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Phosphorus from Sludge: Evaluation of organic polymer substitution of metal coagulants on phosphorus availability for plant uptake

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ABSTRACT

Majority of Norwegian wastewater treatment plants utilize chemical treatments such as coagulation to meet high removal standards for phosphorus in wastewater. Up to 85% of the total sludge produced from these plants are supplied to farmers for use for possibility of reuse of nutrients, such as P, in agriculture. A study done by Tore Krogstad found that the plant availability of phosphorus from sludge is greatly reduced along with higher concentrations of metal coagulants. To enable wastewater treatment plants to continue meeting high removal efficiency while providing sludge with better P fertilizing capacity, some researches have suggested to substitute a part of the inorganic coagulants with cationic polymers.

In this study, varying combinations of dose and polymer additions with commonly used coagulants ALS and PAX are evaluated on their effect on plant available phosphorus when applied to soil and hydroponics systems as fertilizer. Despite improving removal of total phosphorus from wastewater, the simultaneous addition of cationic polyacrylamide to metal salts in coagulation reduced dry mass harvest, most particularly from ALS, with yield reduction documented from 57.5% to 66.1%. Addition of polymers to PAX had a smaller harvest drop ranging from 0.8% to 27%. As compared to mineral fertilizers, nutrient use efficiencies at input P concentration of 6 kg P/daa of the different sludge types were all under 40%, going as low as 6% for ALS + polymer sludge.

Reduction of the yield could be attributed to residual positive charge from the polymer used in the sludge that may have fixed negatively charged phosphates in the soil, the phytotoxic effect of cationic polymers or the mobilization of Al in soil for plant uptake. Further studies are needed to point out the actual mechanism by which the positively-charged polymers inhibit plant growth.

Use of hydroponic growth systems generally reflected soil conditions in terms of plant mass harvest in response to the different sludge types. Yet, evaluations through soil growth were found necessary to address soil interactions not simulated in the hydroponics system such as effect on nutrient uptake.

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INTRODUCTION

The finiteness of current phosphorus reserves pose a threat to global food security. Along with nitrogen and potassium, phosphorus completes the triumvirate of macronutrients that are integral to plant growth, and consequently, food production. However, the plant availability of phosphorus in the soil is hindered by its strong adsorption to soil particles, necessitating constant fertilization of the soil with the said nutrient to produce crops. Mining phosphate rocks for fertilizer has been crucial to sustaining global population demand of phosphorus, with studies projecting exhaustion of current reserves within this century.

Around 17.5 million tons of phosphorus from phosphate rocks are mined per year, with 15 million tons going to P fertilizer production. Of these, approximately 12 million tons P flow from fertilized soil to global agricultural harvests (Cordell et al., 2009). Along with crops, nutrients are taken out of the soil and redistributed for consumption. In the natural phosphorus cycle, the consumed nutrients are recycled locally to the soil through excreta and, eventually, the decomposition of the consumer. However, with increasing urbanization, this cycle is disrupted as phosphorus from excreta are redirected into sewers (Ashley et al., 2011). A quarter of the approximate total of 1 billion metric tons of P mined from the 1950 – 2000 have been traced to water bodies and sanitary landfills (Rosemarin, 2005). This amount is expected to increase globally by a factor of 2.5 to 3.5 between 2000 and 2050 (Van Drecht et al., 2009). In the context of diminishing resources, this linear flow of phosphorus is impractical and unsustainable.

As phosphorus is beneficial in land, it is undesired in water bodies. In the same way it sustains growth of crops, it could trigger algae growth, and eventually, eutrophication. Water and wastewater treatment remove phosphorus through different mechanisms: adsorption, precipitation, uptake through biomass consumption, or as a side-effect of particle removal and, subsequently, concentrated in the sludge (Tchobanoglous et al., 2014).

Utilization of wastewater sludge for the recovery of nutrients is viewed as a feasible solution to address impending peak phosphorus. Popular approaches include direct application to agricultural lands or P recovery through struvite precipitation, KREPRO and BioCon processes (Levlin et al., 2002). Implementation of the latter phosphorus recovery technologies are generally held back by higher operation and maintenance costs as compared to the cost of mining phosphate rocks (Roeleveld et al., 2004). Land application, on the other hand, is viewed to be the cheapest and simplest way to recover phosphorus along with nitrogen and organic matter that improve soil structure and plant growth (Fytili and Zabaniotou, 2008, Levlin et al., 2002, Petersen et al., 2003, Roeleveld et al., 2004, Warman and Termeer, 2005). Land application of sludge not only recirculates phosphorus, but also other plant nutrients such as potassium, sulfur, copper and zinc (Suhadolc et al., 2010). Although other undesired components such as pathogens, organic pollutants and toxic heavy metals may also be transferred, studies have shown that effects are temporary with little effect on plant quality and none at all on consumers (Kidd et al., 2007, Debosz et al., 2002). In Norway, up to 85% of the total sludge produced by wastewater treatment plants are supplied to farmers for the possibility of nutrient reuse (Berge and Mellem, 2010). Thus, improving or modifying sludge for direct sludge spreading on land is a particular focus of this paper.

Plant availability of phosphorus in the sludge has been found to be dependent on the nature of the wastewater treatment and conditioning by which the sludge is derived (Kahiluoto, 2015; Huang, 2012; Krogstad, 2005; Petersen, 2003, Frossard, 1996; Jokinen, 1990). Sludge from biological treatments without chemical additives have been shown to provide relatively higher amount of plant available P (Krogstad et al., 2005). Removal efficiency, however, with respect to phosphorus in the effluent is not as high as other treatments. For countries with high removal standards for phosphorus in wastewater effluent stream, such as Norway, chemical treatments, such as coagulation, are employed. With metal (Fe and Al) coagulants, the process removes 80-90% of influent P at optimal coagulant doses (Tchobanoglous et al., 2014). Phosphorus in the sludge from this type of treatment, however, are believed to be bound as metal phosphates, which are less available for plant uptake – only 10% and 24% for Al and Fe respectively – as opposed to mineral fertilizers (Krogstad et al., 2005). In addition, this type of sludge could increase the metal uptake of the said crops and decrease yield (Cordell et al., 2009, McBride et al., 2004). Calcium coagulants, such as lime, could conditionally provide better availability of phosphorus to plants (Kalbasi and Karthikeyan, 2004). Addition of Ca to alkaline wastewater results to the natural precipitation of calcium phosphate. This precipitate is soluble below pH 6, as in typical soil conditions, and are thus, released and easily made available for plants (Krogstad et al., 2005). This, however, means that Ca is highly dependent on the alkalinity of the solution, resulting to lower performance with respect to P removal as compared to Al and Fe. Efforts to reduce metal Al and Fe coagulants without forsaking

P removal efficiencies are therefore relevant for countries, such as Norway, to promote sludge recycling to farmers while maintaining strict effluent standards.

Substitution of a portion of metal coagulants with cationic polymers has been explored to address the aforementioned problem. Using metal coagulants alone, a part of Al- and Fe- participate in the removal of particles, while the rest for the precipitation of phosphates. This explains why dosage ratios of mole metal (e.g. Al) to mole phosphates in wastewater treatment plants (Al:P ratio) are always higher than the theoretical 1:1 (Ratnaweera, 1991). Addition of cationic polymers are believed to compete with Al- and Fe- coagulants in the removal of particles, such that less metal coagulants are consumed for this mechanism. This effectively lowers the required metal coagulant dosage for the same removal efficiency, while at the same time increasing plant available phosphorus in sludge (Manamperuma et al., 2016).

Effect of this substitution on crop yield has previously been tested in a hydroponics system with results supporting the assumed mechanism (Manamperuma et al., 2016). Although soil and hydroponic growth systems could be comparable techniques for growth experiments (Astolfi et al., 2004, Pritsa et al., 2008), assessment in soil substrate is important in understanding the interactions of the soil and the sludge, as in field conditions, as some studies point out difficulties in determining nutrient availability in hydroponics systems (Thomas and Paparozzi, 2013, Astolfi et al., 2004).

In this study, varying combinations of dose and polymer additions with commonly used coagulants ALS and PAX are evaluated on their effective plant available phosphorus when applied to soil and hydroponics systems as fertilizer. Due to the theorized effect of polymers on the dominant capture mechanism of phosphorus in the coagulation process as observed by Manamperuma et al, the addition of polymers to coagulants are expected to improve the fertilizing capability of the resulting sludge.

MATERIALS AND METHODS

Sludge Preparation

Jar tests were performed in the laboratory using wastewater obtained from Drøbak Wastewater Treatment plant mixed with black water from Fløy 5 lab of tap water. Coagulants used were Kemira ALS (aluminum sulfate) and Kemira PAX-18 (prepolymerized aluminum coagulant). Polymer additions utilized organic cationic polymer SNF Floerger FO-4350.

To demonstrate effect of aluminum content on removal efficiency and sludge fertilizing value, ALS and PAX were applied in two different dosages, with and without polymers. This set-up similarly allows the comparison of the substitution of the metal coagulant with inorganic polymer. Dose D1 pertains to sludge coming from treatment with a lower dose of coagulant containing around 15 mg Al/L, while D2 pertains to a higher dose at approximately 20 mg Al/L.

In 100L jars, the metal coagulant and polymers were added simultaneously and then mixed rapidly for 5 minutes with a hand mixer, followed by another 15 minutes of slow mixing with paddlers. The solution was allowed to settle for 30 minutes. Sludge was thereafter separated from the supernatant.

In the discussion of this paper, sludge that involved the use of polymers in the treatment is marked by “+ polymer”. The number 1 pertains to the lower dosage, while 2 denotes the higher one. These identifiers are assigned after the coagulant type, such that, for example, the label “ALS D1 + polymer" refers to the sludge generated from treating water with a lower dosage of the ALS coagulant and polymer.

Pot Experiment

Both hydroponic and soil set-ups consisted of 45 pots: 15 sets each with three replicates. This included varying levels of P concentrations from mineral fertilizers, which serve as control, and equal P input concentrations equal to 6 kg P/daa from different sludge permutations. The chart below summarizes the details for one system:

Table 1. Matrix for the different coagulant, dose, and polymer combinations for the growth experiments and corresponding sample number assignments

CONTROL*	**Concentration**				
Mineral Fertilizer	**0 kg P/daa**	**1.5 kg P/daa**	**3.0 kg P/daa**	**6.0 kg P/daa**	**9.0 kg P/daa**
	1	4	7	10	13
	2	5	8	11	14
	3	6	9	12	15

	Without polymers		**With polymers**		**Biological Treatment Plant**
	ALS	**PAX**	**ALS**	**PAX**	
Concentration 1	16	19	22	25	28
	17	20	23	26	29
	18	21	24	27	30
Concentration 2	31	34	37	40	
	32	35	38	41	
	33	36	39	42	

No N additions	ALS Concentration 1	ALS Concentration 1 with polymer	PAX Concentration 1
	43	44	45

Due to diluted samples obtained from the biological treatment plant, sets 28 – 30 were not pursued in the experiment.

For the soil system, three liter plastic pots were packed with approximately 3 dm3 of peat soil, equivalent to 1/66667th of the volume of one daa in the upper 20 cm in the field. Peat soil was used to minimize possible P interactions and contributions from the soil. Each pot received 0.3 g of ryegrass seeds (*Lolium perenne*), and was fertilized with 300.0 mg/ pot N, 300.0 mg/pot K, 300.0 mg/ pot Mg, 125 mg/ pot Fe, 62. 5 mg/ pot Mn, 62.5 mg/ pot Cu, 62.5 mg/ pot Zn, 6.3 mg/ pot Bo, and 6.3 mg/ pot Mo, with the exception of phosphorus (and nitrogen for the last 3 sets). (See Appendix A and B.) Pots were watered every other day to 1.8kg.

The hydroponic growth matrix was set-up following previous experiment from Manamperuma (2015), using 0.45 L pots with 0.1g of ryegrass seeds, filled with vermiculite. Initial nutrient concentration are as follows: 99.6 mg/pot N, 96.0 mg/ pot K, 96.0 mg/ pot Mg, 25.0 mg/ pot Fe, 12.5 mg/ pot Mn, 12.5 mg/ pot Cu, 12.5 mg/ pot Zn, 1.3 mg/ pot Bo, and 1.3 mg/ pot Mo. The hydroponic pots were watered every other day, similar to soil pots, to 300grams.

Both systems were housed in a climate-controlled greenhouse kept at 18° C from 06:00 until 22:00 and 15° C from 22:00 until 06:00. HQI lamps provided 200 µmol of light from 06:00 until 22:00. Photocells maintained light intensity by switching off lamps if light detected exceeded the 200 µmol of light limit.

Harvests were done after 34, 63, and 87 days of germination. After every harvest, all macronutrients except P (and N for the last three sets) were replenished. (See Appendix C.)

Plant Analysis

Samples were weighed before and after drying the harvested samples in an oven at 60° C for 72 hours, to correspond to wet and dry mass harvest. Dried samples were eventually grinded and dissolved in 2mL H2O and 5mL ultrapure HNO3 and decomposed in an ultraclave for 2 hours at 260° C and 50 bar. After decomposition, each sample was diluted to 50mL solutions for analysis using the Perkin Elmer Optima 5300 DV – Optical Emission Argon Plasma Spectrometer. Results were verified against measurements using the Systea Analysator.

RESULTS

Effect of the different coagulants on phosphorus removal from wastewater

Analysis of the generated sludge used in the plant experiments have shown that total phosphorus removed were generally improved with the addition of polymers for both low (D1) and high (D2) dosages for ALS and PAX, with the best improvement seen from polymer addition in combination with PAX D2. Best total P removal from the tested permutations was obtained with the combination of high dosage of ALS with the same addition of polymer (ALS D2 + polymer) as seen in Figure 1.

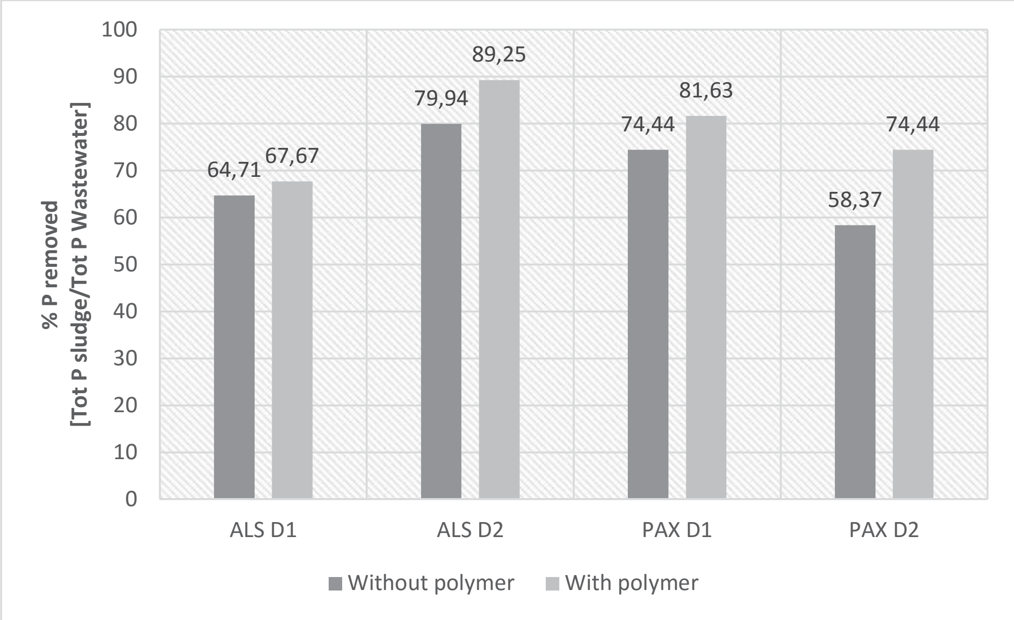
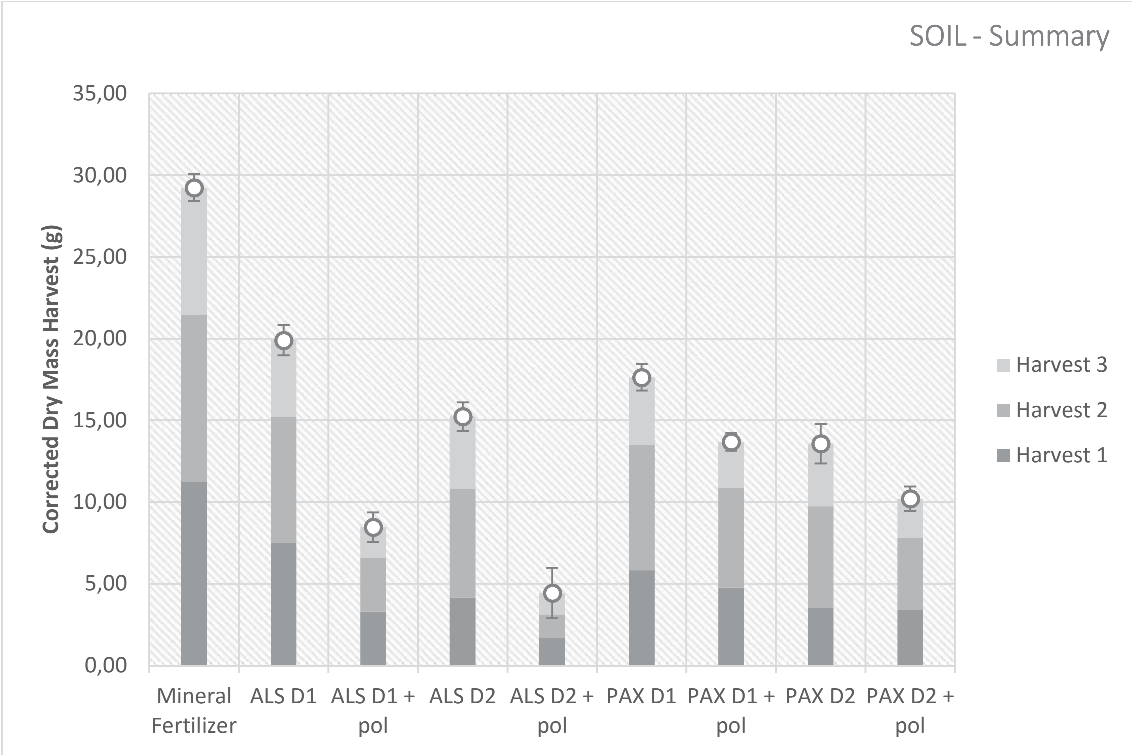


Figure 1. Total phosphorus removal efficiency of the different coagulant, dose, and polymer combinations

Effect of polymers on the sludge quality with respect to plant yield

Yields from dosing the growth medium with approximately the same amount of total P from the different sludge combinations, however, show a different trend (Figure 2).



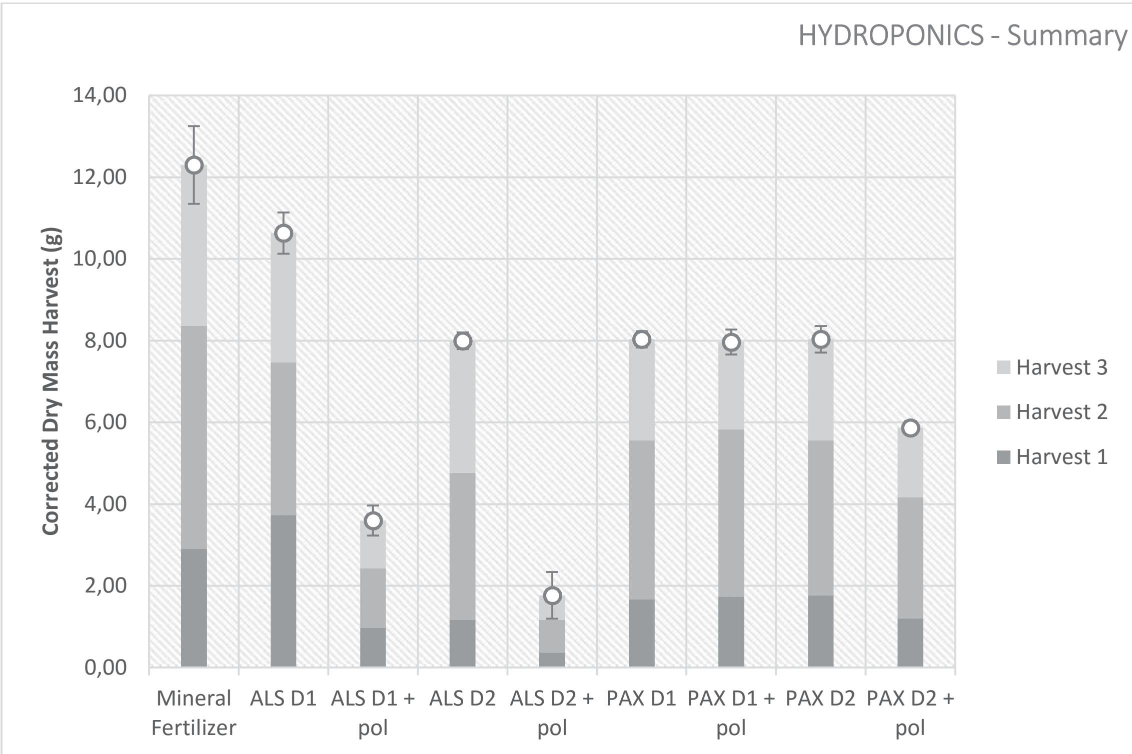


Figure 2. Blank-corrected total dry mass yield over three harvests for the different coagulant, dose, and polymer combinations from the soil and hydroponic systems

In both soil and hydroponics systems, yield generally declined for sludge with polymer additions given the same coagulant type and dose (Table 2). The said difference was especially evident in the pots supplemented with ALS-coagulated sludge with equivalent yield decrease of up to 77.9 %. Only the comparison of PAX D2 with and without polymer for the hydroponic systems had no significant difference.

Table 2. Total dry mass harvest for the different coagulant, dose and polymer combinations in both soil and hydroponics systems

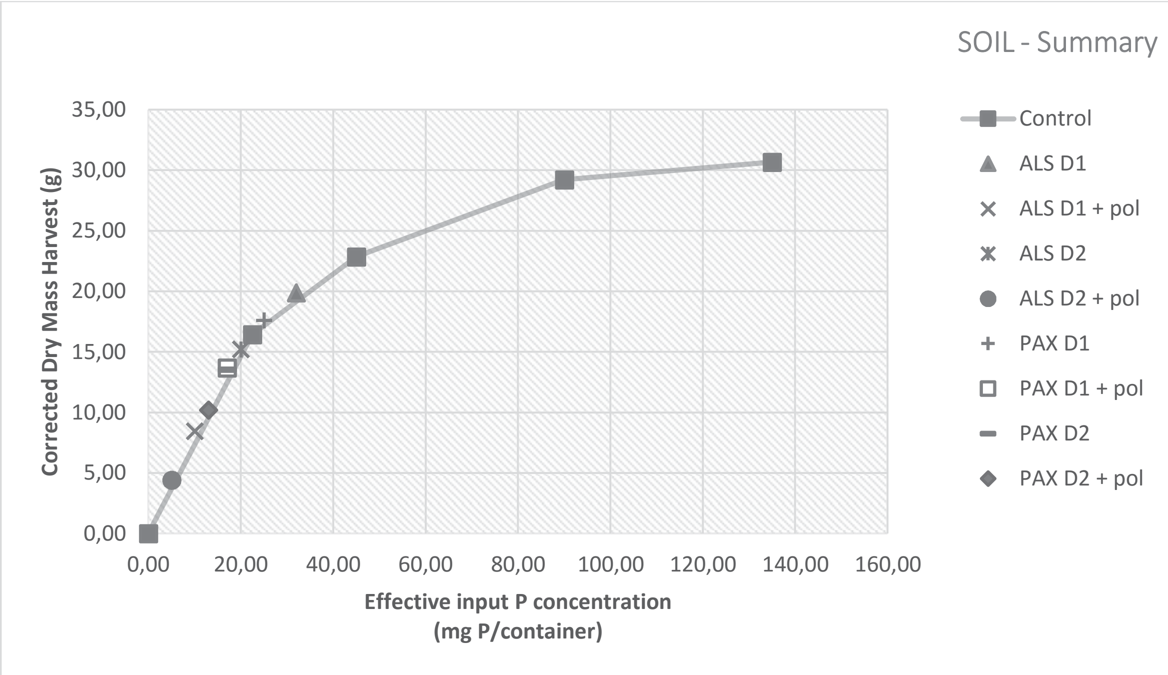
Coagulant	***Soil***			***Hydroponics***		
	Total Dry Mass Harvest (g)	Standard Error (g)	%Reduction (Yield$_{withoutpolymer}$ - Yield$_{withpolymer}$ / Yield$_{withoutpolymer}$ *100%)	Total Dry Mass Harvest (g)	Standard Error (g)	%Reduction (Yield$_{withoutpolymer}$ - Yield$_{withpolymer}$ / Yield$_{withoutpolymer}$ *100%)
Mineral Fertilizer	29,2	0,83		8,4	0,93	
ALS D1	19,9	0,93		10,63	0,50	
ALS D1 + pol	8,5	0,91	57,5	3,60	0,37	66,1
ALS D2	15,2	0,87		8,00	0,20	
ALS D2 + pol	4,4	1,54	70,9	1,77	0,57	77,9
PAX D1	17,6	0,81		8,03	0,20	
PAX D1 + pol	13,7	0,55	22,3	7,97	0,30	0,8
PAX D2	13,6	1,20		8,03	0,32	
PAX D2 + pol	10,2	0,76	24,8	5,87	0,16	27,0

Nutrient use efficiency of the different sludge combinations

To compare how the sludge fared against mineral fertilizers, nutrient use efficiencies for the sludge were computed by setting up a calibration curve of the dry mass harvest with respect to the different input phosphorus concentrations from the mineral fertilizer (Figure 3). Assuming that the optimal concentration of input P ($P_{optimal}$) was 90 mg P/container for the soil system and 66.7 mgP/container for the hydroponics systems, the nutrient use efficiency (NUE) for a given sludge sample was determined by finding the effective concentration the sludge was providing based on its dry mass harvest, $P_{effective}$, and substituting into the equation:

$$NUE = \frac{P_{effective}}{P_{optimal}}\ x\ 100\%$$

All the sludge-amended pots with expected total P concentrations at 90 mg showed nutrient use efficiencies of less than 40%. Sludge ALS D1 without polymer ranked the best at 35.6% NUE for soil and 69% for hydroponic samples, providing the pot with an equivalent of around 32 mg and 46 mg input mineral P in the soil and hydroponic growth systems, respectively. Meanwhile, sludge ALS D2 with polymer gave the worst performance in both medium, contributing only an equivalent of 5 mg mineral P per pot (5.6% NUE) for soil and 6 mg mineral P per pot (9% NUE) for hydroponic growth.



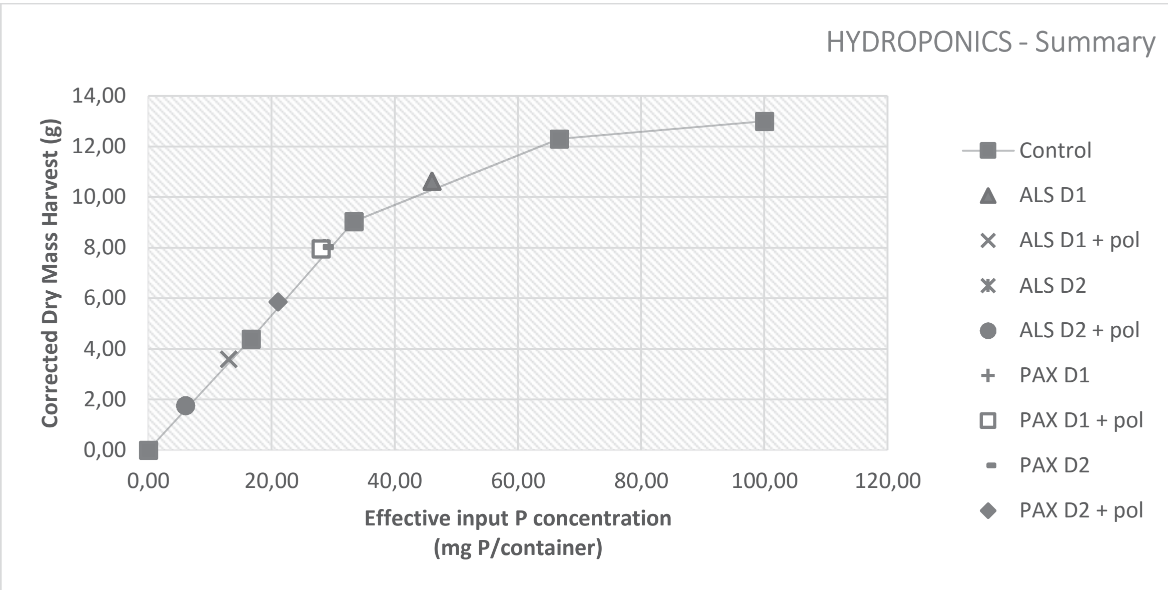


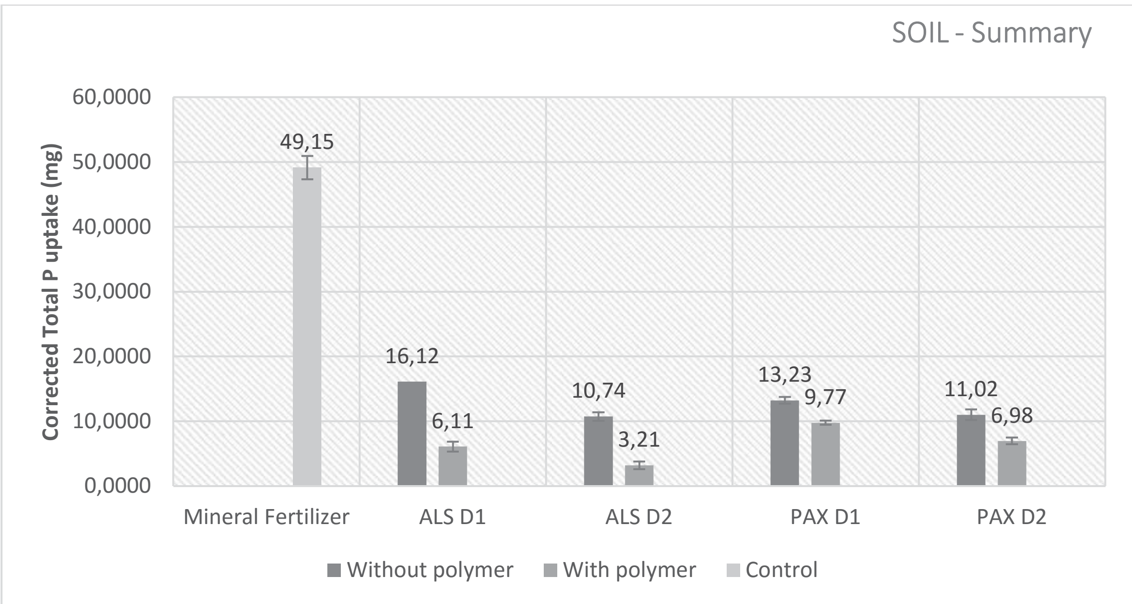
Figure 3. Calibration curves plotting dry mass harvest with respect to input P concentration from mineral fertilizer with effective P input concentrations of the different sludge types for both soil and hydroponic systems

Table 3. Calculated nutrient use efficiencies from dry mass harvest of soil and hydroponic systems

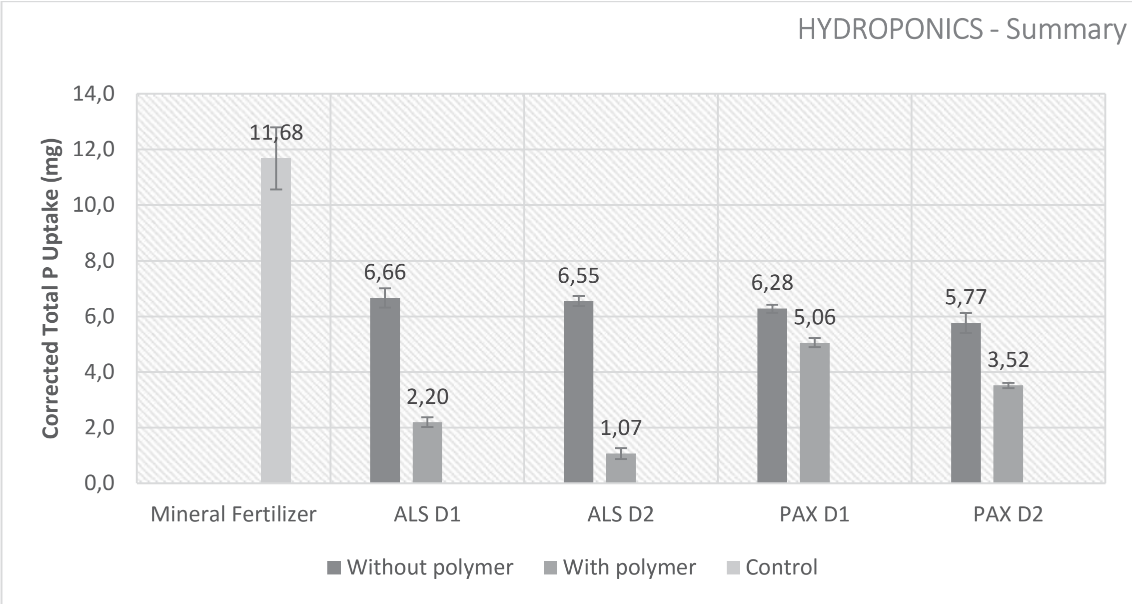
	Soil	***Hydroponics***
Coagulant	NUE (%)	NUE (%)
ALS D1	35,6	69,0
ALS D1 + pol	11,1	19,5
ALS D2	22,2	42,0
ALS D2 + pol	5,6	9,0
PAX D1	27,8	42,8
PAX D1 + pol	18,9	42,0
PAX D2	18,9	42,8
PAX D2 + pol	14,4	31,5

Effect of polymers on the sludge quality with respect to plant nutrient uptake

Looking into the total phosphorus extracted from the plant samples, the trend reflected similar behavior with the yield. Differences for phosphorus uptake were more pronounced, especially in the comparison of the mineral fertilizer and the different sludge types.



(a)



(b)

Figure 4. Total P uptake as derived from plant mass grown in the soil (a) and hydroponic (b) systems

Effect of nitrogen fertilization on the yield

Several control pots were also set-up without additions of nitrogen. Yields were observed to be drastically lower than their optimally-fertilized counterparts, emphasizing the importance of maintaining ideal nutrient concentrations to limit observed effects to the difference of phosphorus input.

Table 4. Total dry mass harvest comparison of pots fertilized with and without nitrogen in the soil and hydroponic system

	ALS D1 (g)	***ALS D1 + polymer (g)***	***PAX D1 (g)***
SOIL			
With N	19,9 ± 0,93	8,47 ± 0,91	17,63 ± 0,81
Without N	6,03 ± 0,41	5,13 ± 0,41	6,63 ± 0,41
HYDROPONICS			
With N	8,57 ± 0,50	3,60 ± 0,37	8,03 ± 0,20
Without N	1,53 ± 0,05	0,73 ± 0,05	1,13 ± 0,05

Despite absence of nitrogen fertilization, the yield obtained from ALS D1 + polymer where lower than ALS D1 in both growth medium, similar to that of the general trend.

DISCUSSION

Effect of the different coagulants on phosphorus removal from wastewater

Removal of phosphorus from wastewater through the addition of coagulants are enabled through two distinct processes – coagulation and precipitation. Coagulation relies on the destabilization of colloidal suspensions to allow aggregation of similarly-charged suspended particles, while precipitation involves the formation of insoluble products, with both processes allowing easier subsequent separation.

A simplified outlook on these two mechanisms points out that with the addition of a metal salt to wastewater, the metal ion (for example, Al^{3+} from $Al_2(SO4)_3$) could react with hydroxide or phosphate ions to form aluminum hydroxide or aluminum phosphate (Equations 1 and 2).

$$Al_2(SO_4)_3 \cdot 18\, H_2O + 3\, Ca(HCO_3)_2 \leftrightarrow 3CaSO_4 + 2Al(OH)_3 + 6\, CO_2 + 18\, H_2O \qquad \textbf{(1)}$$

$$Al^{3+} + (PO_4)^{3-} \leftrightarrow AlPO_4 \quad \textbf{(2)}$$

Aluminum hydroxide mainly removes phosphorus forms adsorbed or enmeshed in its characteristic gelatinous floc, while aluminum phosphate targets easily reactive phosphates in the solution. In wastewater, these two mechanisms compete.

Rapid hydrolysis of the aluminum forms not only aluminum hydroxide, but also a range of partially hydrolyzed species – rendering it unlikely that monomeric Al^{3+} remain in the solution to be able to form the aluminum phosphate precipitate. This allows the conclusion that phosphate removal in the presence of conventional metal coagulants are related more to the coagulation, rather than the precipitation mechanism (Jiang and Graham, 1998). Contributions of precipitation to phosphate removal last only in the first few seconds of coagulation (Klute and Hahn, 1992).

In this study, two different aluminum coagulants were compared, aluminum sulfate (ALS) and PAX, a prepolymerized coagulant. Results show that with these coagulants (with or without the addition of polymers), ALS D2 removes more total phosphorus than ALS D1, yet PAX D1 performs better than PAX D2.

The better phosphorus removal observed at higher dosage of ALS reflects the known need for more dosage of metal salts to overcome competing reactions in wastewater. As proposed by Jiang and Graham (1998), two major coagulation mechanisms may have governed the removal of phosphorus: the formation of aluminum-hydroxo-phosphate complexes: $Al(OH)_{3-x}(PO4)_x$, and the adsorption of phosphate ions to the aluminum hydrolysis species. With ALS, wherein hydrolysis is rapid and uncontrolled, the second mechanism would be more prominent with aluminum hydroxide, $Al(OH)_3$, as the dominant hydrolysis species controlling P removal. Thus for ALS, the more hydroxides are formed, the more phosphorus is removed.

On the other hand, the dominant hydrolysis species of PAX are polymeric species wherein PO_4 ions could form complexes with the positive sites of the said species (Jiang ang Graham, 1998). Pre-polymerized coagulants hold the advantage of adaptability to a wider pH, temperature, and colloid concentration range as compared to conventional metal salts. Pre-polymerization of a metal coagulant minimizes the hydrolysis reaction by reducing the concentration of monomeric aluminum ion in favor of more stable hydrolyzed aluminum complexes. These polymeric complexes are believed to create positive sites that adsorb negatively-charged phosphates or act as centers of precipitation for the metal hydrolysis product. Their large molecular size contributes to easier aggregation of flocs and increases charge neutralization capacity (Tzoupanos and Zouboulis, 2008). Unlike in ALS coagulation, it is not the formation of hydroxides that controls removal efficiency, but rather the bridging and adsorption - charge neutralization mechanisms. The lower removal of PAX D2 as compared to PAX D1 could be the 'hairball effect' observed when too much polymers coat the particle surface limiting bridging and adsorption site availability (Ebeling et al., 2005).

The addition of polyacrylamides (PAMs or polymers) to wastewater aims to improve removal of particles (and possibly, phosphorus) through charge neutralization or bridging as flocculating aids. Vanotti and Hunt (1999) have shown that solids and nutrient content were significantly reduced in flushed swine manure amended with polymers. For polymers with lower molecular weights, charge neutralization is the prevailing mechanism. Flocculation through bridging, linking together suspended particles for easier aggregation, is more prominent in the presence of high molecular weight polymers (Ebeling et al., 2005). In this study, the addition of SNF-4350, a moderate molecular weight, medium-density cationic polymer, improved total P removed for all types of sludge and doses, supporting the benefits of these polymers in improving floc formation. Results agree with previous investigations on the effect of combination of metal coagulants and polymers. Investigating swine and dairy liquid manure, Zhang and Lei (1998) found that addition of polymers to aluminum sulfate and ferric chloride greatly reduced total phosphorus in the effluent. Piccinini and Cortellini (1987) reported 21% better removal from coagulants reinforced with polymers as compared to those without. In both cases, polymers with cationic high charge density were used. Observed differences in this experiment were not as high as the aforementioned studies. Timby et al (2004), however, point out that the use of cationic medium charge density polymers only had minimal effect on total P removal, with improvements more prominent on removal of solids. An evaluation of the content of sludge and effluent, in terms of wastewater treatment parameters, would be ideal for further studies to obtain more insight on the possible mechanisms dominating the coagulation process.

These different mechanisms governing the removal of phosphorus from the different coagulants used and their combinations are expected to affect the fertilizing value of its resulting sludge.

Effect of polymers on the sludge quality with respect to plant yield

The form of phosphorus in soil governs its availability to plant. These forms can be categorized into three pools – soluble, active, and fixed. The soluble pool refers to the phosphorus forms directly available to plants, such as orthophosphates (H2PO4- and HPO42-). This fraction is generally very small and easily depleted. The active pool refers to the phosphorus in plants that are easily mobilized into the soil solution. This pool is much bigger than the soluble fraction and serves to replenish the said pool, making it a good measurement of phosphate fertility in soil. Forms may include phosphorus adsorbed to oxides and hydroxides of Fe or Al or particles, Ca or Al phosphates (depending on soil pH), and easily soluble organically bound phosphorus. The fixed pool contains phosphorus forms that are stable and resistant to transformation to more available P forms, such as insoluble, crystalline inorganic phosphates and organic bound P that are resistant to mineralization by microorganisms in the soil. Plant available phosphorus as referenced in this paper could refer to the P classified under the first two pools.

To evaluate the contribution of sludge to phosphorus available for the soil, this study uses peat for the soil system and vermiculite for the hydroponic system that are relatively inert in terms of phosphorus interactions.

Analysis on the nutrient content of the growing medium shows that vermiculite have Al, Ca, Fe, Mg, and P concentrations pointedly higher than that of peat soil. Despite this, the plant uptake of these nutrients remain minimal, lower even than the control in plant medium, except for magnesium (Table 4).

Table 5. Average nutrient concentration of the growth media and respective plant sample concentrations from control pots at zero input phosphorus

	Al (g/kg)	**Ca (g/kg)**	**Fe (g/kg)**	**Mg (g/kg)**	**P (g/kg)**
GROWTH MEDIUM					
Peat Soil	18,93	12,78	14,83	4,73	1,97
Vermiculite	246,93	63,08	137,79	184,12	17,48
CONTROL POTS					
0 mg P in Peat	0,26	34,67	0,26	6,74	2,43
0 mg P in Vermiculite	0,04	21,92	0,19	16,57	1,97

Krogstad et al (2005) have found that sludge coming from wastewater treatment plants (WWTP) using aluminum and iron coagulants reduced plant available phosphorus as compared to mineral fertilizers and sludge from lime treatment and biological WWTP without chemical additions. Similarly, studies from Bøen (2013) and Øgaard (2015) have documented that higher aluminum and iron content in sludge affect phosphorus availability to plants. Results of this growth experiment support the observed behavior. In general, ALS D2 and PAX D2 (with and without polymers) had significantly lower plant yield than ALS D1 and PAX D1 for both soil and hydroponics. Only PAX D1 and PAX D2 in the hydroponics system gave statistically similar yield despite differing Al content. This inverse relationship of metal content in the treatment process and phosphorus plant availability is ascribed to the increase in the amounts of aluminum hydroxide products formed at higher coagulant dosages, leading to increased reactive surface area in the sludge-amended soil with capacity to fix phosphorus (Cox et al., 1997; Hamad et al., 1992; Loganathan et al., 1987).

The substitution of organic polymers to reduce the concentration of aluminum and iron coagulants in the chemical removal of phosphorus in wastewater has been viewed as a probable solution to improve the plant availability of phosphorus without forsaking removal efficiency of the wastewater treatment (Manamperuma et al., 2016). The concept works under the assumption that it is the reduction of Al and Fe in the sludge that would increase the phosphorus fertilizing capability of chemically-treated wastewater sludge. Based on harvest data, however, it can be concluded that the metal content alone is not sufficient to determine plant available phosphorus. Despite having similar aluminum content in sludge, both coagulants (ALS and PAX) at both doses gave smaller yields upon addition of polymer. Dry mass harvest reductions were particularly prominent in the ALS pots. Yield from ALS D2 + polymer decreased 70.9% and 77.9%, in the soil and hydroponic system respectively, as compared to ALS D2, while it was 57.5% and 66.1% for ALS D1. Addition of PAX to polymers had a smaller harvest drop ranging from 0.8% to 27%.

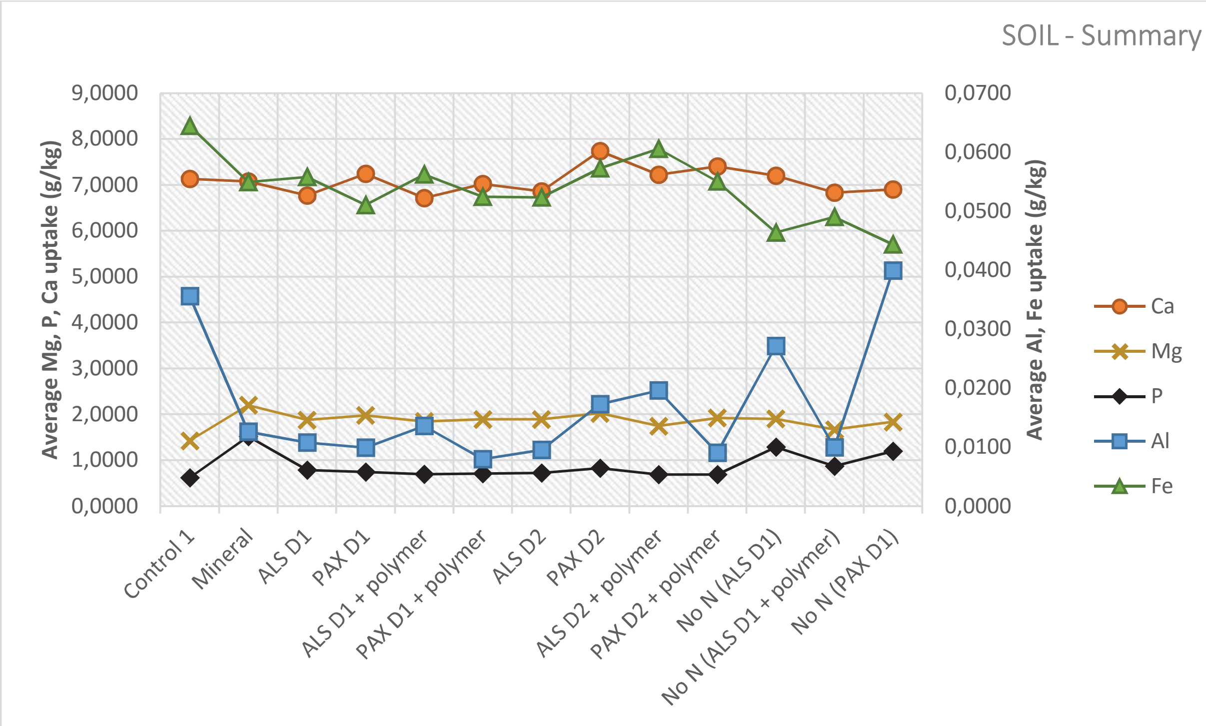
Bugbee and Frink (1985) suggests that the presence of polymeric forms could have led to residual positive charges from the precipitates due to incomplete neutralization. The cumulative positive charge brought about by the addition of the cationic polymer could have introduced more adsorption sites for negatively charged phosphates in soil and water, thus, limiting availability to plants. Cationic polyacrylamides have also been found to be phytotoxic as a result of two mechanisms – physical inhibition of the positively charged polymer around the negatively charged root and accumulation of Cu and Fe (Kuboi and Fujii, 1984). The higher reduction from ALS as opposed to PAX could be due to the resulting phosphate complex interacting with the additional cationic polymer.

As mentioned earlier, the coagulation mechanism of ALS and PAX are different. ALS facilitates coagulation mainly by the formation of $Al(OH)_3$ to cover the surface and adhere to particles through charge neutralization and sweeping sedimentation. Hydroxyl-aluminum clusters formed in PAX show that pre-polymerized coagulants maintain their polycation structure to perform surface complexation and deposition on particles and to aggregate them to form flocs. Evaluation of the adsorption isotherms for the two coagulants show that alum appeared to be Freundlich, while pre-polymerized coagulants were Langmuir. Large amorphous precipitates from alum allowed multi-layer adsorption, while residual charges in the pre-polymerized metal coagulant were limited by their residual charges to a monolayer formation (Tang et al., 2015, Wu et al., 2007). The addition of cationic polymers could have greatly enhanced the multi-layer adsorption allowed by aluminum sulfate.

It is recommended that further experiments perform a thorough analysis of the sludge to determine the forms of phosphorus in the different permutations. A control pot consisting only of sludge from polymer flocculation, despite expectedly low P removal efficiency in terms of water treatment, should be added to observe the isolated effect of polymers to the plant. Similarly, the substitution of metal coagulants with anionic or neutral polymers can also be explored as the reported phytotoxicity of polyacrylamides according to Kuboi and Fujii (1984) were only reported in cationic polymers.

Effect of the different sludge types on nutrient uptake

To evaluate whether the addition of polymers had an indirect effect on plant growth by affecting other nutrient uptake, the concentration of Ca, Mg, P, Al, and Fe in plant tissues were analyzed.



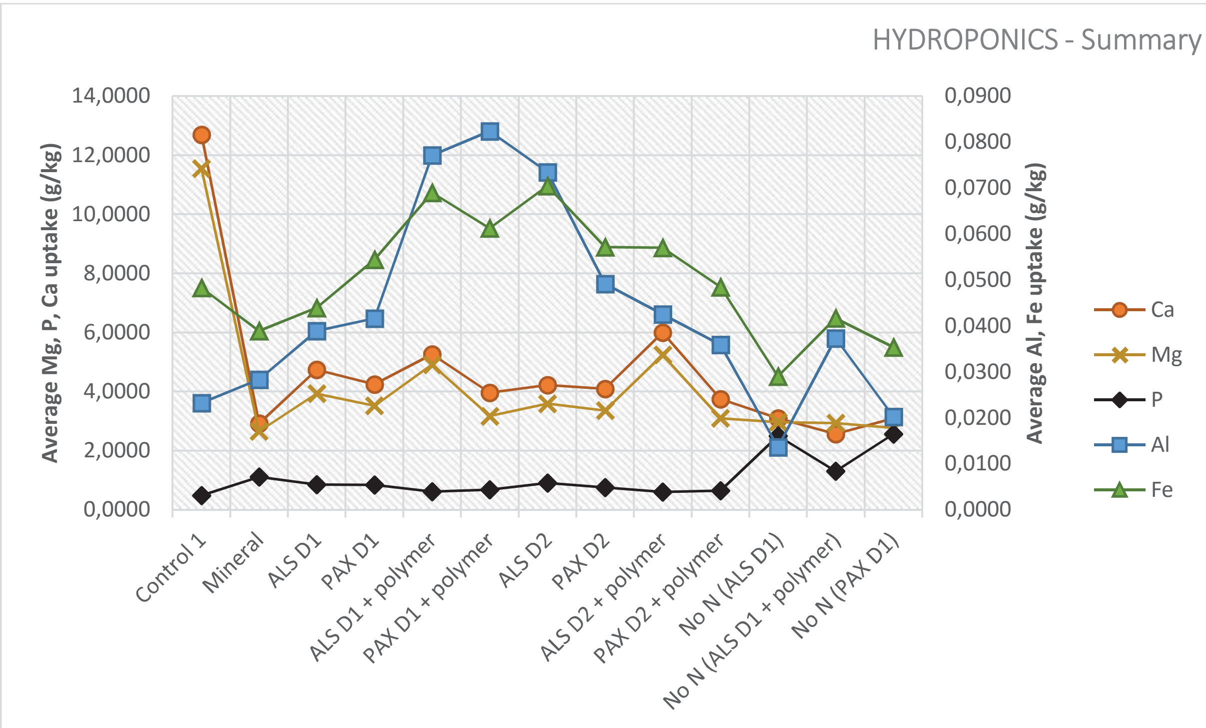


Figure 5. Average Concentration of Al, Ca, Fe, Mg and P in plant tissues in the soil and hydroponic systems

Addition of polymers resulted to differing effects on Al and Fe concentration in plant tissues depending on the coagulant used – ALS + polymer increased the uptake of the said nutrients while PAX + polymer decreased it. Exceptions were ALS D2 and PAX D1 in the hydroponic system for Al, and PAX D1 for both soil and hydroponic pots for Fe. It could be argued that the addition of polymers mobilized Al and Fe in ALS-coagulated sludge and fixed them in PAX, attributing the starker contrast between yields of ALS and ALS + polymer as compared to PAX. However, another possible explanation for this trend could be concentration of the said nutrients due to the low plant mass. Nevertheless, the increase in aluminum uptake brought about by addition of polymers would not be desirable in plants as Al has been found to interfere with uptake of other essential elements (specifically a reduction of Ca, Mg, and P, and initial increase then decrease in Fe), and reduction of biomass yield (Roy et al., 1988).

Calcium and magnesium uptake generally decreased with polymer amendment except for ALS D2 in soil and all ALS pots in the hydroponics system. The exceptions could be similarly attributed to the concentration of Ca and Mg in plant tissue due to lower mass. In addition to possible interference from Al, the reduction in Ca uptake are commonly associated to possible fixation with phosphate in soil (Haynes, 1982). Analysis on the soil media, however, show that although the pH was slightly higher for pots with polymers in soil pots, this could not have been enough to precipitate Ca. Although, this could be a possibility for the hydroponic set-up.

Limits to the analysis done on this study could not allow conclusions on the behavior of the different nutrient uptake. Further testing should be done to eliminate the plausible explanations, specifically nutrient analysis of the growth medium. Nonetheless, the variations in the uptake of the differing nutrients did not greatly affect P concentration in the plant tissues – suggesting that the range of values are still under optimal conditions. Drastic changes were only observed in the pots without nitrogen, wherein the system could be considered under stress.

Effect of the different sludge types on soil pH

Dry mass harvest difference from the study by Krogstad et al (2005) were, among others, attributed to the influence of the applied sludge on soil pH. The availability of nutrients, specifically phosphorus, in soil is influenced by the pH (Figure 6). At higher pH (around 7.5 to 8.5), precipitation of calcium and magnesium phosphates are favored, making them unavailable for plant uptake. More acidic soils (below pH 5.5), on the other hand, favor the adsorption of phosphate to aluminum and iron. Optimal pH levels for phosphorus availability are estimated at 6 to 7.5.

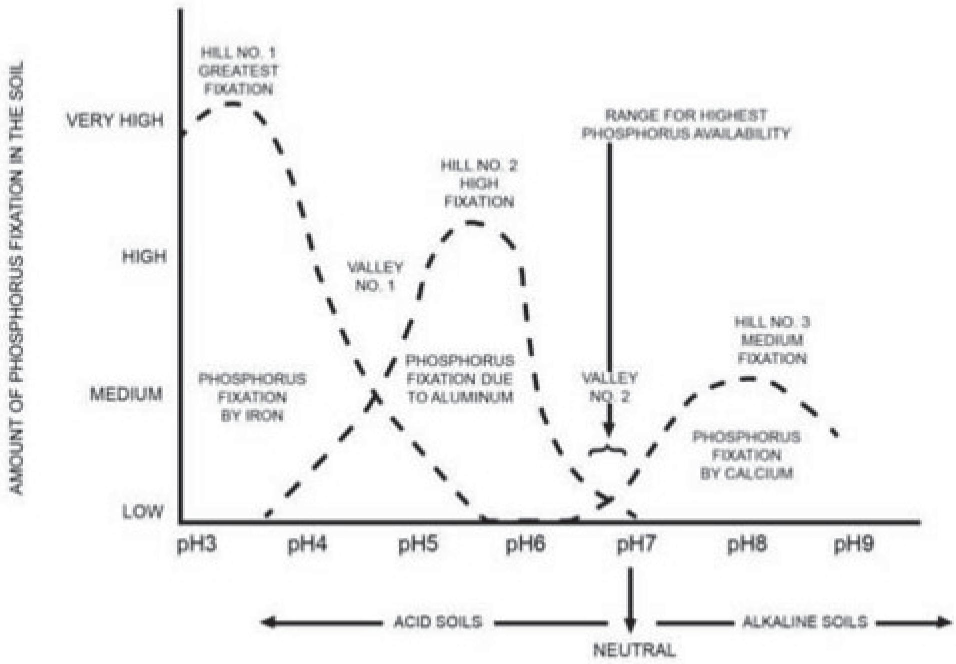
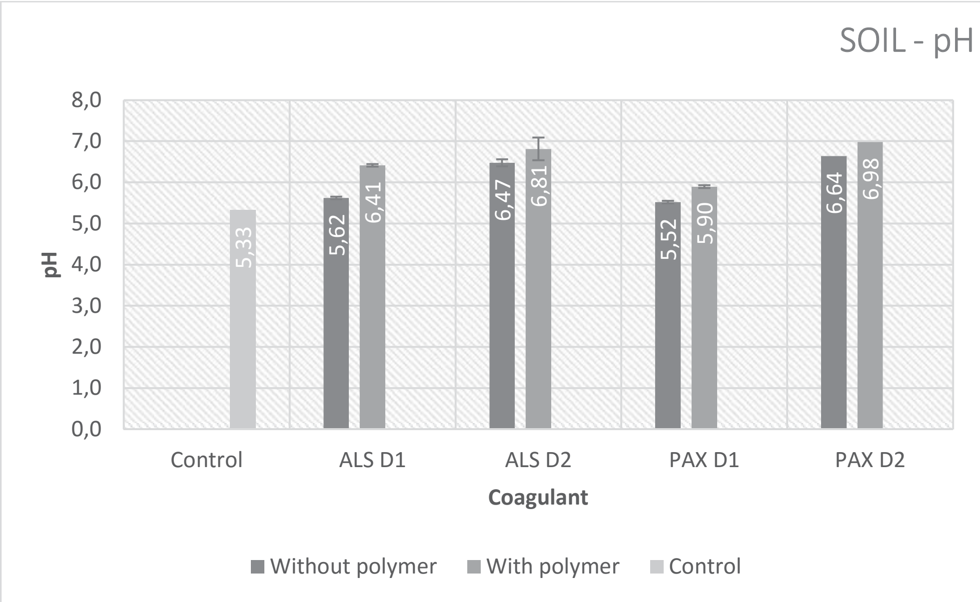


Figure 6. Effect of soil pH on phosphorus availability (California Fertilizer Association, 1995)

Starting off with approximately similar levels, the application of the different fertilizers varied the growth systems' pH. Soil pots registered values between 5.21 and 7.04, with pots containing sludge from metal + polymer coagulants reporting slightly higher pH values than those without additions. Theoretically, based on the phosphorus availability diagram, with the same amount of phosphorus in the soil system, those without polymers should have had fixated a bigger phosphorus fraction due to aluminum. Results, however, show that even at a pH along the range of aluminum fixation, soil pots without polymers gave more yield than their counterparts despite having optimal soil pH. This suggests that the cationic polymer had a detrimental effect to the plant or that the plant available phosphorus provided by the sludge in the soil solution are drastically lowered with the addition of polymers – that even despite optimal pH conditions, they produce less yield.

For this study, the soil pH was not a main factor in limiting nutrient uptake and plant growth. Still, it should be noted that amendment of the sludge with polymers acted as a liming agent and improved soil pH at levels optimal for phosphorus availability, especially as compared to that of mineral fertilizers.



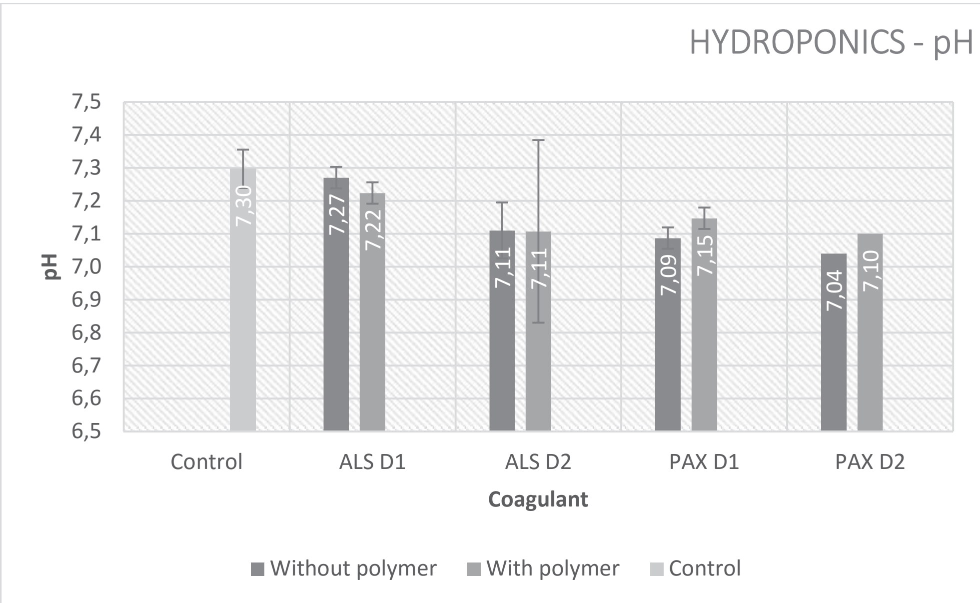


Figure 7. Measured pH values of peat soil and vermiculite after final harvest

Hydroponic pots varied only from pH 6.93 to 7.21. Although not measured in the experiment, higher pH values for the hydroponic systems could be attributed to the nature of vermiculite. Unlike the soil system, the initial hydroponic system's pH was not adjusted for the ideal range at the start of the experiment. Given the relatively similar conditions, it is not likely that the pH contributed greatly to the difference in crop yield between sludge with and without polymers. Future studies done on this topic should sample pH throughout the whole experiment as to determine whether change on pH is gradual or sudden upon application of the sludge.

Effect of growth medium on the pot experiment results

With respect to plant yield, all of the plants grown in the hydroponic system reflected that in the soil medium. Although there was no specific quantitative relationship between the dry mass harvest from the two medium, the trend was largely similar, except for some of the PAX pots. This could suggest that the charged polymers could have an effect on the interaction of soil and nutrients. Incidentally, nutrient uptake in the hydroponic system documented erratic trends and values in relation to the soil growth. Hydroponic systems have been shown to take up more nutrients as compared to soil systems due to minimal to no interactions with the growth medium (Thomas and Paparozzi, 2013, Pritsa et al., 2008, Weiss et al., 2006, Astolfi et al., 2004).

The hydroponic set-up, however, could be improved, as the arrangement in this study was not ideal with the system treating vermiculite as a type of soil medium. The addition of proper aeration and nutrient delivery for the hydroponic system may improve the performance of the system.

Future considerations

It should be noted that the substitution done in the study involved only the simultaneous addition of the inorganic metal coagulant and the cationic organic polymer. In wastewater treatment, the addition of polymer can be done before and after the addition of the metal coagulant. Addition pre-coagulation, specifically, could help reduce total suspended solids. In light of the competing mechanisms of particle removal and phosphorus removal in coagulation, this would mean less metal coagulant dosage needed for the removal of phosphorus. Downside, however, is the need for infrastructure changes in its application to wastewater treatment plants. Still, further exploration of the effect of dosage application could help understand results from this experiment.

CONCLUSION

The simultaneous addition of cationic organic polymers to aluminum sulfate and prepolymerized aluminum chloride improved the total phosphorus removal through coagulation. The positively charged polymer destabilized the suspension and served as flocculating agents that bridged particles to allow faster settling and separation.

The sludge derived from the said coagulation provided phosphorus to plants grown in peat soil and in a hydroponic system. Yield, however, is significantly lower than mineral fertilizer and sludge obtained from metal salt coagulation at similar input phosphorus concentration. Observed nutrient use efficiencies of the sludge fertilizers dropped to

40% as compared to mineral fertilizers, with all polymer-amended coagulation sludge pots going lower than 20%.

Despite improving removal of total phosphorus from wastewater, the simultaneous addition of cationic polyacrylamide to metal salts in coagulation seemed to reduce the fraction of phosphorus available phosphorus, most particularly with the use of aluminum sulfate. The hypothesized possibility of substituting metal coagulants with cationic organic polymers to reduce aluminum concentration in sludge while maintaining good removal efficiency of phosphorus and plant yield was only observed in the pre-polymerized metal coagulant.

Reduction of the yield in polymer-enhanced sludge from coagulation could have been due to residual positive charge from the polymer used in the sludge could that may have fixed negatively charged phosphates in the soil or the phytotoxic effect cationic polymers or the mobilization of Al in soil for plant uptake. Further studies are needed to point out the actual mechanism by which the positively-charged polymers inhibit plant growth.

In general, the use of hydroponic growth systems could be representative of the results in soil conditions in terms of plant mass harvest. Yet, evaluations through soil growth are necessary to address soil interactions not simulated in the hydroponics system

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APPENDIX

A. Sludge Measurements

			SOIL		HYDROPONICS		
Sludge Type	Tot P * (mg/l)	Tot P ** (mg/l)	Calculated P dosage (mL)	Actual P dosage (mL)	Calculated P dosage (mL)	Actual P dosage (mL)	P removed [Tot P sludge/Tot P Wastewater] (%)
AlS D1	15,30	122,40	735,29	740,00	246,67	250,00	64,71
AlS D2	18,90	151,20	595,24	600,00	200,00	200,00	79,94
AlS D1 Polymer	16,00	128,00	703,13	700,00	233,33	230,00	67,67
AlS D2 Polymer	21,10	168,80	533,18	530,00	176,67	180,00	89,25
PAX D1	17,60	140,80	639,20	640,00	213,33	210,00	74,44
PAX D2	13,80	110,40	815,22	820,00	273,33	270,00	58,37
PAX D1 Polymer	19,30	154,40	582,90	580,00	193,33	190,00	81,63
PAX D2 Polymer	17,60	140,80	639,20	640,00	213,33	210,00	74,44
Tot P from Wastewater (mg/L)	189,14						

*Diluted concentration

**Actual concentration'

Actual P dosage is computed to allow the equivalent of 6 kg P/daa input for each pot.

B. Initial Pot Preparations

The volume listed in the pot preparation table refer to the volume of the following reagents:

P	Ca(H2PO4)2 with 3 g P/L
N	Ca(NO3)2 solution with 12 g N/L
K	K2SO4 with 12 g K/L
Mg	MgSO4 with 12 g Mg/L
Bo	Bo solution with 0,25 g Bo/L
Zn	ZnSO4 solution with 2,5 g Zn/L
Fe/Mo	FeSO4/Mo solution with 5 g Fe/L and 0,05 g Mo/L)
Mn/Cu	MnSO4/CuSO4 solution with (2,5 g Mg/L and 2.5 g Cu/L)

SOIL

Set	Pot Numbers	Description	Rye Grass (g)	P	N	K	Mg	Bo	Zn	Fe/Mo	Mn/Cu	Total Container Volume
				mL	mL	mL	mL	mL	mL	mL	mL	L
1	1-3	Control 1	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
2	3-6	Control 2	0,25	7,5	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
3	7-9	Control 3	0,25	15,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
4	10-12	Control 4	0,25	30,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
5	13-15	Control 5	0,25	45,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
6	16-18	ALS D1	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
7	19-21	PAX D1	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
8	22-24	ALS D1 + polymer	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
9	25-27	PAX D1 + polymer	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
10	28-30	Biological Sludge	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
11	31-33	ALS D2	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
12	34-36	PAX D2	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
13	37-39	ALS D2 + polymer	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
14	40-42	PAX D2 + polymer	0,25	0,0	25,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
15	43	No N (ALS D1)	0,25	0,0	0,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
	44	No N (ALS D1 + polymer)	0,25	0,0	0,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0
	45	No N (PAX D1)	0,25	0,0	0,0	25,0	25,0	25,0	25,0	25,0	25,0	3,0

HYDROPONICS

Set	Pot Numbers	Description	Rye Grass (g)	P	N	K	Mg	Bo	Zn	Fe/Mo	Mn/Cu	Total Container Volume
				mL	mL	mL	mL	mL	mL	mL	mL	L
1	1-3	Control 1	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
2	3-6	Control 2	0,10	2,5	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
3	7-9	Control 3	0,10	5,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
4	10-12	Control 4	0,10	10,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
5	13-15	Control 5	0,10	15,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
6	16-18	ALS D1	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
7	19-21	PAX D1	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
8	22-24	ALS D1 + polymer	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
9	25-27	PAX D1 + polymer	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
10	28-30	Biological Sludge	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
11	31-33	ALS D2	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
12	34-36	PAX D2	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
13	37-39	ALS D2 + polymer	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
14	40-42	PAX D2 + polymer	0,10	0,0	8,3	8,0	8,0	5,0	5,0	5,0	5,0	0,45
15	43	No N (ALS D1)	0,10	0,0	0,0	8,0	8,0	5,0	5,0	5,0	5,0	0,45
	44	No N (ALS D1 + polymer)	0,10	0,0	0,0	8,0	8,0	5,0	5,0	5,0	5,0	0,45
	45	No N (PAX D1)	0,10	0,0	0,0	8,0	8,0	5,0	5,0	5,0	5,0	0,45

C. Pot Supplements

Supplements were done after every harvest. Both pot and hydroponics growth systems received two dosages of the listed concentrations above. The volumes listed refer to the amount of the following reagents:

N	Ca(NO3)2 solution with 12 g N/L
K	K2SO4 with 12 g K/L

SOIL

Set	Pot Numbers	Description	N	K
			mL	mL
1	1-3	Control 1	15,0	15,0
2	3-6	Control 2	15,0	15,0
3	7-9	Control 3	15,0	15,0
4	10-12	Control 4	15,0	15,0
5	13-15	Control 5	15,0	15,0
6	16-18	ALS D1	15,0	15,0
7	19-21	PAX D1	15,0	15,0
8	22-24	ALS D1 + polymer	15,0	15,0
9	25-27	PAX D1 + polymer	15,0	15,0
10	28-30	Biological Sludge	15,0	15,0
11	31-33	ALS D2	15,0	15,0
12	34-36	PAX D2	15,0	15,0
13	37-39	ALS D2 + polymer	15,0	15,0
14	40-42	PAX D2 + polymer	15,0	15,0
15	43	No N (ALS D1)	0,0	15,0
	44	No N (ALS D1 + polymer)	0,0	15,0
	45	No N (PAX D1)	0,0	15,0

HYDROPONICS

Set	Pot Numbers	Description	N	K
			mL	mL
1	1-3	Control 1	5,0	5,0
2	3-6	Control 2	5,0	5,0
3	7-9	Control 3	5,0	5,0
4	10-12	Control 4	5,0	5,0
5	13-15	Control 5	5,0	5,0
6	16-18	ALS D1	5,0	5,0
7	19-21	PAX D1	5,0	5,0
8	22-24	ALS D1 + polymer	5,0	5,0
9	25-27	PAX D1 + polymer	5,0	5,0
10	28-30	Biological Sludge	5,0	5,0
11	31-33	ALS D2	5,0	5,0
12	34-36	PAX D2	5,0	5,0

13	37-39	ALS D2 + polymer	5,0	5,0
14	40-42	PAX D2 + polymer	5,0	5,0
15	43	No N (ALS D1)	0,0	5,0
	44	No N (ALS D1 + polymer)	0,0	5,0
	45	No N (PAX D1)	0,0	5,0

D. Dry Mass Harvest

SOIL			Harvest 1		Harvest 2		Harvest 3		Total		Corrected Total	
Set	Pot Numbers	Description	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE
1	1-3	Control 1	0,3	0,0	2,0	0,2	2,8	0,4	5,1	0,4	0,0	0,5
2	4-6	Control 2	7,5	0,6	7,9	1,0	6,1	0,3	21,5	1,2	16,4	1,2
3	7-9	Control 3	10,5	1,2	10,0	0,2	7,4	0,3	27,9	1,2	22,9	1,3
4	10-12	Control 4	11,5	0,6	12,2	0,3	10,5	0,3	34,3	0,7	29,2	0,8
5	13-15	Control 5	10,8	0,7	13,4	0,2	11,6	0,4	35,7	0,9	30,7	1,0
6	16-18	ALS D1	7,8	0,7	9,7	0,3	7,5	0,3	25,0	0,8	19,9	0,9
7	19-21	PAX D1	6,1	0,6	9,7	0,2	6,9	0,3	22,7	0,7	17,6	0,8
8	22-24	ALS D1 + polymer	3,6	0,4	5,3	0,6	4,6	0,2	13,5	0,8	8,5	0,9
9	25-27	PAX D1 + polymer	5,0	0,3	8,1	0,2	5,6	0,2	18,8	0,4	13,7	0,6
11	31-33	ALS D2	4,4	0,5	8,7	0,5	7,2	0,4	20,3	0,8	15,2	0,9
12	34-36	PAX D2	3,8	1,1	8,2	0,2	6,6	0,3	18,6	1,1	13,6	1,2
13	37-39	ALS D2 + polymer	2,0	0,3	3,5	0,7	4,1	0,5	9,5	0,9	4,4	1,0
14	40-42	PAX D2 + polymer	3,7	0,1	6,4	0,6	5,2	0,2	15,3	0,6	10,2	0,8
15	43	No N (ALS D1)	5,0		3,8		2,3		11,1		6,0	0,4
	44	No N (ALS D1 + polymer)	3,9		4,2		2,1		10,2		5,1	0,4
	45	No N (PAX D1)	5,7		3,7		2,3		11,7		6,6	0,4

HYDROPONICS			Harvest 1		Harvest 2		Harvest 3		Total		Corrected Total	
Set	Pot Numbers	Description	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE	Dry Mass Harvest (g)	SE
1	1-3	Control 1	0,2	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,1
2	4-6	Control 2	2,6	0,8	1,6	0,3	0,5	0,1	4,7	0,9	4,4	0,9
3	7-9	Control 3	3,3	0,6	4,2	0,1	1,8	0,2	9,3	0,6	9,0	0,6
4	10-12	Control 4	3,1	0,9	5,5	0,2	3,9	0,2	12,6	1,0	12,3	1,0
5	13-15	Control 5	2,9	0,8	6,1	0,4	4,3	0,1	13,3	0,9	13,0	0,9
6	16-18	ALS D1	1,9	0,5	3,8	0,2	3,2	0,1	8,8	0,5	8,6	0,5
7	19-21	PAX D1	1,9	0,2	3,9	0,0	2,5	0,1	8,3	0,2	8,0	0,2
8	22-24	ALS D1 + polymer	1,2	0,2	1,5	0,3	1,2	0,2	3,9	0,4	3,6	0,4
9	25-27	PAX D1 + polymer	2,0	0,2	4,1	0,2	2,1	0,1	8,2	0,3	8,0	0,3
11	31-33	ALS D2	1,4	0,1	3,6	0,1	3,2	0,1	8,3	0,2	8,0	0,2
12	34-36	PAX D2	2,0	0,3	3,8	0,2	2,5	0,1	8,3	0,3	8,0	0,3
13	37-39	ALS D2 + polymer	0,6	0,1	0,8	0,2	0,6	0,2	2,0	0,3	1,8	0,3
14	40-42	PAX D2 + polymer	1,4	0,0	3,0	0,1	1,7	0,1	6,1	0,2	5,9	0,2
15	43	No N (ALS D1)	1,1		0,5		0,2		1,8		1,5	0,0
	44	No N (ALS D1 + polymer)	0,4		0,4		0,2		1,0		0,7	0,0
	45	No N (PAX D1)	0,8		0,4		0,2		1,4		1,1	0,0

E. Total Phosphorus Uptake

SOIL			Harvest 1		Harvest 2		Harvest 3		Total	
Set	Pot Numbers	Description	P (mg/pot)	SE	P (mg/pot)	SE	P (mg/pot)	SE	P (mg/pot)	SE
1	1-3	Control 1	0,000	0,017	0,000	0,103	0,000	0,319	0,000	0,336
2	4-6	Control 2	5,942	0,436	3,349	0,799	1,722	0,316	11,013	0,964
3	7-9	Control 3	15,521	1,589	4,706	0,601	2,351	0,274	22,577	1,721
4	10-12	Control 4	30,114	1,508	12,028	0,782	7,011	0,625	49,154	1,810
5	13-15	Control 5	36,991	1,589	21,728	0,204	10,777	0,420	69,496	1,657
6	16-18	ALS D1	8,445	0,592	4,818	0,155	2,859	0,236	16,121	0,656
7	19-21	PAX D1	5,889	0,716	4,656	0,279	2,688	0,255	13,232	0,810
8	22-24	ALS D1 + polymer	2,875	0,510	2,079	0,508	1,161	0,253	6,115	0,763
9	25-27	PAX D1 + polymer	4,620	0,202	3,578	0,102	1,576	0,231	9,774	0,323
11	31-33	ALS D2	4,107	0,423	4,126	0,137	2,506	0,252	10,739	0,511
12	34-36	PAX D2	4,404	1,272	4,554	0,376	2,066	0,276	11,024	1,355
13	37-39	ALS D2 + polymer	1,407	0,312	0,916	0,387	0,884	0,352	3,208	0,609
14	40-42	PAX D2 + polymer	3,162	0,198	2,503	0,414	1,315	0,258	6,980	0,526
15	43	No N (ALS D1)	4,644	0,012	3,892	0,073	1,911	0,226	10,446	0,237
	44	No N (ALS D1 + polymer)	3,354	0,012	1,722	0,073	0,477	0,226	5,552	0,237
	45	No N (PAX D1)	5,430	0,012	3,012	0,073	1,681	0,226	10,122	0,237

HYDROPONICS			Harvest 1		Harvest 2		Harvest 3		Total	
Set	Pot Numbers	Description	P (mg/pot)	SE	P (mg/pot)	SE	P (mg/pot)	SE	P (mg/pot)	SE
1	1-3	Control 1	0,000	0,017	0,000	0,021	0,000	0,003	0,000	0,027
2	4-6	Control 2	1,399	0,354	0,625	0,113	0,298	0,052	2,322	0,375
3	7-9	Control 3	3,159	0,309	1,678	0,031	1,014	0,070	5,851	0,318
4	10-12	Control 4	5,707	1,092	3,658	0,223	2,313	0,113	11,678	1,120
5	13-15	Control 5	6,770	1,348	6,188	0,429	3,262	0,057	16,221	1,416
6	16-18	ALS D1	2,190	0,284	2,478	0,080	1,992	0,184	6,660	0,348
7	19-21	PAX D1	2,227	0,062	2,451	0,091	1,600	0,090	6,278	0,142
8	22-24	ALS D1 + polymer	0,796	0,110	0,780	0,113	0,621	0,081	2,197	0,177
9	25-27	PAX D1 + polymer	1,919	0,131	2,048	0,089	1,090	0,049	5,057	0,166
11	31-33	ALS D2	1,723	0,157	2,528	0,084	2,301	0,030	6,552	0,180
12	34-36	PAX D2	2,180	0,329	2,223	0,125	1,365	0,043	5,768	0,354
13	37-39	ALS D2 + polymer	0,294	0,089	0,421	0,134	0,358	0,108	1,073	0,194
14	40-42	PAX D2 + polymer	1,240	0,014	1,406	0,074	0,870	0,058	3,516	0,095
15	43	No N (ALS D1)	2,433	0,012	1,185	0,015	0,540	0,002	4,158	0,019
	44	No N (ALS D1 + polymer)	0,239	0,012	0,465	0,015	0,360	0,002	1,064	0,019
	45	No N (PAX D1)	1,903	0,012	0,865	0,015	0,580	0,002	3,348	0,019

F. Average Nutrient Plant Uptake

SOIL

Pot Numbers	Description	Al	Ca	Fe	Mg	P	P - $P_{Control1}$
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1-3	Control 1	0,04 ± 0,03	7,13 ± 0,70	0,064 ± 0,007	1,42 ± 0,09	0,62 ± 0,07	0,00 ± 0,10
3-6	Control 2	0,01 ± 0,01	6,27 ± 0,42	0,052 ± 0,004	1,86 ± 0,16	0,65 ± 0,07	0,03 ± 0,10
7-9	Control 3	0,01 ± 0,01	6,52 ± 0,55	0,053 ± 0,002	2,01 ± 0,19	0,88 ± 0,08	1,00 ± 0,11
10-12	Control 4	0,01 ± 0,01	7,08 ± 0,59	0,055 ± 0,003	2,20 ± 0,16	1,51 ± 0,16	0,89 ± 0,18
13-15	Control 5	0,01 ± 0,00	7,17 ± 0,73	0,052 ± 0,005	2,19 ± 0,12	2,09 ± 0,24	2,00 ± 0,26
16-18	ALS D1	0,01 ± 0,01	6,77 ± 0,41	0,056 ± 0,016	1,88 ± 0,20	0,78 ± 0,10	0,16 ± 0,13
19-21	PAX D1	0,01 ± 0,00	7,24 ± 0,17	0,051 ± 0,002	1,98 ± 0,07	0,74 ± 0,06	3,00 ± 0,09
22-24	ALS D1 + polymer	0,01 ± 0,01	6,71 ± 0,38	0,056 ± 0,003	1,84 ± 0,12	0,69 ± 0,05	0,07 ± 0,09
25-27	PAX D1 + polymer	0,01 ± 0,00	7,02 ± 0,50	0,052 ± 0,002	1,89 ± 0,10	0,71 ± 0,03	4,00 ± 0,08
28-30	Biological Sludge						
31-33	ALS D2	0,01 ± 0,00	6,86 ± 0,60	0,052 ± 0,005	1,89 ± 0,09	0,72 ± 0,03	5,00 ± 0,08
34-36	PAX D2	0,02 ± 0,02	7,73 ± 0,41	0,057 ± 0,003	2,02 ± 0,19	0,82 ± 0,04	0,20 ± 0,08
37-39	ALS D2 + polymer	0,02 ± 0,01	7,22 ± 1,18	0,061 ± 0,005	1,74 ± 0,23	0,69 ± 0,08	6,00 ± 0,11
40-42	PAX D2 + polymer	0,01 ± 0,00	7,40 ± 0,68	0,055 ± 0,003	1,92 ± 0,18	0,69 ± 0,06	0,07 ± 0,09
43	No N (ALS D1)	0,03 ± 0,01	7,20 ± 0,49	0,046 ± 0,008	1,90 ± 0,35	1,29 ± 0,17	7,00 ± 0,18
44	No N (ALS D1 + polymer)	0,01 ± 0,00	6,83 ± 0,41	0,049 ± 0,012	1,67 ± 0,30	0,87 ± 0,06	0,25 ± 0,10
45	No N (PAX D1)	0,04 ± 0,02	6,90 ± 0,60	0,044 ± 0,008	1,83 ± 0,32	1,19 ± 0,12	8,00 ± 0,14

HYDROPONICS

Pot Numbers	Description	Al	Ca	Fe	Mg	P	P - $P_{Control1}$
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1-3	Control 1	0,02 ± 0,01	12,69 ± 4,40	0,048 ± 0,009	11,54 ± 4,10	0,49 ± 0,02	0,00 ± 0,03
3-6	Control 2	0,04 ± 0,04	5,38 ± 2,26	0,053 ± 0,023	3,68 ± 1,04	0,55 ± 0,10	0,06 ± 0,10
7-9	Control 3	0,07 ± 0,11	3,73 ± 0,64	0,069 ± 0,067	2,96 ± 0,52	0,67 ± 0,10	0,18 ± 0,10
10-12	Control 4	0,03 ± 0,03	2,92 ± 0,51	0,039 ± 0,012	2,66 ± 0,45	1,11 ± 0,37	0,62 ± 0,37
13-15	Control 5	0,02 ± 0,01	2,92 ± 0,31	0,039 ± 0,013	2,82 ± 0,37	1,42 ± 0,22	0,93 ± 0,22
16-18	ALS D1	0,04 ± 0,02	4,74 ± 0,62	0,044 ± 0,009	3,93 ± 0,44	0,85 ± 0,14	0,37 ± 0,14
19-21	PAX D1	0,04 ± 0,05	4,24 ± 0,24	0,054 ± 0,034	3,52 ± 0,29	0,84 ± 0,07	0,35 ± 0,07
22-24	ALS D1 + polymer	0,08 ± 0,07	5,27 ± 0,83	0,069 ± 0,049	4,91 ± 1,22	0,61 ± 0,06	0,13 ± 0,07
25-27	PAX D1 + polymer	0,08 ± 0,13	3,97 ± 0,35	0,061 ± 0,047	3,17 ± 0,30	0,68 ± 0,04	0,20 ± 0,04
28-30	Biological Sludge						
31-33	ALS D2	0,07 ± 0,06	4,22 ± 0,26	0,070 ± 0,043	3,59 ± 0,18	0,91 ± 0,10	0,42 ± 0,11
34-36	PAX D2	0,05 ± 0,05	4,09 ± 0,28	0,057 ± 0,036	3,36 ± 0,19	0,76 ± 0,05	0,27 ± 0,05
37-39	ALS D2 + polymer	0,04 ± 0,03	6,00 ± 2,05	0,057 ± 0,019	5,24 ± 0,99	0,60 ± 0,07	0,12 ± 0,07
40-42	PAX D2 + polymer	0,04 ± 0,03	3,74 ± 0,28	0,048 ± 0,012	3,10 ± 0,23	0,64 ± 0,02	0,16 ± 0,03
43	No N (ALS D1)	0,01 ± 0,00	3,10 ± 0,59	0,029 ± 0,005	2,97 ± 0,62	2,50 ± 0,15	2,01 ± 0,15
44	No N (ALS D1 + polymer)	0,04 ± 0,02	2,57 ± 0,43	0,042 ± 0,010	2,93 ± 0,79	1,31 ± 0,31	0,83 ± 0,31
45	No N (PAX D1)	0,02 ± 0,01	3,10 ± 0,58	0,035 ± 0,003	2,77 ± 0,55	2,57 ± 0,23	2,08 ± 0,23

G. Soil pH

Set	Pot Number	Coagulant	pH	
			SOIL	HYDROPONICS
1	1	Control 1	6,59	7,37
	2	Control 1	6,47	7,39
	3	Control 1	6,49	7,30
2	4	Control 2	5,91	7,22
	5	Control 2	5,88	7,46
	6	Control 2	5,23	7,32
3	7	Control 3	5,44	7,93
	8	Control 3	5,01	7,66
	9	Control 3	5,37	7,52
4	10	Control 4	5,31	7,39
	11	Control 4	5,46	7,31
	12	Control 4	5,21	7,19
5	13	Control 5	5,00	7,30
	14	Control 5	5,22	7,15
	15	Control 5	5,05	7,34
6	16	ALS D1	5,73	7,46
	17	ALS D1	5,61	7,17
	18	ALS D1	5,52	7,18
7	19	PAX D1	5,35	7,10
	20	PAX D1	5,61	7,15
	21	PAX D1	5,60	7,01
8	22	ALS D1 + polymer	6,70	7,22
	23	ALS D1 + polymer	6,28	7,24
	24	ALS D1 + polymer	6,26	7,21
9	25	PAX D1 + polymer	6,38	7,08
	26	PAX D1 + polymer	5,42	7,20
	27	PAX D1 + polymer	5,89	7,16
10	28	Biological Sludge	-	-
	29	Biological Sludge	-	-
	30	Biological Sludge	-	-
11	31	ALS D2	6,42	7,13
	32	ALS D2	6,47	7,14

	33	ALS D2	6,53	7,06
12	34	PAX D2	6,59	7,07
	35	PAX D2	6,64	6,97
	36	PAX D2	6,70	7,08
13	37	ALS D2 + polymer	6,76	7,12
	38	ALS D2 + polymer	6,81	6,93
	39	ALS D2 + polymer	6,87	7,27
14	40	PAX D2 + polymer	6,93	7,09
	41	PAX D2 + polymer	6,98	7,12
	42	PAX D2 + polymer	7,04	7,09
15	43	No N (ALS D1)	7,10	6,91
	44	No N (ALS D1 + polymer)	7,15	6,97
	45	No N (PAX D1)	5,60	7,19

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