can be organically bound, exchangeable or in crystalline

332 form (Kluckza et al., 2017). The Al species expected at the pH in our study are $Al(OH)_3$,

333 $Al(OH)^{2+}$ and $Al(OH)_2^+$ (Meriño-Gergichevich et al., 2010). Understanding the speciation of Al

334 in the soil explains a lot about their interaction. In this study however, Al uptake occurred even

335 in the control which could be due to the solubility of Al in the soil. Kluckza et al. (2017)

336 explained that increase in Al around neutral pH is mostly due to exchangeable Al in the soil and

337 Al bound to organic matter.

338 The duration of Al species incubation in the soil can also affect its bioavailability (Iqbal, 2012).

339

340 **pH**

341 There was a significant P source × cycle interaction for soil pH (Fig. 6, Table 2). In cycles 1 and

342 2, the pH did not differ significantly between sludge and MAP. It is noteworthy that, in cycle 1,

343 the pH of both MAP and sludge amended soils were in the alkaline range, while in cycle 2, the

344 pH of both P source treated soils were near neutral indicating a reduction in pH in cycle 2 (Fig.

345 6). In cycle 3 however, the pH for MAP amended soils was in the acidic range (6.3) and was

346 significantly lower than pH for sludge amended soils (7.8). This reduced pH in MAP amended

347 pots in the third cycle may be due to the excretion of organic acids by the roots in the soil. Since

348 available P may have been diminished, organic acid excreted by roots may be able to solubilize P

349 from metal P salts and make it available for utilization (Hinako et al., 2021). In cycle 4, there

350 was no significant difference between pH of MAP and sludge amended soils (Table 2). Calba et

351 al. (2006) reported a reduction in soil pH of about 0.23 units upon continuous maize cropping

352 using organic and inorganic fertilizer in acidic soil of pH 4.8. Similar to Calba et al. (2006), we

353 observed a decreasing trend for MAP until cycle 3, however there was an increase in pH in cycle

354   4. This alkalinity reduction could mostly be due to the buffering capacity of the soil (Keramati.,

355   2010).

356   Generally, at the soil pH in cycles 3 and 4, we would not expect high Al exchange in the soil.

357   The increased uptake of Al in the 3rd and 4th cycles for alum-P pots could be part of the effect of

358   incubation duration and an effect of organic matter mineralization due to the incorporation of

359   roots into the pots after each cycle (Grzyb et al., 2020; Hadas et al., 2004). Schwesig et al. (2003)

360   highlighted that the mineralization of organic matter in the soil would result in increased

361   concentrations of free Al^{3+} in soil solution.

362   There was also a significant rate effect on soil pH (Fig. 7). Across all cycles and both P sources,

363   there was a numerical increase in pH with amendment rate. Soil pH was not significantly

364   different between rates 9.7 and 29.1 mg kg^{-1}, however, pH in soil amendment with the highest P

365   rate (38.8 mg kg^{-1}) was significantly higher than pH in pots amended at P rates of 9.7 and 19.4

366   mg kg^{-1}. Contrary to our finding, Arvas et al., 2011 reported that the lowest pH values were

367   identified in pots of the highest application rate of sewage sludge; this they attributed to the

368   effect of root biomass in the soil. Ahmad et al. (2019) observed the highest values in units with

369   the highest DAP application rates while single superphosphate showed a slight decrease in pH.

370   **Olsen P and TP**

371   There was a significant effect of P rate on soil Olsen P (Table 2). As expected, there was a

372   numerical increase in soil Olsen P as the amendment rate increased. At the lower P application

373   rates, there was no significant difference in soil Olsen P between P sources. The highest Olsen P

374   recorded in our study was at the highest P application rate. Wen et al. (2016) and Zhan et al.

375   (2016) indicated that the increase in Olsen-P at higher rates was as a result of increased

376   decomposition of organic matter in the soil. Rehim et al. (2016) also found a similar increase in

377 Olsen-P with respect to increasing rate of P application while lower Olsen-P values could be

378 attributed to efficient P usage by the crops.

379 There was also a significant cycle effect on soil Olsen P. The highest soil Olsen P was observed

380 in cycle 2, and this was significantly greater than Olsen P in other cycles. Overall decrease in

381 Olsen-P could have resulted in declining PRE trend observed for MAP.

382 For soil total P, there was a significant cycle and P source effect. Total P decreased with cycle

383 until cycle 3, and no significant change was observed in cycle 4. TP trend was cycle 1> cycle 2 >

384 cycle 3= cycle 4. This was as expected as it clearly shows that accumulated soil P was being

385 utilized for subsequent crop growth (Zhang et al., 2020). TP measured in sludge amended pots

386 was significantly greater than in MAP amended pots. This was not surprising as sludge

387 properties showed that it contained a large amount of total P (Tolofari et al., 2021).

388 **Conclusions**

389 Our results demonstrate the effectiveness of P uptake from Al-P sludge using maize as a test crop

390 in a growth room. Maize yield significantly increased with the application of Al-P sludge

391 compared to MAP; however, there was a general decrease in biomass yield as the number of

392 cropping cycles increased. PRE significantly increased with Al-P sludge application relative to

393 conventional fertilizer. In addition, as the application rate increased, there was no significant

394 difference in PRE for the different application rates of Al-P sludge. Generally, as the cropping

395 cycle increased, P uptake decreased alongside TP and soil Olsen-P concentrations. Also in most

396 cases, at all cycle and in all rates, P uptake from Al-P sludge amended soil differed significantly

397 from MAP amended soil.

398 Overall, Al-P sludge could be an alternative source of P in a world with an ever-increasing P

399 demand, thus reducing the demand for inorganic fertilizers such as MAP. This can promote the

400   dedicated use of Al-P sludge to produce feedstock for biofuel, leading to diversified P usage.

401   Based on the sludge application rates in this study, the lowest application rate of 9.7 mg P kg^{-1}

402   soil showed adequate PRE that is comparable to higher rates and hence may be the most suitable

403   for future use to prevent overapplication. Although the one-time application of Al-P sludge is

404   beneficial to subsequent crops, we recommend that care should be taken in the use of Al-P

405   sludge as application based on available P may lead to P accumulation and pose a potential risk

406   to the environment.

407

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408

409

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412

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Figure 1

Effect of the cropping cycle × rate interaction on maize dry matter yield

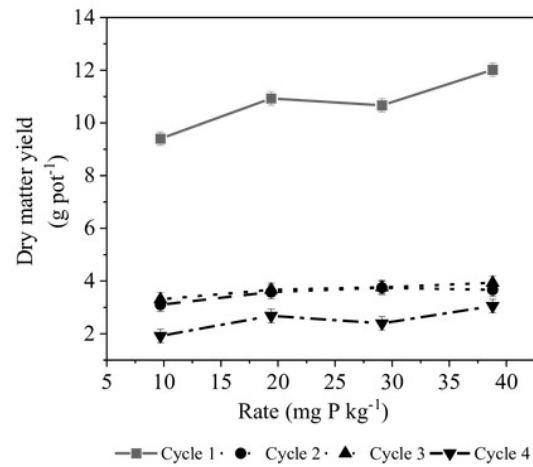



Figure 2

Effect of rate x cycle x P source interaction on P-uptake by maize

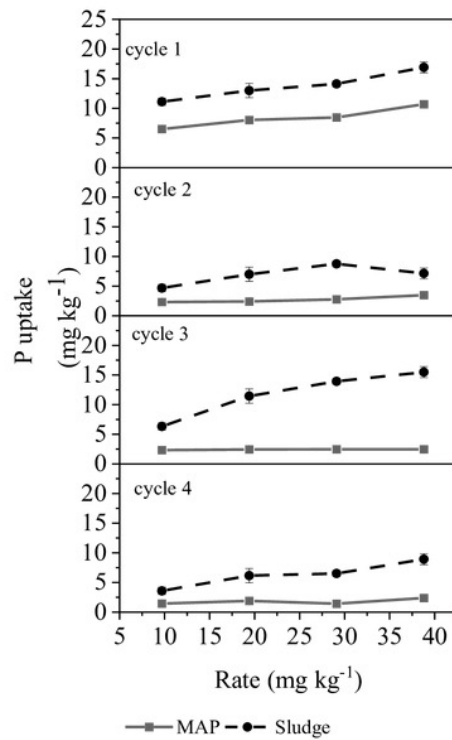



Figure 3

P source x rate interaction on PRE

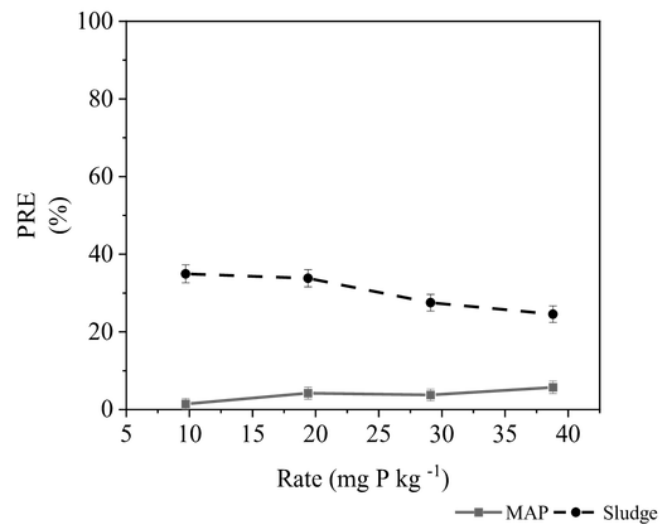



Figure 4

P source x cycle interaction on PRE

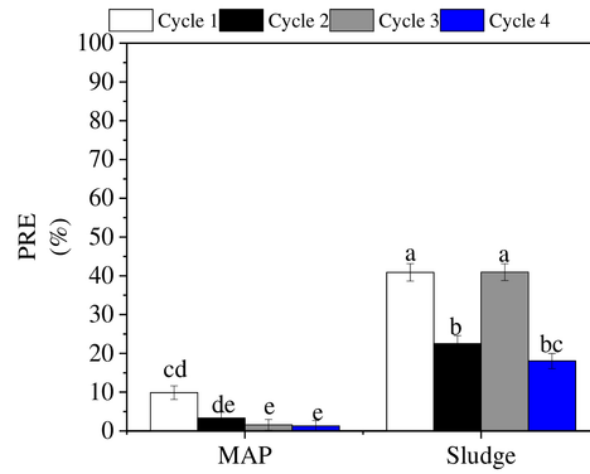



Figure 5

Effect of P source x cycle on aluminum uptake

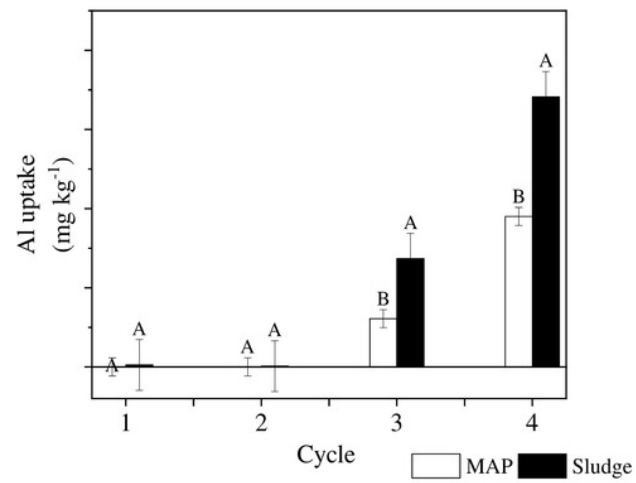



Figure 6

Rate x cycle interaction on soil pH

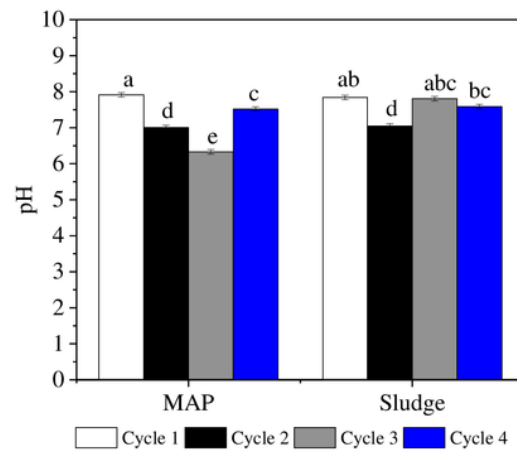
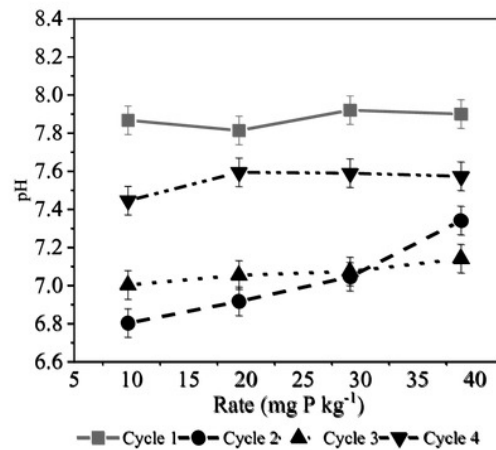



Figure 7

P source x cycle interaction on soil pH

Chemical properties of the soil

1   Table 1: Chemical properties of the soil

Properties	Roseisle
Nitrate (mg kg⁻¹)	33.6
Olsen P (mg kg⁻¹)	3
Potassium (mg kg⁻¹)	46
Organic C (g kg⁻¹)	25
Carbonates (CCE) (g kg⁻¹)	12
Soil pH	8.2
Cation exchangeable capacity cmol$_c$ kg⁻¹	25.1
Sulfur (mg kg⁻¹)	26.9
Baron (mg kg⁻¹)	2
Zinc (mg kg⁻¹)	0.44
Iron (mg kg⁻¹)	32.3
Manganese (mg kg⁻¹)	1.7
Copper (mg kg⁻¹)	0.2
Magnesium (mg kg⁻¹)	912
Calcium (mg kg⁻¹)	3402
Sodium (mg kg⁻¹)	86
Electrical conductivity (dS m⁻¹)	0.25

DMY, phosphorus uptake, PRE, aluminum uptake, pH, and EC as affected by sludge and MAP Application

1 Table 2: DMY, phosphorus uptake, PRE, aluminum uptake, pH, and EC as affected by sludge
2 and MAP Application[†].

Effect	DMY	P uptake	PRE	Al uptake	pH	Olsen P	Soil TP
	g kg⁻¹ ($g\ kg^{-1}$)	mg P kg⁻¹ ($mg\ P\ kg^{-1}$)	%	mg Al kg⁻¹ ($mg\ Al\ kg^{-1}$)		mg P kg⁻¹ ($mg\ P\ kg^{-1}$)	mg P kg⁻¹ ($mg\ P\ kg^{-1}$)
Cycle (C)							
1	10.8	11.1a	23.6	0.1b	7.9a	13.4ab	563a
2	3.5	4.8c	11.4	0.0b	7.0c	22.4a	510b
3	3.7	7.1b	17.0	4.9b	7.1c	12.4ab	405c
4	2.5	4.0c	8.2	13.3a	7.6b	10.0b	424c
P-source (P)							
Control	1.6c	2.6c		2.2b	8.1a	10.2	456b
Sludge	6.05a	9.7a	30	6.0a	7.6b	14.1	510a
MAP	4.3b	3.8b	3	3.1b	7.2c	13.3	440b
Rate (R, mg P kg⁻¹) ($R,\ mg\ P\ kg^{-1}$)							
0	1.68	2.6d		2.2	8.05a	10.2	456
9.7	4.4	4.8c	14.5	4.7	7.3c	11.1	446
19.4	5.2	6.5b	16.4	5.4	7.3c	12.0	486
29.1	5.1	7.3b	13.6	4.3	7.4bc	14.6	478
38.8	5.7	8.4a	13.9	3.9	7.5b	18.0	491
		P-value					
C	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.57	<0.0001
R	<0.0001	<0.0001	0.68	0.59	0.007	0.007	0.06
P × C	0.38	<0.0001	<0.0001	0.001	<0.0001	0.49	0.14
P × R	0.30	<0.0001	0.01	0.18	0.89	0.80	0.13
R × C	0.04	0.01	0.28	0.88	0.09	0.91	0.10
P × R × C	0.62	0.002	0.35	0.20	0.97	0.86	0.13

4 [†]Means followed by different letters within a column are significantly different at $p \leq 0.05$