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Evaluation of amendments to control phosphorus losses in runoff from pig slurry applications to land

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Running Head Title: Amendment to pig slurry

Nonstandard abbreviations: Flue gas desulphurization by-product (FGD); poly-aluminium chloride (PAC); alum-based water treatment residual (Al-WTR);

Keywords: Agitator test; dissolved reactive phosphorus; land application; pig slurry.

Abstract

If spread in excess of crop requirements, incidental phosphorus (P) losses from agriculture can lead to eutrophication of receiving waters. The use of amendments in targeted areas may help reduce the possibility of surface runoff of nutrients. The aim of this study was to identify amendments which may be effective in reducing incidental dissolved reactive phosphorus (DRP) losses in surface runoff from land applied pig slurry. For this purpose, the DRP losses under simulated conditions across the surface of intact grassland soil cores, loaded with unamended and amended slurry at a rate equivalent to 19 kg P ha^{-1}, were determined over a 30 h period. The effectiveness of the amendments at reducing DRP in overlying water were (in decreasing order): alum (86%), flue gas desulphurization by-product (FGD) (74 %), poly-aluminium (Al) chloride (PAC) (73%), ferric chloride (71 %), flyash (58%) and lime (54%). Flue gas desulphurization by-product was the most costly of all the treatments (€7.64/m^3 for 74% removal). Ranked in terms of feasibility, which takes into account effectiveness, cost and other potential impediments to use, they were: alum, ferric chloride, PAC, flyash, lime and FGD.

1 Introduction

The application of slurry in excess of crop requirements can give rise to elevated soil test phosphorus (P) concentrations, which may take years-to-decades to be reduced to agronomically optimum levels [1]. In addition, it can lead to eutrophication of receiving waters [2]. Phosphorus losses occur in runoff from two sources: a) ‘incidental P losses’ take place when a rainfall event occurs shortly after slurry application and before slurry infiltrates the soil, while b) ‘chronic P losses’ is a long-term loss of P from soil as a result of a build-up in soil test P caused by application of inorganic fertilisers and manure [1, 3]. The use of amendments may allow the application of manure to soil in intensive farm systems, such as pig farms, while reducing incidental and chronic P losses. This paper proposes a novel and relatively realistic way to identify such amendments.

Alum, aluminium chloride ($AlCl_3$), lime and ferric chloride are commonly used as coagulants in slurry and wastewater separation operations. Smith et al. [4] found in a field-based study that aluminium chloride, added at 0.75% of final manure volume to pig slurry, could reduce DRP by up to 84%. Smith et al. [5] found that alum and $AlCl_3$, added in a field-based study to pig slurry at 430 mg Al L^{-1}, reduced DRP in runoff water by 84% and DRP in manure by over 99%. In an incubation study, Dou et al. [6] found that technical-grade alum, added to pig slurry at 0.25 kg kg^{-1} of manure dry matter, and flue gas desulpherisation by-product (FGD), added at 0.15 kg kg^{-1}, each reduced DRP by 80%. Dao [7] amended stockpiled cattle manure with caliche, alum and flyash in an incubation experiment, and reported water extractable P reductions in amended manure compared to the control of 21, 60 and 85%, respectively.

Batch experiments, wherein an amendment and slurry are mixed, are a good way to determine if the addition of a particular amendment is appropriate to reduce P in surface runoff from land applied slurry, but do not account for the interaction between applied slurry and soil, and the effect of infiltration and skin formation on the release of P to surface runoff. An agitator test, wherein an intact soil core, placed in a beaker, is overlain with continuously-stirred water [8, 9], enables achievement of batch experiment results, but also simulates the situation in which slurry is applied to soil, allowed to dry, and then subjected to overland flow.

The aim of this study was to: (i) investigate the effectiveness of various pig slurry amendments to control incidental P losses in runoff applied to permanent grassland; (ii) identify optimum amendment application rates for each amendment; (iii) estimate the cost of each treatment; and (iv) discuss the feasibility of using amendments in a real on-farm scenario.

2 Materials and Methods

2.1 Slurry collection and characterisation

Pig slurry was taken from an integrated pig unit in Teagasc Research Centre, Moorepark, Fermoy, Co. Cork. The sampling point was a valve on an outflow pipe between two holding tanks, which were sequentially placed after a holding tank under the slats. To ensure a representative sample, this valve was turned on and left to run for a few minutes before taking a sample. The entire sample used for both the batch study and agitator test was taken as one sample. The slurry was stored in a 25 L drum in a cold room at 11°C prior to testing. The total phosphorus (TP) and total nitrogen (TN) were determined using persulfate digestion. Ammonium-N (NH_4-N) was determined by adding 50 mL of slurry to 1 L of 0. 1M HCl, shaking, filtering through No. 2 Whatman filter paper, and analysing using a nutrient analyser (Konelab 20, Thermo Clinical Lab systems, Finland). Slurry pH was determined using a pH probe (WTW, Germany). Dry matter (DM) content was determined by drying at 105°C for 24 hr. The physical and chemical characteristics of the pig slurry used in this experiment and characteristic values of pig slurry from other farms in Ireland and internationally are presented in Table 1.

2.2 Soil preparation and analysis

Grassed soil samples were collected from a local dry stock farm in Galway, Republic of Ireland. 120-mm-high, 100-mm-diameter aluminium (Al) coring rings were used to collect undisturbed soil core samples (n=60). Soil samples (n=3) – taken from upper 100 mm from the same location - were air dried at 40 °C for 72 hr, crushed to pass a 2 mm sieve and analysed for soil test P using Morgan's extracting solution [10]. Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water-to-soil. The particle size distribution was determined using a sieving and pipette method [11], and the organic content of the soil was determined using the loss of ignition test [12]. The soil used was a poorly-drained, sandy loam textured, topsoil (58% sand, 27% silt, 15% clay) with a soil test P of 16.72±3.58 mg L^{-1}, total potassium of 127.39±14.94 mg L^{-1}, a pH of 7.65±0.06, and an organic matter content of 13±0.1%.

2.3 Batch study to determine potential amendments

A batch study was carried out to identify appropriate amendments for the agitator test and the rates at which they should be applied to pig manure to reduce water extractable P, an environmental indicator of potential P loss in slurry. The following amendments were added in the batch study: (i) commercial grade liquid alum (8% Al_2O_3) (ii) commercial-grade liquid poly-Al chloride (PAC) (10 % Al_2O_3) (iii) commercial-grade liquid ferric chloride (38% $FeCl_3$) (iv) analytical-grade ferric sulphate ($FeSO_4.7H_2O$) (v) analytical-grade lime ($Ca(OH)_2$) (vi) flyash (vii) flue gas desulphurisation by-product (FGD) (viii) bottom ash (ix) gypsum (x) aluminium-based water treatment residuals (Al-WTR), sieved to less than 2 mm (Al-WTR-1), and (xi) Al-WTR homogenised sludge (Al-WTR-2). Tests i – v were applied based on a metal:TP stoichiometric ratio and vi – xi were applied based on a kg kg^{-1} weight basis (slurry dry matter). The Al-WTR was provided by Galway City Water Treatment Plant. Coal combustion by-products (flyash, FGD and bottom ash) were provided by the Electricity Supply Board. The compositions of all the amendments used are shown in Table 2.

The pH of the amended slurry was measured after application of amendments at t = 0 h. Amendments were added at 5 different rates to 50g of slurry and mixed for 10 s. All tests were carried out in triplicate (n=3). At t = 24 h, samples were tested for water extractable P after Kleinman et al. [13]. An unamended sample was also used as a study control.

2.4 Agitator Test

The agitator test has been used to investigate the release of P from soil [8] and from amended dairy cattle slurry to soil [9]. This experiment replicates the way in which slurry is applied to soil, allowed to dry, and then subjected to overland flow. Although no validation of test results with actual runoff was undertaken, the test provided comparable conditions for assessment of the effectiveness of the amendments at reducing the release of P from land-applied slurry in a realistic way.

In the agitator test, the following treatments were examined in triplicate (n=3) within 21 d of sample collection: a) a grassed sod-only treatment with no slurry applied; b) a grassed sod with unamended slurry applied at a rate of 19 kg TP ha^{-1} (the control study); c) grassed sods receiving amended slurry applied at a rate of 19 kg TP ha^{-1}. Six different amendments (selected from the batch study above) were applied at three different rates (low, medium and high) based on the results obtained from the batch study. Amendments were added to slurry in a 100 mL plastic cup and mixed for 10 s. Prior to the start of the agitator test, the intact soil samples – at approximately field capacity – were taken from their sampling cores and cut to a height of 45 mm; this was considered sufficient to include the full depth of influence on release of P to overland flow [8]. They were then transferred into 1 L glass beakers. The slurry and amended slurry was then applied to the soil cores (t = 0 h) and left to interact for 24 h prior to the sample being saturated. At t = 24 h, the samples were gently saturated by adding deionised water to the soil at intermittent time intervals over 24 h until water pooled on the surface. Immediately after saturation (t = 48 h), 500 mL of deionised water was added to the beaker. The agitator paddle was lowered to mid-depth in the water overlying the soil sample and the paddle was set to rotate at 20 rpm for 30 h to simulate overland flow (Figure 1).

Water samples (4 ml) were taken from mid-depth of the water overlying the soil at 0.25, 0.5, 1, 2, 4, 8, 12, 24 and 30 h after the start of each test (i.e after the 500 ml was added). All samples were filtered immediately after sample collection using 0.45 μm filters and prior to being analysed colorimetrically for DRP using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). pH readings were taken in the overlying water at 1 h and 30 h after the start of each test.

2.5 Cost

The effects of amendments on slurry viscosity or handling were not considered in the cost analysis. It was assumed that amendments would be added upon delivery, so storage cost on site was excluded from the analyses. In the case of lime, the cost was estimated using commercial grade lime. The calculated costs took into account the fixed and operational costs for a 75 kW tractor and 2000 gal. splash-plate slurry tanker.

3 Results

3. 1 Batch study

The most effective amendments at reducing water extractable P after 24 h were (in decreasing order of effectiveness): alum (99%), lime (99%), ferric chloride (98%), PAC (95%), flyash (87%), FGD (76%), gypsum (39%), ferric sulphate (27%), bottom ash (24%), Al-WTR-2 (15%) and Al-WTR-1 (0%) (Figure 2).

For all solutions, there was a point beyond which further additions of amendments did not significantly reduce water extractable P (Figure 2). On the basis of inspection of the results, the amendments and their application rates to be used in the agitator test were: (i) alum (0.29:1, 0.58:1, 0.88:1 [Al:P]); (ii) PAC (0.18:1, 0.36:1, 0.72:1 [Al:P]); (iii) ferric chloride (0.34:1, 0.62:1, 0.89:1 [Fe:P]); (iv) lime (3.86:1, 5.79:1, 7.79:1 [Ca:P]); (v) flyash (0.857, 1.71, 3.43 kg kg^{-1} DM); and (vi) FGD (2.7, 3.78, 4.86 kg kg^{-1} DM).

3.2 Agitator test

Figure 3 shows the mass of DRP in the overlying water and DRP concentrations over the study duration. The percentage reduction in DRP for each treatment at each rate is shown in Table 3. The unamended slurry had a DRP concentration of 17.8 mg L^{-1} in the overlying water. The DRP concentrations in the overlying water, ranked from best to worst, were: alum, 2.5 mg L^{-1}; FGD, 4.6 mg L^{-1}; PAC, 4.7 mg L^{-1}; ferric chloride, 5.2 mg L^{-1}; flyash, 7.5 mg L^{-1}; and lime, 8.1 mg L^{-1}. These compare to the water overlying the grassed sod-only treatment, which had a DRP concentration of 2.0 mg L^{-1}.

3.3 Cost

Table 3 shows the estimated cost of addition of amendments and estimations of spreading and agitation costs as a result of their use. In order of increasing cost of use, per m^3 of pig slurry, they are: ferric chloride (€1.89); flyash (€2.00); PAC (€2.09); alum (€2.18); lime (€2.84) and FGD (€4.10). Figure 4 shows the total cost of amendment (€ $tonne^{-1}$) versus percentage reduction in DRP release to overlying water (%) and the reduction in DRP released from soil (kg ha^{-1}). The addition of FGD led to dry matter contents of above 10%, which would require water to be added to produce dry matter of a low enough consistency for slurry spreading operations. Addition of water would require agitation and these, combined with the high volume of addition per m^3, significantly increased the total cost of FGD above the other amendments. Alum, although clearly the best performing amendment, was still competitively priced compared to the other amendments.

4 Discussion

In the batch study, Al-WTR- 1 and Al-WTR-2 increased the water extractable P of the slurry when added at some weights. This may be attributable to the fact that there were small quantities of P within Al-WTR- 1 and Al-WTR-2 (Table 2). There was also P present in flyash and FGD, but these amendments contained much more calcium (Ca) and magnesium (Mg), which are P sorbing elements. Lime required a much higher stoichiometric addition rate to achieve significant water extractable P reduction, however this is acceptable as lime is often added to land by farmers and has widespread public acceptance. Ferric sulphate was not tested above a stoichiometric rate of 0.332, as there was a poor response relative to the other amendments at the same addition rate. The reduction in water extractable P compared favorably to that of Dao et al. [7], who reported reductions of 60% and 85% in water extractable P concentrations after adding alum and flyash, respectively, to stockpiled cattle manure.

Taking into account costs, land application of metals and potential DRP reductions in overlying water, the amendments, ranked in decreasing order of feasibility, were: alum, ferric chloride, PAC, flyash, lime and FGD.

There was a high initial rise in DRP at the start of each test, with the rate of increase reducing over time towards the end of the study (Figure 3). It can be seen in almost all cases that the higher the addition rate for each amendment, the lower the peak in DRP concentration. The amendments used in the agitator test all reduced the DRP concentrations in the overlying water. However, they did not reduce the concentrations to below that of the grassed sod-only treatment, which itself was well above 30 μg P L^{-1}, the median phosphate level above which significant deterioration may be seen in river ecosystems [14]. The reason for this is the amendments only reduce the contribution of the slurry to the overlying water DRP and do not affect the contribution of the soil to the overlying water DRP. The reductions in DRP were broadly similar to Smith et al. [5], who achieved reductions in DRP of 84% in runoff water when adding both alum and $AlCl_3$ to pig slurry at 430 mg Al L^{-1} in a field-based study.

The effect of amendments on slurry pH is a potential barrier to their implementation as it affects P sorbing ability [15] and ammonia (NH_3) emissions from slurry [16]. The use of acidifying amendments can lead to increased release of hydrogen sulphide gas (H_2S) from slurry, which is believed to be responsible for human and animal deaths when slurry is being agitated on farms. However, the results from this experiment show the pH of the overlying water not to be significantly affected by the use of amendment.

From the cost analysis, it can be seen that the use of amendments may only be worth pursuing where focused application may be adopted. As legislation allows less slurry to be spread on high P index soils, farmers with these soils have less land available on which to spread slurry. The addition of amendment to pig slurry has the potential to relieve this problem. If a farmer has more than one P index level on a farm, then a way to potentially reduce the cost associated with amending the slurry would be to only amend the slurry that is applied to areas of the farm with a higher soil test P. However, this will only reduce the impact of landspreading on the potential loss of P in runoff and will not impact on the soil test P, which will still be a potential pollution source.

Although this study did not investigate the release of metals due to the amendment of slurry, previous studies that have found no added risk was posed by amending land applied pig [4] or poultry [17] manure. Moore et al. [17] also investigated whether using alum as an amendment affected Al concentrations in the soil or Al uptake by plants. They showed that the use of alum did not negatively affect either. The reason that Al availability was not affected is because Al availability in soils is virtually independent of the level of total Al, but instead is controlled by the geochemical conditions present, with pH being the major influencing factor. Acidic conditions result in the dissolution of clay minerals and Al oxides, causing high concentrations of exchangeable Al. The pH would be expected to increase, resulting in decreased available Al. Moore et al. [17] also calculated that it would take up to 400 years of annual application of alum-treated litter to increase the level of total Al in the soil from 7 to 8%, as alum is already the most abundant metal in most soils.

5 Conclusions

The findings of this study are:

1. All of the amendments trialled in the agitator test have the potential to reduce the release of P in surface runoff from land-applied slurry.
2. Taking into account costs and land application of metals, suitable amendments which may reduce the risk of surface runoff of P from land applied pig slurry are (in decreasing order of feasibility): alum, ferric chloride, PAC, flyash, lime and FGD.
3. As there are significant costs associated with the use of these amendments, it is recommended that they are used strategically in areas which are likely to have potential nutrient loss problems. As land surrounding pig farms tend to have high soil test phosphorus, the use of amendments may be deemed necessary. Although they reduce the impact of nutrient loss from land application of pig slurry, they do not prevent the loss of nutrients from soil of high nutrient content.

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Legend

Figure 1. The agitator experimental setup.

Figure 2. Concentration of water extractable P in pig slurry (mg L^{-1}) as a function of stoichiometric ratio of Al added as alum and poly-Al chloride (PAC); Fe added as ferric chloride and ferric sulphate; and Ca as lime to total P in pig slurry (a), and mass of flyash, flue gas desulphurization by-product (FGD), bottom ash, gypsum, and Al-based water treatment residuals sieved to less than 2 mm (Al-WTR- 1) and homogenized sludge (Al-WTR-2) added per dry matter of pig slurry (b).

Figure 3. The mass of dissolved reactive P (DRP) (mg m^{-2}) and DRP concentration (mg L^{-1}) in water overlying grassed sod-only treatment; grassed sod with unamended slurry; and grassed sod with slurry amended with alum, poly-Al chloride (PAC), ferric chloride, lime, flyash and flue gas desulphurization by-product (FGD), each applied at three different rates, plotted over the 30 h of the test.

Figure 4. Total cost of amendment (€ $tonne^{-1}$) of pig slurry plotted against the reduction in dissolved reactive P (DRP) lost to overlying water (kg ha^{-1}) and the percentage reduction in DRP release to overlying water from slurry amended with alum, poly-Al chloride (PAC), ferric chloride, lime, flyash and flue gas desulphurization by-product (FGD), each applied at three different rates.

Table 1. Physical and chemical characteristics of the pig slurry used in this experiment and characteristic values of pig slurry from other farms in Ireland and internationally.

Location	Total P (mg L^{-1})	Total N (mg L^{-1})	Total K (mg L^{-1})	NH_4-N (mg L^{-1})	pH	Dry matter (%)	Reference
Ireland	560	2150±212		1248 ±40	8.9 ± 0.3	3.5± 0.2	The present study
	800	4200					S.I. No. 610 of 2010
	1630	6621	2666			5.77	18[a]
	900±7	4600±21	2600±10			3.2±2.3	19[a]
Spain	820	3220	1008	1860	7.59	3.2	20
U.S.A.	707	2037	1412	1366		2	21

a) Values changed to mg L^{-1} assuming densities of 1 kg L^{-1}.

Table 2. Characterisation of amendments used in the batch and agitator tests (mean ± standard deviation) tests carried out in triplicate.

Amendment		Alum	Poly-Al chloride	Ferric Chloride	Ferric Sulphate	Lime	Flyash	FGD	Bottomash	Gypsum	Al-WTR-1	Al-WTR-2
		8% Al_2O_3	10 % Al_2O_3	38% $FeCl_3$	$FeSO_4.7H_2O$	$Ca(OH)_2$					(<2mm)	(sludge)
pH		1.25	1.0 – 3.0				11.2± 0.04	8.6± 0.0			7.9± 0.1	6.9± 0.2
WEP	mg kg^{-1}	0					<0.01	<0.01			<0.01	
Al	%	4.23					5.7± 0.2	0.1± 0.0	0.42	1.1	11± 0.0	5.3± 0.2
Ca						54.1	4.9± 0.2	20± 0.3	0.4	28	1.3± 0.1	0.11
Fe		<0.01		38	20		2.2± 0.1	0.1± 0.0	1.6	0.5	0.2± 0.0	0.01
K							0.1	0.03	0.04	0.01	0.03± 0.0	<0.01
As	mg kg^{-1}	1	<1.0	<2.8			13± 0.6	<0.01			6.2±1.1	<0.01
Cd		0.21	<0.2	<3.4			0.6± 0.0	0.2± 0.02	0.28		0.16± 0.0	<0.01
Co							33± 1	0.3± 0.1	0.43		0.5± 0.3	<0.01
Cr		2.1	<2.0	<48			88± 2	3± 0.1	14.3		3.8± 0.21	0.3± 0.02
Cu				<65			32.7±1.5	37± 13	8.1		31.7± 1.5	0.6± 0.03
Mg							12,200± 610	2,950± 58	2120	12,061	165± 33	3.2± 1.7
Mn				<1370			347± 160	31± 0.6	92		79± 1	6.9± 0.1
Mo							7.7± 0.5	0.73± 0.3	0.63		0.47± 0.2	<0.01
Na							1370± 610	660± 93	859	371	611± 180	65± 14
Ni		1.4	<1.0	<48			44± 1	11± 0.6	9.9		4.8± 0.06	0.6±0.2
P							5460± 630	65± 20	171	218	234± 5.3	18.7± 1.6
Pb		2.8	<2.0	<14			30± 2	0.74± 0.4	3.9		1.2± 0.8	<0.01
V							155± 5	49± 2	13.7		3± 0.2	0.2± 0.01
Zn							75± 31	9.4± 2	19.7		17	0.8± 0.1
Sb			<1.0	<2.8								
Se			<1.0	<2.8								
Hg			<0.2	<0.7								

WEP-water extractable phosphorus; Al-WTR-alum-based water treatment residual; FGD-flue gas desulphurisation product.

Table 3. Table showing amendments in order of feasibility score, breakdown of costs[a], cost/m^3 slurry[b] , cost for 500 sow integrated unit, percentage reduction in DRP in overlying water at 30 h.

Amendment[c]	Feasibility score	Addition rate[d]	Cost[e]	Rate	Cost of amendment	Spreading	Agitation	Cost water[f]	Total	500 sow integrated unit[g]	DRP Removal	Spreading rate of metal	Within max allowable metal spreading rates[h]
			€/tonne	kg/m^3	€/m^3	€/m^3	€/m^3	€/m^3	€/m^3	€/farm	%	kg/ha	Yes/No
Control					0.00	1.56	0.00	0.00	1.56	16,182	0		
Alum	1	0.29:1 Al: P	150	4	0.58	1.60	0.00	0.00	2.18	22,672	55	5.51	No limit
		0.58:1 Al: P		8	1.16	1.56	0.00	0.00	2.72	28,309	64	11.02	
		0.88:1 Al: P		12	1.76	1.57	0.00	0.00	3.33	34,613	86	16.72	
Ferric Chloride	2	0.34:1 Fe: P	250	1	0.34	1.55	0.00	0.00	1.89	19,704	48	6.46	No limit
		0.62:1 Fe: P		2	0.62	1.55	0.00	0.00	2.18	22,655	52	11.78	
		0.89:1 Fe: P		4	0.90	1.56	0.00	0.00	2.45	25,500	71	16.91	
Poly-Al chloride	3	0.18:1 Al: P	280	2	0.53	1.55	0.00	0.00	2.09	21,689	43	3.42	No limit
		0.36:1 Al: P		4	1.07	1.56	0.00	0.00	2.62	27,258	42	6.84	
		0.72:1 Al: P		8	2.13	1.56	0.00	0.00	3.69	38,396	73	13.68	
Flyash	4	0.030 kg/kg	14	30	0.40	1.6	0.00	0.00	2.00	20,815	43		Yes
		0.060 kg/kg		60	0.81	1.64	0.00	0.00	2.45	25,488	48		
		0.120 kg/kg		120	1.62	1.74	0.00	0.00	3.36	34,910	58		
$Ca(OH)_2$ (Lime)	5	3.86:1 Ca: P	312	4	1.28	1.56	0.00	0.00	2.84	29,511	30	73.34	No limit
		5.79:1 Ca: P		6	1.92	1.56	0.00	0.00	3.48	36,206	53	110.01	
		7.71:1 Ca: P		8	2.56	1.56	0.00	0.00	4.12	42,866	54	146.49	
FGD	6	0.095 kg/kg	14	95	1.28	1.98	0.43	0.42	4.10	42,634	66		Yes
		0.132 kg/kg		132	1.79	2.49	0.54	1.09	5.91	61,467	67		
		0.170 kg/kg		170	2.3	2.98	0.64	1.73	7.64	79,474	74		

DRP-dissolved reactive P; FGD-flue gas desulphurisation product; a) Calculations based on an integrated pig unit with 500 sows, or equivalent stocking rate, indoors for 52 weeks; b) Slurry properties: Total P = 560 mg L^{-1} and 3.5% dry matter (DM); c) In the case of $Ca(OH)_2$, cost was estimated using commercial grade lime; d) Addition rates for Flyash and FGD quoted as kg of ammendment/kg of slurry; e) Cost includes delivery of material and addition of material to slurry in storage tank; f) Addition of some amendments resulted in DM >10%-water addition needed for spreading. In this case, agitation is required for process of adding water; g) Calculations based on 0.4 m^3 of slurry/sow/week; h) Max allowable metal application rates take from S.I. No. 267/2001-Waste Management (Use of Sewage sludge in Agriculture) (Amendment) Regulations, 2001 (www.irishstatutebook.ie).

Figure 1.

Figure 2 b).

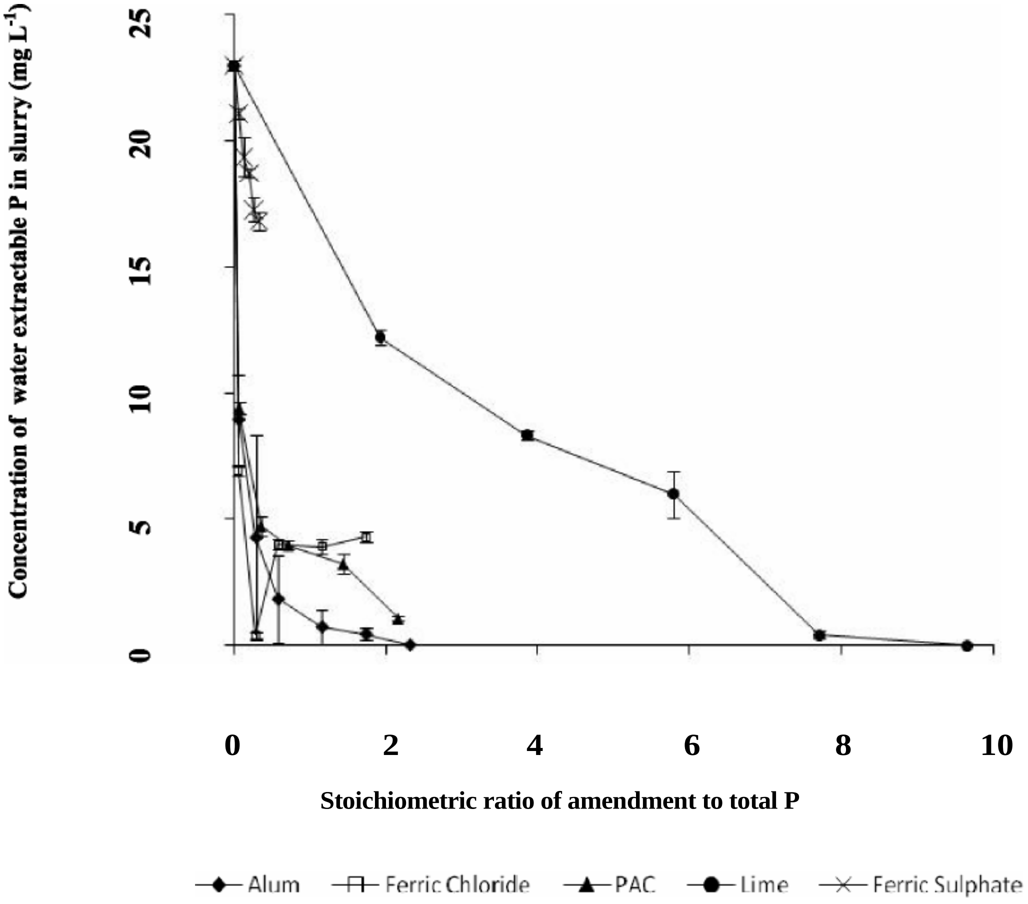

Concentration of water extractable P in slurry (mg L^{-1})
0
5
10
15
20
25
0
2
4
6
8
10
Stoichiometric ratio of amendment to total P
Alum
Ferric Chloride
PAC
Lime
Ferric Sulphate

Figure 2 b).

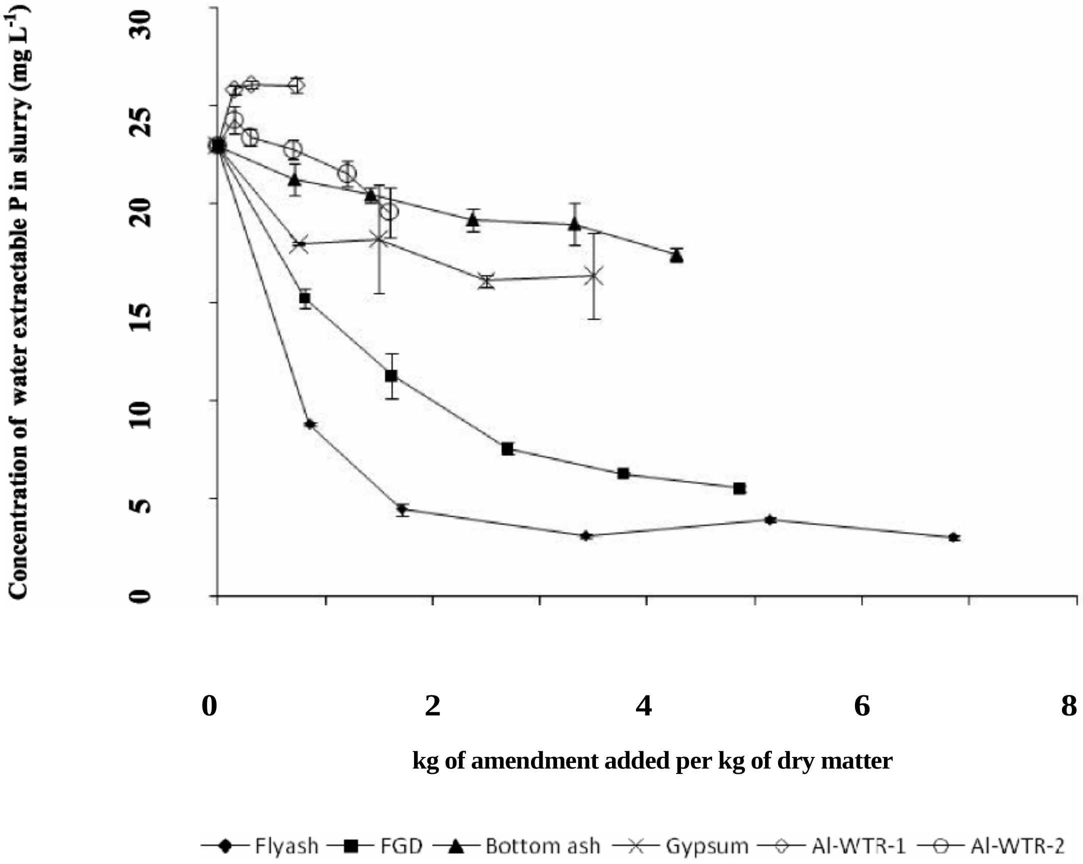

Concentration of water extractable P in slurry (mg L^{-1})
0
5
10
15
20
25
30
0
2
4
6
8
kg of amendment added per kg of dry matter
Flyash
FGD
Bottom ash
Gypsum
Al-WTR-1
Al-WTR-2

Figure 3.

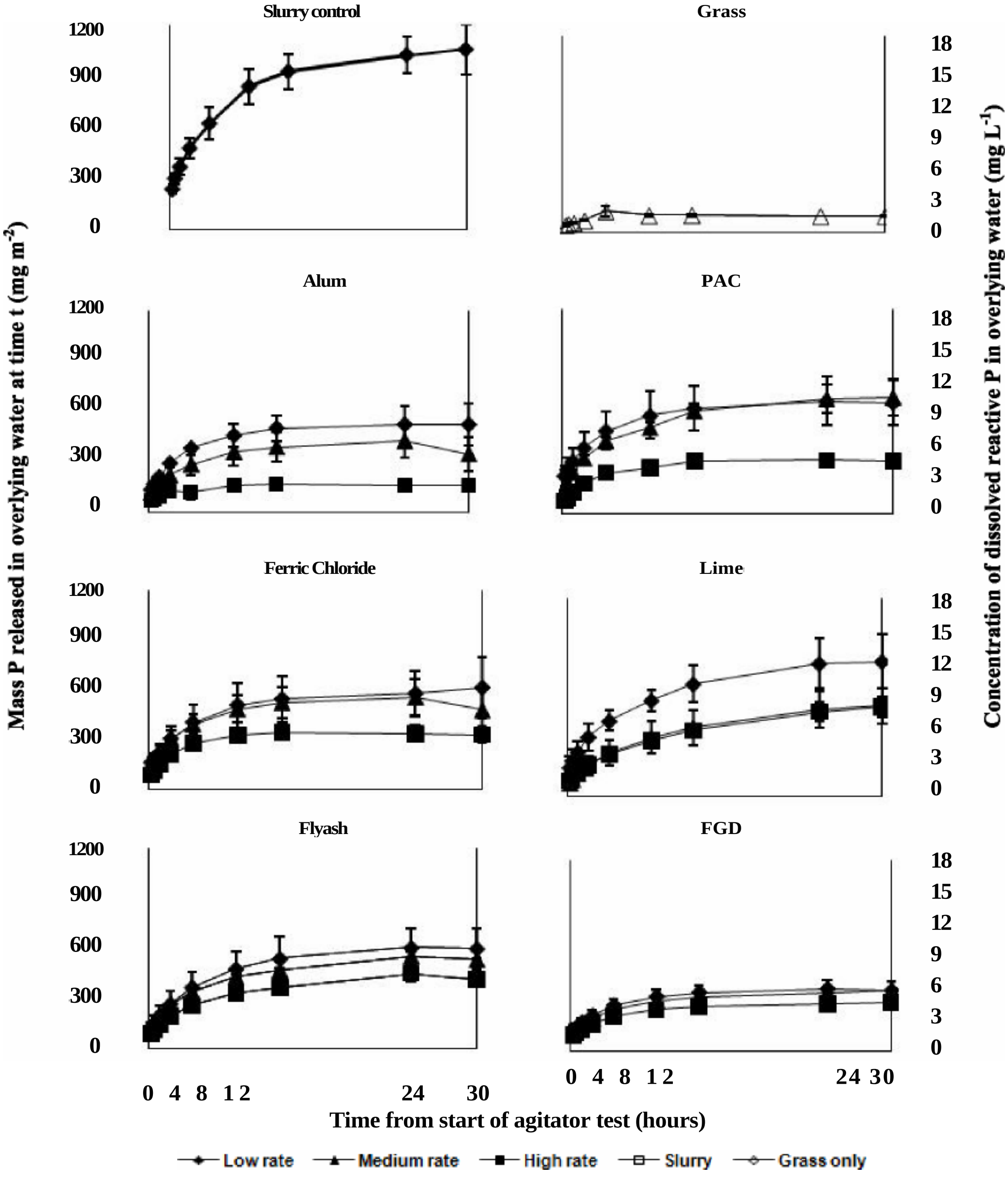
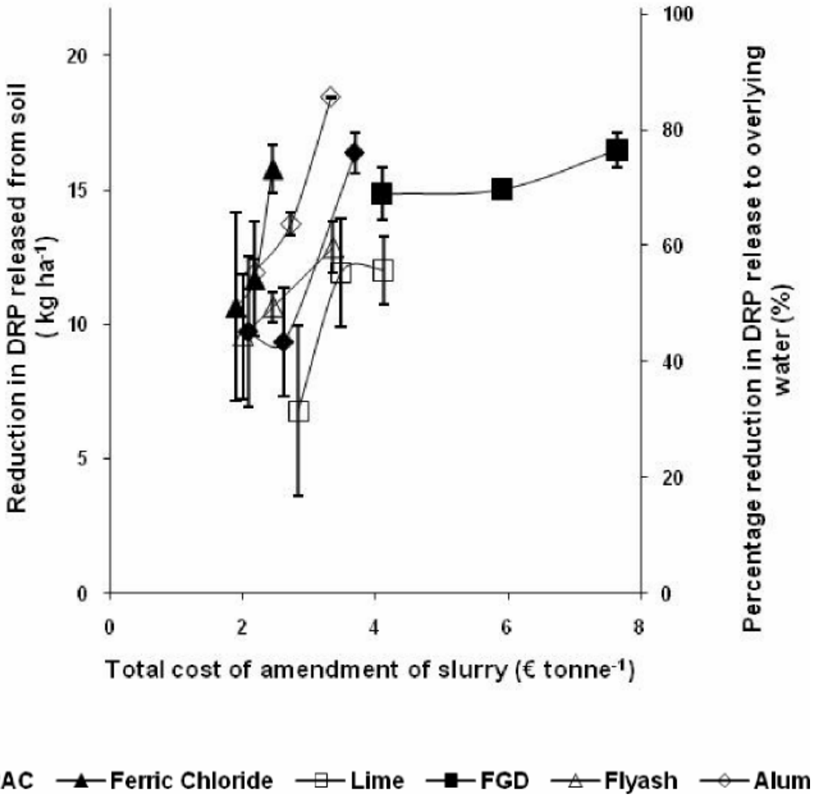

Slurry control
Grass
Alum
PAC
Ferric Chloride
Lime
Flyash
FGD
1200
900
600
300
0
18
15
12
9
6
3
0
Mass P released in overlying water at time t (mg m-2)
Concentration of dissolved reactive P in overlying water (mg L-1)
0 4 8 12 24 30
Time from start of agitator test (hours)
Low rate
Medium rate
High rate
Slurry
Grass only

Figure 4.


Reduction in DRP released from soil (kg ha^{-1})
Percentage reduction in DRP release to overlying water (%)
Total cost of amendment of slurry (€ tonne^{-1})
0
5
10
15
20
0
20
40
60
80
100
0
2
4
6
8
PAC
Ferric Chloride
Lime
FGD
Flyash
Alum