Agronomic Effectivity of Poultry Litter Ash

Comparison of results of pot- and incubation experiments with data from literature

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A limited literature research has been conducted to support the pot- and incubation experiments that were conducted to serve the technical file for including of hydrated poultry litter ash as PK fertiliser in Annex I of the European regulation on fertilisers 2003/2003. The review focusses on composition and efficacy of phosphorus, potassium and acid neutralising value of hydrated poultry litter ash. Results of review supports results of pot- and incubation experiments. Both phosphorus and potassium of hydrated poultry litter ash have an acceptable agricultural value as PK fertiliser. The acid neutralising value adds to the agronomic value. Main agronomic function in use of hydrated poultry litter ash is maintenance of soil fertility.

Keywords: Poultry litter ash, phosphorus, potassium, acid neutralising value, fertiliser, liming material, efficacy, apparent recovery, fertiliser replacement value

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Contents

Summary

In 2014 and 2015 pot experiments with green bean (*Phaseolus vulgaris L.*) and rye grass (*Lolium perenne L.*) were conducted by Alterra Wageningen UR to assess the efficacy of hydrated poultry litter ash of BMC Moerdijk as a phosphorus and potassium fertilizer. An incubation experiment with soil was conducted to assess the efficacy of hydrated poultry litter ash as liming material (Ehlert & Nelemans, 2015a, 2015b, 2015c, 2015d, 2015e). The reports on these pot experiments and incubation experiments served as essential requirements for the Technical File of BMC for including hydrated poultry litter ash in Annex 1 of the Regulation on fertilisers 2003/2003. This report places the results of the experiments in a broader perspective by comparing the results of the experiments with results cited in peer-reviewed scientific literature. The same questions as formulated for the pot- and incubation experiments are answered with data published in literature sources. A limited literature research has been conducted focussed on composition and agronomic efficacy of phosphorus and potassium of poultry litter ashes.

The composition of poultry litter ashes appears variable. Variation is caused by differences in animal and farming system. Broilers, egg laying hens, turkeys and ducks have different nutritional requirements which cause a different composition of manure. Incineration of these different compositions of manures leads to different compositions of resulting ashes (Tables 2, 3, 4 and 5 and Annexes 1, 2 and 3). A major source of variation in ashes is due to the ratio between broiler litter manure and egg laying hen manure. The 2 to 3 times higher calcium requirement of egg laying hens results in manures more enriched with calcium. Nutrients (P, K, Ca, Mg, Na, S and micronutrients) of hydrated poultry litter ash of BMC Moerdijk fit well in the ranges found for literature data. Literature points to the presence of (amorphous) apatite next to silicates and calcite in poultry litter ashes. Apatite is a component of phosphate rock.

The efficacy of phosphorus was derived from responses of crops on P fertilisation and from changes in soil phosphorus due to residual fertiliser phosphorus remaining in soil after harvest of crops. Apparent recovery (ARE) and phosphorus fertiliser replacement values (PFRV) were calculated.
Overall ARE (excluding turkey manure ash) for phosphorus averaged to 4.5% with a range of 0.2-15.8% and PFRV averaged to 70% with a range of 26.6-140.8% (Table 6). Data reported for green bean (Ehlert & Nelemans, 2015e) and rye grass (Ehlert & Nelemans, 2015a) fit well within the ranges based on literature data.

Data on soil phosphorus, i.e. plant available phosphorus in soil (soil test phosphorus (STP)), were highly variable due to the many different analytical soil test methods used for fertiliser recommendations in Europa and USA and are also due to differences in soil type. Despite this variation, data from literature clearly show that residual phosphorus from poultry litter ashes increases STP values. Residual phosphorus from poultry litter ashes is therefore plant available and indicates that poultry litter ashes can contribute to a maintenance and/or an increase of soil fertility status.

The efficacy of potassium of poultry litter ashes derived from literature data is similar to the efficacy of mineral potassium fertiliser (muriate of potassium) i.e. 100% found in the pot experiments with hydrated poultry litter ash of BMC Moerdijk.

The data on calcium carbonate equivalence reported in literature are similar to the acid neutralising value of hydrated poultry litter ash of BMC Moerdijk, when taking into account variation introduced by absorption of CO_2 on $Ca(OH)_2$ formed by addition of water .

Literature on effects of grinding poultry litter ash on the efficacy of phosphorus, potassium and acid neutralising value has not been found.

Both phosphorus and potassium of hydrated poultry litter ash have an acceptable agricultural value as PK fertiliser. The acid neutralising value adds to the agronomic value. Main agronomic function of hydrated poultry litter ash is maintenance of soil fertility.

1 Introduction

BMC Moerdijk is producing green energy by incineration of approximately 450,000 tons of poultry manure per year. This is about a third of the total quantity of poultry litter produced each year in the Netherlands (http://www.bmcmoerdijk.nl/en/home.htm).

When processing poultry litter into green energy, an ash is produced (poultry litter ash). The volume of poultry litter ash is approximately 60,000 tons per year. The poultry litter ash is processed by BMC to a fertiliser by adding water. The main nutrients of hydrated poultry litter ash are phosphorus (P) and potassium (K). Next, hydrated poultry litter ash has a neutralizing value (NV) due to the presence of carbonates and hydrated burnt lime. In addition, other minerals are present in high percentage (Ca) or in lower percentages (Mg, S). Table 1 gives an average of the composition.

Hydrated poultry litter ash of BMC is currently used in France and Belgium as a compound PK fertiliser.

Table 1. *Average composition of minerals in processed hydrated poultry litter ash (data period 2013-2014).*

Parameter	Unit	Average
Dry matter	% product	88.7
Primary nutrients		
P_2O_5	% product	10.3
K_2O	% product	12.4
Secondary nutrients		
CaO	% product	27.5
MgO	% product	5.1
Na_2O	% product	2.0
SO_3	% product	5.2
Micro-nutrients		
B	mg kg^{-1} dry matter	159.0
Co	mg kg^{-1} dry matter	5.5
Cu	mg kg^{-1} dry matter	347.2
Fe	mg kg^{-1} dry matter	5,403
Mn	mg kg^{-1} dry matter	2,298
Mo	mg kg^{-1} dry matter	15.8
Zn	mg kg^{-1} dry matter	1,748

Data on dry matter, P_2O_5, K_2O and CaO are bases on 234 analyses of BEAGx[1]; other data are based on 58 analyses of LABZVL[2].

In 2014 and 2015 pot experiments with green bean (*Phaseolus vulgaris L.*) and rye grass (*Lolium perenne L.*) were conducted to assess the efficacy of phosphorus and potassium of hydrated poultry litter ash of BMC Moerdijk. An incubation experiment with soil was conducted to assess the efficacy of hydrated poultry litter ash as liming material (Ehlert & Nelemans, 2015a, 2015b, 2015c, 2015d, 2015e). The reports on these pot experiments and incubation experiments served as essential requirements for the Technical File of BMC for including hydrated poultry litter ash in Annex 1 of the Regulation on fertilisers 2003/2003[3].

This review report places the results of the experiments in a broader perspective by comparing the results of the experiments with results cited in scientific literature. The same questions are formulated but answers are obtained from published literature sources; summarizing, these questions are the following.

[1] Bureau d'études environnement et analyses of the University of Liège, Belgium
[2] EUROFINS Lab Zeeuws-Vlaanderen, the Netherlands.
[3] Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers

1. What is the efficacy of hydrated poultry litter ash compared to the reference fertiliser potassium sulphate in terms of yield increase (fresh, dry matter) and potassium uptake?
2. Has the hydrated poultry litter ash an acceptable agronomic value as a potassium fertiliser?
3. What is the efficacy of hydrated poultry litter ash compared to the reference fertilisers dicalcium phosphate and triple superphosphate in terms of yield increase (fresh, dry matter) and phosphorus uptake?
4. Has the hydrated poultry litter ash an acceptable agricultural value as a phosphorus fertiliser?
5. What is the efficacy of hydrated poultry litter ash compared to the reference lime materials calcium carbonate of chalk and calcium hydroxide of hydrated burnt lime in terms of lowering soil acidity (or increasing soil pH)?
6. Has the hydrated poultry litter ash an acceptable agricultural value as a liming product for maintenance of soil pH?
7. Has grinding an effect on these agronomic values.

Not only BMC Moerdijk produces a PK fertiliser from ashes from incineration of poultry manure (60 kton/annum). The first fertilisers of this type were produced by Fibrowatt Ltd in the UK (Thetford (38.5 MWe), Eye (12.7 MWe), Glanford (13.5 MWe - now switched to burning meat and bonemeal) and Westfield (9.8 MWe). Total volume of ashes is estimated at 1500 kton[4]. In the USA Fibrowatt LLC build the plant FibroMinn at Benson (55 MWe). The total volume of ashes is estimated at 80-100 kton/annum[5]. Small scaled incineration plants are located in Ireland.

Data from literature on the composition and solubility of plant nutrients of ashes of poultry manures have been collected. The literature study is limited to the composition and agronomic efficacy of these ashes. The study does not address scientific publications on the combustion process. Chapter 2 reports the results on composition of poultry manure ashes. Next the agronomic effectivity of phosphorus, potassium and acid neutralising value is reported in chapter 3. Results are discussed and conclusion are drawn in chapter 4.

[4] https://www.scribd.com/document/266424932/Kellog-FibroVA-04102012-VMI-Presentation
[5] http://biomassmagazine.com/articles/1196/generating-poultry-power

2 Composition

2.1 Primary nutrients

Literature data on the composition of ashes of incinerated broiler litter, poultry litter, poultry manure, egg layer manure, chicken manure turkey manure, duck manure are published by Chastain et al (2012), Codling (2002), Codling (2006), Codling (2013), Faridullah et al (2008, 2009a, 2009c, 2013), Hasimoto et al (2009), Huang et al (2011), Komiyama et al (2013), Yusiharni et al (2007), Pagliari et al (2010ª), Richardson (1994), Kuligowski et al (2010), Lynch et al (2013), Rubæk et al (2006), Bachmann & Eichler-Löbermann (2010), McClurg et al (1971), Siegel et al (1977), Mukhtar et al (2002), Blake & Hess (2014) and Eichler-Löbermann et al (2008). No publication listed a complete composition on primary, secondary and micro nutrients. Combining these data on the composition of ashes of incineration of different types of poultry manure leads to the summary given in Table 2. Annex 1 gives an overview of data found in literature.

Most often, data are given of analysis of only one sample of poultry litter ash, thus not providing information on variation in composition. Few data are specifically addressing the origin of poultry manure: broiler, laying hen, turkey or duck (Annex 1). The summary given in Table 2 provides insight in the variation found next to the total counts in case reported data have been summarised as a group. As moisture content or dry matter content are not systematically reported, standardisation to nutrient contents in dry matter is not possible. Phosphorus (P), potassium (K) and the basicity as pH are often given. K content is less often reported (19 counts) than P content (31 counts). Solubility of P and K in various extractants is less often reported. There is insufficient material to make a comparison of the solubility's of P and K of ashes of incinerated poultry manure. This hinders the evaluation of data from literature on agronomic effectivity of extractants in solubilisation of these plant nutrients.

Table 2. *Composition of ashes of incineration of poultry manures and poultry litters, dry matter, organic matter, organic carbon and primary nutrients.*

Parameter	Unit	Average	Median	Minimum	Maximum	Counts
pH	[-]	12.1	11.9	11.3	13.3	21
EC	mS/cm	30.5	29.5	1.6	84.9	11
Dry matter	g/kg	978.7	996.0	903.1	1000	9
Organic matter	g OM/kg	70.9	70.9	65.3	76.4	2
Organic carbon	g C/kg	39.1	6.2	0.3	231.0	10
N total	g N/kg	4.1	1.0	0	18.5	7
P total (*)	g P/kg	75.4	75.9	4.8	139.2	31
P water soluble	g P/kg	1.1	0.2	0	6.0	11
P citrate soluble	g P/kg	72.3	66.4	20.0	143.9	8
P neutral ammonium acetate	g P/kg	39.6	41.6	23.3	53.8	3
P ammonium acetate	g P/kg	32.8	24.0	18.5	56.0	3
K total (**)	g K/kg	72.6	47.7	3.9	223.6	19
K water soluble	g K/kg	81.0	67.5	48.9	117.0	3(***)
K citrate soluble	g K/kg	37	.	.	.	1
K neutral ammonium acetate	g K/kg	13.2	.	.	.	1
K ammonium acetate	g K/kg	7.3	.	2.3	12.3	2
K exchangeable	g K/kg	61.5	71.1	6.3	82.3	5

* : P * 2.29 = P_2O_5; ** : K * 1.205 = K_2O; *** : Pagliari et al (2010a & b) reported a high K water solubility leading which was twice higher than reported by Rubæk et al (2006) and Faridullah et al (2013). Pagliari et al (2010 a&b) did not report K total.

Data reported by Faridullah et al (2008), Yusiharni et al (2007), Pagliari et al (2010a), Kuligowski et al (2010) and Rubæk et al (2006) show that on average 63% of P total is citrate soluble (range 40-99%). Data of Faridullah et al (2008) and Yusiharni et al (2007) show that 40% (range 31-49%) of P-total is soluble in neutral ammonium citrate.

The hydrated poultry litter ash of BMC has 10.3% P_2O_5 (= 44.9 g P/kg) and 12.4% K_2O (= 102.8 g K/kg). The K total content is similar to the average value found in the literature. The P total content, although lower, fits in the range found. Both nutrients are very dependent on the feed (see textbox on dietary requirement) and feed composition for the poultry that depends on the growth stage and production purpose (meat, egg). A cause for a lower P total value of the hydrated poultry litter ash of BMC Moerdijk than the average of values found in literature can be a different – lower - dietary P content of feed used in the Netherlands compared to poultry farming systems in other countries (USA, Japan) which might lead to lower P excretions by the animals[6].

	Current dietary P-content (average, g/kg, CBS 2009	P-requirement (g absorbable P/kg, CVB, 2010)	Ca-requirement (g Ca/kg, CVB, 2010)
Broilers			
0 – 10 d	5.3	4.0	8.8-9.2
10 – 30 d		3.1	6.8-7.1
30 – 40 d		2.8	6.2-6.4
40 – 50 d		2.7	5.9-6.2
Laying hens			
20 – 28 wk	4.9	3.2	
28 – 35 wk		3.0	
35 – 55 wk		3.0	
> 55 wk		2.8	

Source: Krimpen, M.M. van, R.M.A. Goselink, J. Heeres & A.W. Jongbloed, 2010. Fosforbehoefte van melkvee, vleesvee, varkens en pluimvee; een literatuurstudie. Wageningen UR Livestock Research, report 574. http://edepot.wur.nl/201513 .

Higher nutrient contents were found for ashes of fresh poultry litter (Mukhtar et al, 2002) compared to ashes from egg laying hens (Huang et al, 2011; Komiyama et al, 2013).

Poultry manure (faeces) is often mixed with litter (wood chips, saw dust and other bedding materials). The composition of poultry manure differs from litter (bedding materials). From literature data, no general observation can be derived of the effect of the quantity or ratio of manure versus litter on the composition of the poultry manure ash. This ratio is most likely a major factor in determining the composition of the ashes from incineration of poultry manure.

Next, data on dry matter content or moisture content where given in only nine cases. So in general no factual information is available on the effect of moisture content (?) on the composition of ashes treated with water to obtain an hydrated ash. Literature given in annex 1 however does not clearly provide information on the addition of water. Therefore, it is assumed that data given represent none-hydrated ashes. Hydrating poultry litter ash lowers the nutrient content two ways: 1. the P total content is lowered proportional to the quantity of water added. 2. Adding water to ashes which contain CaO leads to the formation of calcium hydroxide. Calcium hydroxide reacts with carbon dioxide to calcium carbonate. During this chemical process reactive water is released but remains in the ashes. So both the addition of water and the absorption of carbon dioxide dilutes the original nutrient content of the ashes[7].

[6] In the Netherlands phytate in feeding stuff for poultry is an important issue in order to reduce phosphorus surpluses. As phytase is available to make phytate of plant origin available to the animal additional mineral P (most often di calcium phosphate) is lowered to feeding stuff. In other countries phytate-P is considered not be not available to the animal and not included in the dietary P requirements of the animal. P excretion might under these circumstances be higher.

[7] Per mol CaO, the reaction to $Ca(OH)_2$ by reaction with water leads to an weight increase of a factor 74/56 = 1.32 (excluding not reacted water). Absorption of CO_2 leads to another weight increase of a factor 100/74 = 1.35 (formation of water not accounted for). So in total there is an increase of weight of 1.32*1.35 = 1.78 proportional to the quantity of CaO present in none hydrated poultry litter ash. Hydrated poultry litter ash contains 33.9% acid neutralising value expressed as CaO on product basis or 33.9/(0.01*95.9)=35.5% NV in the dry matter (Ehlert & Nelemans, 2014d). If assumed that formation of $CaCO_3$ is complete, it is estimated that none hydrated poultry litter ash contains 20% CaO.

Phosphorus of hydrated poultry litter ash of BMC has different solubility properties when using designated analytical methods for fertilisers compared to other mineral phosphate fertilisers. Approximately 60% of the mineral acid soluble phosphorus is soluble in 2% citric acid. In neutral ammonium citrate 30-50% is soluble and in alkaline ammonium citrate (Petermann) around 30% is soluble. The solubility of phosphorus in water is negligible. These values are very similar to the data reported in literature.

Faridullah et al (2009c) reported on the solubility of P in citric acid a function of the incineration temperature of chicken litter and duck litter (range, 200, 400, 600, 800 and 900°C). A incineration temperature of 600°C yielded the highest quantity of P extracted. The higher the temperature the lower the solubility of P in water became (Faridullah et al, 2008). Incineration temperature determines P fractions which are considered plant available.

2.2 Secondary nutrients

Data on total nutrient contents of Ca, Mg are less frequently reported than data for primary nutrients. Data of Na and S are even less available (Table 3, Annex 2). Few publications provide information on the solubility of secondary nutrients in water, citrate, neutral ammonium citrate, ammonium citrate or ammonium acetate (extractable or exchangeable cations) and acid neutralising value expressed as calcium carbonate equivalence (Faridullah et al (2008,2009a, 2009b, 2013), Yusiharni et al, 2007, Chastain et al (2012), Lynch et al (2013)).

Table 3. *Composition of ashes of incineration of poultry manures and poultry litters, secondary nutrients.*

Parameter	Unit	Average	Median	Minimum	Maximum	Counts
Ca total	g Ca/kg	184.6	167.0	57.5	348.0	17
Ca water soluble	g Ca/kg	0.5	*	*	*	1
Ca citrate soluble	g Ca/kg	165.8	*	*	*	1
Ca neutral ammonium citrate	g Ca/kg	72.1	*	*	*	1
Ca ammonium acetate	g Ca/kg	37.5	37.5	4.6	70.3	2
Ca extractable	g Ca/kg	1.4	1.5	0.1	2.0	5
Mg total	g Mg/kg	28.1	26.5	12.5	50.0	17
Mg water soluble	g Mg/kg	0.4	*	*	*	1
Mg citrate soluble	g Mg/kg	16.7	*	*	*	1
Mg neutral ammonium citrate	g Mg/kg	14.0	*	*	*	1
Mg ammonium acetate	g Mg/kg	5.9	5.9	0.2	11.6	2
Mg extractable	g Mg/kg	1.8	1.0	0.5	5.4	5
Na total	g Na/kg	19.0	18.6	0.2	48.4	11
Na citrate soluble	g Na/kg	16.7	*	*	*	1
Na neutral ammonium citrate	g Na/kg	7.3	*	*	*	1
Na ammonium acetate	g Na/kg	6.3	*	*	*	1
S total	g S/kg	31.1	27.5	11.5	70.0	6

Faridullah et al (2009c) reported an increase in ammonium acetate extractable (~ exchangeable) Ca and Mg if incineration temperature increased from 200 to 600°C; at temperatures of 800 and 900°C the amounts of extractable Ca and Mg decreased. This coincide with a decrease in solubility of P (citric acid) at increasing temperatures.

Hydrated poultry litter ash of BMC Moerdijk consists on average of 27.5% CaO (196 g Ca/kg), 5.5% MgO (30 g Mg/kg), 2.0% Na_2O (15 g Na/kg) and 5,2% SO_3 (21 g S/kg). The contents of Mg, Na and S are within the range reported in literature. Hydrated poultry litter ash has a higher Ca total content than broiler litter ash. Data of annex 2 give some information on the contents of Ca, Mg, Na and the origin of the ashes (Table 4).

Table 4. *Total content of calcium, magnesium, sodium and sulphur of ashes of different poultry farm systems.*

Poultry farm system	Ca total, g Ca/kg	Mg total, g Mg/kg	Na total, g Na/kg	S total, g S/kg
Broiler litter ash	137	34	23	25
Duck litter ash	126	25	*[1]	*
Egg laying hen litter ash	258	28	13	70
Poultry litter ash (not specified)	193	23	21	*

[1] no value

Egg laying hens require in their diet two to three times more calcium than poultry of other farming systems (McDonald et al, 2011). Due to their feed requirements, egg laying hens produce manures which contain more calcium than poultry of other farming systems. This is reflected in the Ca total content of the incineration ashes (Codling, 2013; Komiyama et al, 2013). The Ca total of ashes of egg laying hen litter is about twice as that of ashes of broilers. Poultry litter ash (mixtures of ashes of incineration of unknown ratios of broiler and egg laying hen manures) has a value in between broiler litter ash and egg laying hen litter ash. The higher Ca total content of hydrated poultry litter ash of BMC Moerdijk is partly caused by the use of calcium hydroxide (Sorbacal®) which is used in de absorption reactor to remove HCl and SO_2 from flue gasses. Next, spillage of grit (soluble and insoluble) during feeding may contribute to the higher Ca total content of the hydrated poultry litter ash.

2.3 Micronutrients

Table 5 summarizes data on micronutrients found in literature. Annex 3 gives an overview of the data with references.

Few data were found for B, Co, Fe and Mo; Cu, Mn and Zn have more data. From the micronutrients Fe is most abundantly present (5.9 g Fe/kg ash),followed by Mn and Zn and Cu and B.

Table 5. *Composition of ashes of incineration of poultry manures and poultry litters, micro nutrients.*

Parameter	Unit	Average	Median	Minimum	Maximum	Counts
Boron (B)	mg B/kg	557	270	150	1250	3
Cobalt (Co)	mg Co/kg	9.4	9.4	8.8	10.0	2
Copper (Cu)	mg Cu/kg	450	335	43	1700	17
Iron (Fe)	mg Fe/kg	5690	5900	3010	8440	7
Manganese (Mn)	mg Mn/kg	1468	1393	1.3	4200	16
Molybdenum (Mo)	mg Mo/kg	55	55	30	79	2
Zinc (Zn)	mg Zn/kg	1770	1080	600	9500	17

The Fe content given in the publications is higher than what can be expected from feed. Presumably Fe has been added amongst others to control P leaching from manures when applied to soil. High contents of Fe coincide with high contents of Al (Annex 3). Al compounds and Fe compounds are also used to control ammonia volatilisation (Nahm, 2005, Do et al, 2005, Choi & Moore, 2008). However, this use of Fe and Al as acidifiers are not common in the Netherlands. Use of these compounds to control odour (volatile acids), H_2S in biogas (Fe) and to increase separation efficiency (flocculants) is common in the Netherlands. Also air-washers and biogas cleaning steps make use of these compounds. Control measures to avoid emissions during manure treatment are therefore most likely causes for enrichment of manures with Al and Fe compounds and thus of the resulting product after incineration.

Hydrated poultry litter ash from BMC contains on average 110 mg B, 5,6 mg Co, 333 mg Cu, 4407 mg Fe, 1950 mg Mn, 12.1 mg Mo and 1621 mg Zn per kg ash. In terms of magnitude these average values agree with values (averages and median) found in literature.

2.4 Sequential fractionation and XRD analyses

Sequential fractionation

Bioavailability of nutrients is quite often predicted by using fractionation procedures. These procedures consists of a series of sequential extractions with chemicals starting with a mild extraction (e.g. water) followed by other extractants with increased ionic strength (e.g. water, bicarbonate, sodium hydroxide and hydrochloric acid). Weaker extractants are considered to predict the – direct – available (labile) pools of phosphorus in soil while the more rigid (stronger) extractants provide estimates for the more stable phosphorus pools which replenishes the labile pools. Fractionation procedures are commonly named after it's developer and bear great importance in soil science as they provide insight in plant available nutrients on short and on long term thus leading to understanding of soil fertility. Fractionation procedures are less common in fertiliser research. Traditionally, next to total content, one other – organic acid – extractant is used. For instance for basic slag (P) citric acid is used, for phosphate alkaline ammonium citrate according to Petermann is used and for rock phosphate formic acid (EU regulation on fertilisers 2003/2003). For potassium normally only the solubility in (boiling !) water is used to assess fertiliser quality and thus it's bioavailability.

Colding (2006) used extraction procedure of Hedley et al (1982) commonly used in soil science. Colding (2006) extracted poultry litter (PL) and poultry litter ash (PLA) sequentially with water, 0.5 M $NaHCO_3$, 0.1 M NaOH and 1.0 M HCl. The largest portion of P in the PL was soluble in H_2O (55% of total inorganic P) while in PLA this was low (2.0%). The effectiveness in removing inorganic P of PL ranked, from highest to lowest, as H_2O > HCl > sodium bicarbonate > sodium hydroxide, whereas from PLA the ranking is HCl > sodium bicarbonate > sodium hydroxide = H_2O. The largest portion of inorganic P of PLA was soluble in HCl (82%) while in PL this was 34%. Incineration thus lowers phosphorus pools which are considered direct plant available.

Yusihari et al (2007) found with prolonged extraction times (120 hours) that total P dissolves increased in the sequence citric acid > neutral ammonium citrate > alkaline ammonium citrate. Apatites present in ashes dissolved in citric acid after prolonged extraction times but not in neutral ammonium citrate or alkaline ammonium citrate.

Faridullah et al (2008) also applied a Hedley procedure. Faridullah et al (2008) addressed these fractions as readily plant-available P, labile inorganic P, sesquioxide[8]-associated P and Ca-associated P by sequentially extracting with deionized water, 0.5 $NaHCO_3$, 0.1 M NaOH and 1 M HCl respectively. This extraction procedure was applied on ashes of chicken and duck litter incinerated at different temperatures (200, 400, 600, 800 and 900°C) Faridullah et al (2008). Except for water soluble P, all other P fractions increased with increasing incineration temperature. For both manures P release from its ashes decreased in the order: Ca-associated P > labile inorganic P > sesquioxide-associated P > readily plant available P. For ashes from chicken litter the sum of inorganic P was found at its peak at 600°C and was 4.2 fold higher than from original (fresh) chicken litter. This coincides with the solubility in citric acid. Faridullah et al (2008) found an increased weight loss (LOI) when increasing the temperature. Although the authors do not conclude this: through incineration inorganic P is formed that apparently is not soluble in 1 M HCl.

XRD analyses

Speciation of phosphorus forms in ashes by XRD analyses (Röntgen diffraction procedures) provides insight on readily available and on long term available quantities. Speciation techniques are indicative, as absolute references for the chemical species are not available. Generally phosphorus species presumed to be present, result from a modelling of results of XRD[9] spectra.

Hashimoto and Sato (2007) examined the XRD spectra of ash of incinerated poultry waste (manure). Ash of incinerated poultry waste was washed with distilled water and dried at 50°C. For hydroxy apatite they found characteristic peaks in their XRD spectra while for the ash, broad or slightly shifted

[8] Aluminium and iron soil compound
[9] XRD spectra: X-ray diffraction analyses

peaks were found which were assumed to be indicators for poorly-crystalline hydroxy apatite (Figure 1).

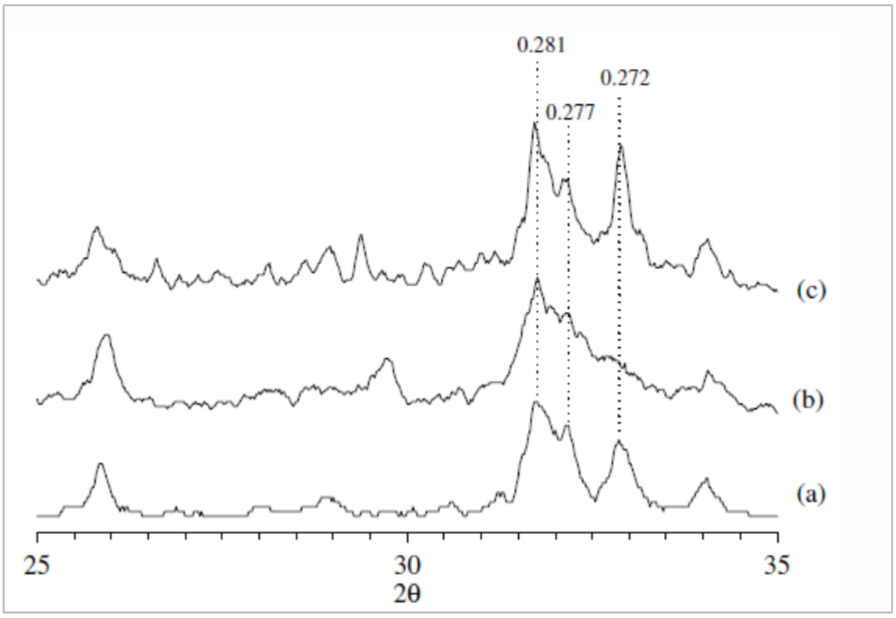

Figure 1. *XRD spectra for a. hydroxy apatite, b. gypsum waste of a ceramic industry and c. ash of poultry manure (Hashimoto & Sato, 2007).*

Komiyama et al (2013) examined ashes from incineration of cattle manure, pig manure, layer manure (i.e. egg laying hen manure) and broiler litter with XRD analyses (Figure 2). The phosphate compounds of cattle and sine manure ashes were determined as $Ca_9Fe(PO_4)_7$ or $Ca_9MgK(PO_4)_7$. Hydroxy apatite ($Ca_5(PO_4)_3(OH)$) was detected in layer manure and broiler litter ashes. By acid treatment of ash, P and K availability of the fertiliser made from layer manure ash was equivalent to that of conventional chemical fertiliser (Komiyama et al, 2013).

Yusiharni et al (2007) found that partially burnt chicken litter ash and fully burnt litter ash mostly consists of mixtures of mineral apatite with calcite and quartz.

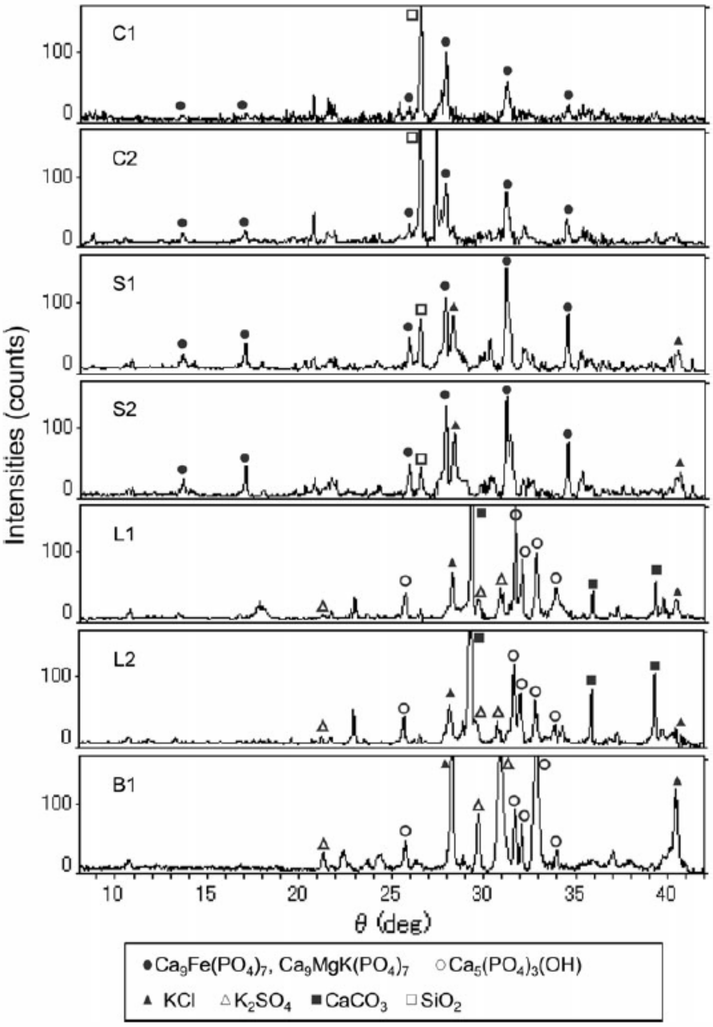

Figure 2. *X ray diffraction patterns of ashes of cattle manure (C1 and C2), swine manure (S1 and S2), layer manure (L1 and L2) and broiler manure (B1) according Komiyama et al (2013).*

3 Agronomic efficacy

In this chapter the agronomic efficacy expressed as apparent recovery (ARE) and fertiliser replacement value (PFRV) of phosphorus and potassium from incineration ashes of poultry litter manure derived from peer reviewed publications are reported. The derivation followed similar calculation methods as given by Ehlert and Nelemans (2015a, 2015b, 2015c, 2015e)[10].

Crop, reference fertiliser, soil and experimental conditions differ per publication. This chapter summarised data from literature. Details on crop, soil, treatments and references fertilisers are given in the annexes 4, 5 and 6 accompanying summarising Tables of paragraph 3.1 and 3.2.

By focussing on apparent recovery and fertiliser replacement value, literature is selected on published data of yield, nutrient content and fertiliser application rate. In peer reviewed articles these data are more frequently reported than in none peer review reports ('grey literature'). Data on the agronomic performance of phosphorus were more readily available than on potassium. Data on the agronomic performance of ashes as liming materials related to acid neutralising value are scarce.

Agronomic efficacy is commonly derived from the response of a crop on fertilisation, at given plant available nutrient status of the soil. For phosphorus, data of residual fertilisation effects of poultry litter ashes are published. These data have also been collected and ARE and PFRV were calculated according footnote 10 by modified equations using soil phosphorus test values (STP) by replacing uptake into change in STP (treatment – control treatment).

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[10] Apparent recovery efficiency of applied phosphorus or potassium with reference fertiliser or hydrated poultry litter ash was calculated according Dobermann (2007):

$$ARE = 100*(U_p - U_0)/ F_p \qquad (1)$$

With:

ARE = Apparent recovery efficiency of phosphorus or potassium as percentage (%)

U_p = Uptake of phosphorus or potassium of fertiliser treatment (unit depending of publication)

U_0 = Uptake of phosphorus of control treatment, no P fertilization (unit depending of publication)

F_p = Application rate fertiliser treatment (unit depending of publication).

ARE depends on the congruence between plant demand for P and the release of P from fertiliser.

The phosphorus or potassium fertiliser replacement value (PFRV) of hydrated poultry litter ash can be calculated if differences in ARE between the hydrated poultry litter ash and reference fertilisers are statistical significant different, according:

$$PFRV = 100*ARE_{Poulty\ litter\ ash}/ARE_{Reference\ fertiliser} \qquad (2)$$

With:

$ARE_{Hydrated\ poultry\ litter\ ash}$ = Apparent recovery efficiency of phosphorus of hydrated poultry litter ash (%)

$ARE_{Reference\ fertiliser}$ = Apparent recovery efficiency of phosphorus of reference fertiliser, reference fertiliser shall be given.

Reference fertilisers are given in annexes 4, 5 and 6.

Equation 1 and 2 were modified when using soil phosphorus test values (STP) by replacing uptake into change in STP (treatment – control treatment). As ARE values are low (< 5%) P application rates were not corrected for P offtake by the crop.

3.1 Phosphorus

3.1.1 Crop response

Bachman & Eichler-Löbermann (2010), Codling et al (2002), Codling (2013), Eichler-Loebermann et al (2008), Faridullah et al (2009), Faridullah et al (2013), Lopez et al (2009), Pagliari et al (2010b), Richardson (1994), Siegel et al (1977) and Yusiharni et al (2007) reported data from which ARE and PFRV can be derived. Table 6 summarises calculated ARE and PFRV per ash type for all given publications. Annex 4 specifies crop, soil, reference fertiliser and treatment.

Table 6. *Apparent recovery (ARE) and fertiliser replacement values (PFRV) for phosphorus for different ashes from incineration of poultry manure based on crop data.*

Ash	ARE, %				PFRV, %			
	Average	Minimum	Maximum	Counts	Average	Minimum	Maximum	Counts
Broiler litter ash	0.9	0.5	1.3	6	33.0	26.6	47.2	6
Duck litter ash	8.1	5.1	13.1	6	*	*	*	*
Egg laying hen manure ash	1.8	1.2	2.1	6	67.1	60.1	78.1	6
Poultry litter ash (not specified)	5.3	0.2	15.8	40	81.8	33.0	140.4	40
Turkey manure ash	47.8	41.6	55.5	5	88.7	75.1	99.6	5
All ashes of incineration of poultry litter	7.6	0.2	55.5	71	70.2	26.6	140.8	71
All ashes of incineration of poultry litter without Turkey manure ash	4.5	0.2	15.8	66	68.0	26.6	140.8	66

* Farming system not specified

Statistical parameters of Table 6 are based on a variety of crops[11] and soils[12]. Crops and stages of their harvest are mostly provided, but information on soils is not always given. Sometimes data are reported for a combination of soils (e.g. Codling et al, 2002). In general, increasing the application rate of phosphorus lowers PFRV.

ARE and PFRV depend strongly on the experimental conditions. In general values for ARE are low (< 10%) which is quite common for P from fertilisers. For ashes of turkey manure Pagliari et al (2010b) reported data from a pot experiment that gave high values for ARE. The conditions of this pot experiment with technique used are causing these much higher values but the order of magnitude of PFRV is similar to other literature values(Table 6).

In general only data of one crop are reported. This prevents general conclusions on the efficacy of P from ashes on short and long term as crop, soil and conditions are too different to allow for a general summary. There are two exeptions.

Bachman and Eichler-Löbermann (2010) reported on phacelia, buckwheat, ryegrass (2 cuts) and oil radish. From their data ARE values (%) are derived respectively of 7.8, 4.3, 4.7 and 15.8. PFRV values (%) are respectively 123, 66, 36 and 73. Phacelia is a crop with a high root density. Ryegrass had only 2 cuts. Results of Bachman and Eichler-Löbermann (2010) points to a higher efficacy of P from poultry litter ash for crops that are able to explore soil more intensively with their roots over a prolonged period.

[11] Buckwheat, Corn, Japanese mustard spinach (*Brassica rap L*, cv perviridis), Maize, 1 month, maize, 2 months, maize, 52 day after emergence, oil radish, Phacelia, Ryegrass (2 cuts), Ryegrass, 1th cut, Ryegrass, 2 cuts, Ryegrass, 2 months, one cut, Ryegrass, 2nd cut, Ryegrass, 4th cut, Ryegrass, 6th cut, Soybean after wheat after corn, Wheat after corn, Wheat boot stage;

[12] sandy loam, silt loam, sandy loam, limed, silt loam, limed, Lateric gravel, loam, loam (mesic aquic hapludol), loamy sand loamy sand (Haplic Luvisol), loamy sand (Masa), soil not specified high pH 8.2, soil not specified normal pH 6.4, soil not specified probably loamy sand, sand dune soil, sandy loam (mesic typic fragiudult)

Codling (2013) reported data of succession of corn, soybean after corn and wheat after corn. Values for ARE averaged over different application rates were respectively 1.0, 1.6 and 1.3% and PFRV were 44.5, 53.4 and 52.2%. From Codling's data derived PFRV values points out that residual phosphorus of poultry litter ash is available to the crop.

Overall ARE (excluding turkey manure ash) averaged to 4.5% with a range of 0.2-15.8% and PFRV averaged to 70% with a range of 26.6-140.8% (Table 6). Data reported for green bean (Ehlert & Nelemans, 2015e) and rye grass (Ehlert & Nelemans, 2015a) are for ARE respectively 4,4% and 2.1%. For ryegrass data were too variable to derive PFRV, for green been a value for PFRV of 37% was derived. Both ARE and PFRV values fit well within ranges based on literature data.

Phosphorus content and uptake are not standard parameters in practical fertiliser testing procedures. This literature study has focussed on ARE and PFRV and has therefore excluded agronomic research in which the effect of fertilisers made from poultry litter ash (PLA) was tested on yield or crop quality only. Data of Wells (2013) are not suitable for calculation of ARE and PFRV values, but do show positive results of poultry litter ash (PLA) application as an alternative fertiliser to superphosphate. Wells (2013) conducted experiments to determine effects of PLA application on growth and quality of two greenhouse crops (*Verbena canadensis* Britton "Homestead Purple' and *Lantana camara L.* 'New Gold'), substrate chemical properties, and P losses during greenhouse crop production. Compared to superphosphate PLA did not reduce biomass of *Verbena* or *lantana*. Leachate-dissolved reactive phosphorus (DRP) and effluent-total phosphorus concentrations were reduced >92% and >69%, respectively, through PLA application without adverse effecting plant growth. Although DRP was reduced, this did not adversely affect plant growth. Water solubility of PLA-P decreased markedly as combustion temperature increased. Topdressing resulted in a greater reduction of DRP than incorporation of PLA (134% versus 24% respectively). Plant quality was improved with PLA incorporation. Results of Wells (2013) indicate that, while P loss reduction can be achieved through PLA application, lower P concentrations do not necessarily reduce plant growth or quality.

3.1.2 Plant available phosphorus in soil

Bachman & Eichler-Löbermann (2010), Codling et al (2002), Codling (2013), Eichler-Loebermann et al (2008), Faridullah et al (2013), Lopez et al (2009), Pagiliari et al (2010a) and Yusiharni et al (2007) published data on STP from which ARE and PFRV can be derived.

Soils were different[13] as well as STP methods[14] limiting means for condensation of information. Interpretation of changes in STP requires inclusion of the soil type, as soil chemical properties determine the magnitude of changes. In this study STP methods were almost uniquely related to a specific soil type, therefore data are summarised per STP method[15]. STP methods differ in their strength to solubilise phosphorus. STP methods were therefore ranked according findings of Neyroud and Lischer[16] (2003). Table 7 summarises the data, Annex 5 gives all data.

If FeO and Bray 1 are excluded (only 2 counts) an increase in strength of extraction indeed increases the quantity of phosphorus that is extracted (Table 7). PFRV for extraction with water, P-DL and P Mehlich – 3 are on average higher than 100% indicating that residual P from ashes of poultry litter is relatively more effective in these STP than residual phosphorus of reference fertilisers. The higher

[13] sandy loam, silt loam, limed sandy loam, limed silt loam, lateric gravel, loam (mesic aquic hapludol), loamy sand (Haplic Luvisol), loamy sand (Masa), sand dune soil, sandy loam, sandy loam (mesic typic fragiudult) or not specified

[14] 0.01 M $CaCl_2$, 0.01 M HNO_3, 0.05 M EDTA, 0.1 M HNO_3, 0.1 M NH_4OAc, 1 M HNO_3, 1 M NH_4NO_3, Bray-1, Colwell, FeO, H_2O, Mehlich-3, Olsen, P-DL and Resin

[15] Usually the classification of plant available phosphorus measured as STP depends on the soil type.

[16] P total >P oxal. >P AL >P Me3 >P Bray > P AAEDTA, P DL ,P CAL, > P Olsen >P paper strip (FeO), P AAAc, P Morgan >P H_2O ,P CO_2, ,P $CaCl_2$

effectivity is attributed to introduction of other effects of poultry litter ashes such as changes in pH and addition of silicates (Si) which compete with phosphorus for the same sorption sites on soil components. Absorption of Si can increase STP. As ARE values are small, differences in phosphorus surpluses per treatment are considered to have a small or neglectable effect on the phosphate mass balance of the soil.

Data of FeO (iron filter paper strip method) used by Pagiliari et al (2010a) appeared to have a higher extraction strength than Neyroud and Lischer (2003) found. Use of P Olsen data from Bachmann & Eichler-Löbermann (2010) led to negative values of PFRV caused by lower STP values of reference fertiliser (KH_2PO_4) compared to the control treatment (Annex 5). Faridullah et al (2013) published data for other extraction methods and ranked their results according to 1 M HNO_3 > 0.1 M HNO_3 ~ EDTA > 0.01 M HNO_3 > NH_4NO_3 ~ NH_4OAc > $CaCl_2$ > H_2O thus valorising residual phosphorus of ashes of incineration of chicken manure and duck manure at 600°C (i.e. not a complete incineration). Overall a positive effect of residual phosphorus from poultry litter ashes on STP values.

Table 7. *Apparent recovery (ARE) and fertiliser replacement values (PFRV) for phosphorus for ashes from incineration of poultry manure based on soil test phosphorus (STP) data.*

Strength extraction	STP	ARE, %				PFRV, %			
		Average	Minimum	Maximum	Counts	Average	Minimum	Maximum	Counts
Weak	Water	0.8	0.3	1.9	16	165	25.1	760.1	16
↓	FeO	16.2	14.2	17.6	2	68.8	67.7	70.0	2
	Olsen	1.6	-1.0	5.5	7	-14.7	-120.2	45.0	7
	Resin	3.4	1.2	5.5	4	65.7	52.1	88.6	4
	P-DL	13.5	5.8	30.0	6	145.3	101.7	185.3	6
	Bray-1	89.2	83.3	95.0	2	89.2	83.3	95.0	2
Strong	Mehlich-3	29.2	7.0	48.0	16	114.7	46.8	237.4	16

3.2 Potassium

Faridullah et al (2009), Lopez et al (2009) and Richardson (1994) published data from which values for ARE and PFRVA for potassium can be derived. Table 8 summarises these data, Annex 6 gives the details.

As for phosphorus, crops[17] and soils[18] were different limiting the quantification of effects of factors that influence availability of potassium from poultry litter ash to the crop.

ARE values for potassium are higher than those for phosphorus (Table 8).

Table 8. *Apparent recovery (ARE) and fertiliser replacement values (PFRV) for potassium for different ashes from incineration of poultry manure.*

Ash	ARE, %				PFRV, %			
	Average	**Minimum**	**Maximum**	**Counts**	**Average**	**Minimum**	**Maximum**	**Counts**
Duck litter ash	12.4	4.1	29.1	5	*	*	*	*
Poultry litter ash (not specified)	25.1	4.6	54.2	11	95.8	74.3	118.2	11
All ashes of incineration of poultry litter	21.1	4.1	54.2	16	95.8	74.3	118.2	11

* Farming system not specified

In general increasing the application rate of potassium lowered ARE and PFRV (Annex 6). For green bean Ehlert and Nelemans (2015b) reported values for ARE of 25 to 65%. Lowest values were caused

[17] Japanese mustard spinach (*Brassica rap L, cv perviridis*), Oil radish, Ryegrass, 2 cuts, Ryegrass, 4th cut, Ryegrass, 6th cut

[18] Sand dune soil or not specified.

by the highest application rates. Values for PFRV ranged from 91 to 125%. For ryegrass values for ARE ranged from 90-100% and for PFRV from 97-104%. A major difference with the values derived from literature is that total potassium uptake by ryegrass is accounted for in the research for BMC Moerdijk while data from literature are from one harvest component only. Example given: Richardson (1994) reports 4th and 6th cut with nutrient contents. Total potassium uptake for all cuts is not known. However, the more potassium is harvested, the higher values become. The effect of an increase of potassium uptake with increase of the application rate does not affect PFRV values because these are relative values per application rate. PFRV values derived from literature are similar to those found in the pot experiments with hydrated poultry litter ash of BMC Moerdijk.

3.3 Acid neutralising value

Chastain et al (2012), Yusiharni et al (2007) and Lynch et al (2013) reported on the calcium carbonate equivalent of poultry litter ashes. The calcium carbonate equivalency (CCE[19]) is defined as the acid neutralising value relative to pure calcium carbonate. Data are summarised in Table 9, individual data are given in Annex 2.

Table 9. *Composition of ashes of incineration of poultry manures and poultry litters, secondary nutrients.*

Parameter	Unit	Average	Minimum	Maximum	Counts
Calcium carbonate equivalency	%	41	15	97	4

CCE values are determined by titration[20]. LUFA Nord West Hameln, Germany, determined CCE of the BMC poultry litter ash as neutralising value (CaO) following EN 12945:2014. The measurement resulted in a CCE value of 33.9%. This value is lower than the average value from literature (Table 9) but fits well within the (limited) range of data found in literature. Compared to none-hydrated poultry litter ashes, a lower value is expected due to absorption of CO_2 and consequently followed by in weight increase leading to an dilution effect (see foot note 5)

[19] For the energy plant BMC Moerdijk CCE will have another interpretation: Carbon conversion efficiency. In this study CCE bears the meaning of the acronym used in soil fertility research.

[20] CCE results from an analytical measurement in the laboratory. In principle it is a measurement based on titration of a base with acid. CCE determines the acid-neutralising capacity of liming materials and is also used for materials like poultry litter ash. In international studies of the AOAC 1.005 procedure (AOAC 1975) is followed. This method is similar to the method NEN-EN 12945:2014 EN Liming materials - Determination of neutralizing value - Titrimetric methods.

4 General observations and conclusions

A limited literature research has been conducted support the pot- and incubation experiments conducted to serve the technical file for application for a PK fertiliser with designation EU-fertiliser. The questions addressed in this study are all focussing on the composition and resulting efficacy of poultry litter ash as a PK-fertiliser compared to single mineral P- or K-fertilisers and liming materials. All these questions have been positively addressed by results published in peer-reviewed scientific publications. All studies showed a positive agronomic value of poultry litter ash. These publications however describe results obtained from straight poultry litter ashes not treated with water as an aid to reduce dust formation, transportation and storage (a form of polishing secondary raw materials to a fertiliser product).

The composition of poultry litter ashes appear variable. Variation is caused by animal and farming system. Broilers, egg laying hens, turkeys and ducks have different nutritional requirements which causes a different composition of manure[21]. This leads to different compositions of resulting ashes (Tables 2, 3, 4 and 5 and Annexes 1, 2 and 3).

Literature provides information on the P minerals in poultry litter ash but not on K. The literature points to the presence of (amorphous) apatite next to silicates and calcite. Apatite is a major phosphate compound of rock phosphate. Amorphous minerals (not arranged in regular arrays) have a higher solubility than crystalline minerals (regular ordered arrays of components). Apatites are known slow release phosphate fertilisers. By grinding, the efficacy is increased.

Nutritional requirements differ per animal and the growth phase. As in the Netherlands the efficiency of P in animal feed is maximised as a measure to reduce phosphorus surpluses, lower P contents in manure might result (although a reduction in P content in poultry litter manure is difficult to assess).

A major source of variation in ashes is introduced by the ratio between broiler litter manure and egg laying hen manure. This is due to the 2 to 3 times higher calcium requirement of egg laying hens, so their feed is more enriched with calcium. Higher calcium contents lead to an ash with higher CaO contents. As BMC Moerdijk produces a fertiliser by adding water to the ash - about 10% which leads to the formation of $Ca(OH)_2$) - additional variation is introduced. This is due to absorption of CO_2 on formed $Ca(OH)_2$ resulting in the formation of $CaCO_3$. Nutrients (P, K, Ca, Mg, Na, S and micronutrients) of hydrated poultry litter ash of BMC Moerdijk fit well in the ranges found from data from literature.

The efficacy of phosphorus was derived from responses of crops on P fertilisation and from residual phosphorus remaining in soil after harvest of crops or incubation experiment by use of soil phosphorus methods for fertiliser recommendations.

Overall ARE (excluding turkey manure ash) for phosphorus averaged to 4.5% with a range of 0.2-15.8% and PFRV averaged to 70% with a range of 26.6-140.8% (Table 6). Data on ARE reported for green bean (Ehlert & Nelemans, 2015e) and rye grass (Ehlert & Nelemans, 2015a) are respectively 4,4% and 2.1%. For ryegrass data were too variable to derive PFRV, for green been a value for PFRV of 37% was derived. Both ARE and PFRV values fit well within found ranges based on literature data.

Data on soil test phosphorus in literature, i.e. plant available phosphorus in soil (STP), were highly variable caused by different analytical soil test methods used for fertiliser recommendations in Europa and USA and differences between soil types. It is a fact that fertiliser recommendations between EU countries and even within a country use different STP methods. Despite this variation, data from

[21] http://www.kennisakker.nl/kenniscentrum/handleidingen/adviesbasis-voor-de-bemesting-van-akkerbouwgewassen-samenstelling-en-wer

literature clearly show that residual phosphorus from poultry litter ashes increases STP values. Residual phosphorus from poultry litter ashes is therefore plant available. All different STP showed overall a positive effect of residual phosphorus from poultry litter ashes thus indicating that poultry litter ashes contribute to a maintenance and increase of soil fertility status.

The efficacy of potassium of poultry litter ashes derived from literature data equals the efficacy of mineral potassium fertiliser (muriate of potassium) i.e. 100%.

Nutrient content and uptake are not standard parameters in practical fertiliser testing procedures. This literature study has focussed on ARE and PFRV and has therefore excluded agronomic research in which the effect of fertilisers made from poultry litter ash (PLA) was tested on yield or crop quality only.

Information on the efficacy of poultry litter ashes as liming material has not been traced in this limited literature research. Data on calcium carbonate equivalence have been reported and are similar to the acid neutralising value of hydrated poultry litter ash of BMC Moerdijk taken into account variation introduced by absorption of CO_2 on $Ca(OH)_2$ formed by addition of water .

Literature on effects of grinding poultry litter ash on the efficacy of phosphorus, potassium and acid neutralising value has not been found.

Incineration of poultry manure saves emissions from fossil fuel combustion, resulting in a reduced environmental impact in the impact category climate change (Billen et al, 2014). Electricity production from manure outperforms land spreading of manure in impact categories terrestrial acidification, particulate matter formation, marine eutrophication and photochemical oxidant formation (Billen et al, 2014). The ash is recovered as a PK fertiliser, which is odourless, dry, sterile and has a lower mass and volume than poultry manure, making it more suitable for export to regions with a high P demand (Billen et al, 2014).

Data reported by Ehlert & Nelemans (2015a, 2015b, 2015c, 2015d, 2015e) and the results of this literature review show that hydrated poultry litter ash has an agronomic effectivity as PK fertiliser. This agronomic effectivity is lower for crops with a short growing season compared to conventional regular mineral fertilisers. For crops with longer growing seasons the agronomic effectivity is similar to regular mineral fertiliser. Both phosphorus and potassium of hydrated poultry litter ash have an acceptable agricultural value as PK fertiliser. The acid neutralising value adds to the agronomic value. The main agronomic function in use of hydrated poultry litter ash is maintenance of soil fertility.

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Annex 1 Composition primary nutrients

Type(*)	pH	EC	Dry matter	Organic matter	Organic carbon	N-total	P-total	P water soluble	P citrate soluble	P NAC (**)	PAAC (**)	K-total	K water soluble	K citrate soluble	K NAC (**)	KAAC (**)	K exchangeable	Counts	Reference
	[-]	ms cm^{-1}	g/kg	g/kg	g C/kg	g N/kg	g P/kg					g K/kg						[-]	[-]
BLA	11.6	*	989.9	*	*	0.23	39.4					64.54						12	Chastain et al, 2012
PLA	12.2	27.5	*	*	*	*	53.0					3.90						1	Codling, 2002
PLA+sawdust	11.9	*	*	*	3.7	*	114.0	1.90				*						1	Codling, 2006
PLA+sawdust	11.6	*	*	*	7.9	*	98.2	2.20				*						1	Codling, 2006
PLA+sawdust	11.8	*	*	*	6.3	*	111.0	1.80				*						1	Codling, 2006
PLA+sawdust	12.2	*	*	*	7.7	*	75.9	0.01				*						1	Codling, 2006
ELMA	12.5	27.8	*	*	*	*	42.2	0.002				54.7						1	Codling, 2013
BLA	11.3	84.9	*	*	*	*	72.5	0.23				105						1	Codling, 2013
Chicken litter ash (900°C)	11.8	33.7	*	76.4	123.4	6	133.6	0.16	132.7	41.6	56.0	*	*	*	*	*	80.3	1	Faridullah et al, 2008
Duck litter ash (900°C)	13.3	12.3	*	65.3	1.1	0.27	139.2	0.06	89.8	53.8	24.0	*	*	*	*	*	71.1	1	Faridullah et al, 2008
PLA	11.5	31.1	*	*	*	*	114.7										6.3	1	Faridullah et al, 2009a
Chicken litter ash (900°C)	11.8	*	*	*	*	*	*		143.9			17.94					79.7	1	Faridullah et al, 2009c
Duck litter ash (900°C)	13.2	*	*	*	*	*	*		90.3			9.36					70.3	1	Faridullah et al, 2009c
PLA	13.0	*		nd	*	*	81.0					*						1	Hasimoto et al, 2009
ELMA						1	32.8					70.5						3	Huang et al, 2011
ELMA	13.2	29.6	1000		3.4	nd	6.7					7.34						1	Komiyama et al, 2013
ELMA	13.1	26.7	1000		6.1	nd	4.8					6.02						1	Komiyama et al, 2013
Broiler	12.4	29.5	996		0.3	nd	10.1					16.1						1	Komiyama et al, 2013
Chicken litter ash	11.3	1.6					47.5		38.5	23.3	18.5	41.1		37.0	13.2	12.3		1	Yusiharni et al, 2007
Turkey manure ash	12.2						84	6	43				117					1	Pagliari et al, 2010a, b
PLA			969			3	127.1					97.9						*	Richardson, 1994
PLA	11.5	31.1			231	18.5						154	48.9			2.31		1	Faridullah et al, 2013
Thermally gasified poultry manure	11.35						50.0		20									3	Kuligowski et al, 2010
BLA							110.0					170						1	Lynch et al, 2013

Type(*)	pH	EC	Dry matter	Organic matter	Organic carbon	N-total	P-total	P water soluble	P citrate soluble	P NAC (**)	PAAC (**)	K-total	K water soluble	K citrate soluble	K NAC (**)	KAAC (**)	K exchangeable (**)	Counts	Reference
	[-]	ms cm^{-1}	g/kg	g/kg	g C/kg	g N/kg	g P/kg					g K/kg						[-]	[-]
Fibrophos®							*					*						*	Lynch et al, 2013
Thermally gasified poultry manure							50.0	0.1	20			77	77					1	Rubaek et al, 2006
PLA							39.9	0.0005										1	Bachmann & Eichler-Löbermann, 2010
PLA	*	*	950	*	*	0	68.2	*	*	*	*	47.4	*	*	*	*	*	1	McClurg et al, 1971
PLA							51.0											1	Siegel et al, 1977
PLA							96.0											1	Siegel et al, 1977
BLA freshly excreted	*	*	1000	*	*	*	108.3					223.6						1	Mukhtar et al, 2002
BLA clean out	*	*	1000	*	*	*	109.7					137.0						1	Mukhtar et al, 2002
PLA	*	*	*	*	*	*	100.8	*	*	*	*	76.4	*	*	*	*	*	1	Blake & Hess, 2014
PLA	*	*	*	*	*	*	39.9	*	*	*	*	*	*	*	*	*	*	1	Eichler-Löbermann et al, 2008

* BLA: broiler litter ash, PLA: poultry litter ash, ELMA: Egg layer manure ash

** NAC: neutral ammonium citrate soluble, AAC: ammonium acetate soluble, K exchangeable : 1 M ammonium acetate exchangeable K

Annex 2 Composition secondary nutrients

Type	Ca-total,	Ca-wo	Ca citrate soluble	Ca NAC	CaAAC	Ca exchangeable	Mg-total,	Mg-wo	Mg citrate soluble	Mg NAC	MgAAC	Mgexchangeable	Na-total,	Na citrate soluble	Na NAC	NaAAC	S-total,	CCE	Counts	Reference
	g Ca/kg						g Mg/kg						g Na/kg				g S/kg	%		
Broiler	58						12						18				11	32	12	Chastain et al, 2012
ELMA	149.6						16.4												1	Codling, 2013
BLA	169						33.8												1	Codling, 2013
Chicken litter ash (900°C)						2.0						2.0							1	Faridullah et al, 2008
Duck litter ash (900°C)						1.5						10.6							1	Faridullah et al, 2008
PLA						0.1						0.8	*				*	*	1	Faridullah et al, 2009a
Chicken litter ash (900°C)	114.2					2.0	20.8					1.1							1	Faridullah et al, 2009b
Duck litter ash (900°C)	126.2					1.5	25.3					5.4							1	Faridullah et al, 2009b
PLA	348						28												1	Hasimoto et al, 2009
ELMA	31.4						2.7						0.7				*		1	Komiyama et al, 2013
ELMA	32						1.8						0.3				*		1	Komiyama et al, 2013
Broiler	17.4						3.8						2.0				*		1	Komiyama et al, 2013
Chicken litter ash (700oC)	180.2		165.8	72.1	70.3		19.4		16.7	14.0	11.6		18.6	16.7	7.3	6.3	*	97	1	Yusiharni et al, 2007
Turkey manure ash	*		*	*	*		*		*	*	*		*	*	*	*	17	*	1	Pagliari et al, 2010a
PLA	100	0.5			4.63		20.3	0.4			0.16								1	Faridullah et al, 2013
BLA	160						39						20				26	19	1	Lynch et al, 2013
Fibrophos®	250						50						30				70	15	*	Lynch et al, 2013
PLA	248	*	*	*	*	*	22.2						0.16						1	McClurg et al, 1971
BLA freshly excreted	107.7						45.1						27.6				33.3		1	Mukhtar et al, 2002
BLA clean out	153.6						35.6						48.4				28.9		1	Mukhtar et al, 2002
PLA	166.8	*	*	*	*	*	26.5	*	*	*	*	*	43.4	*	*	*	*	*	1	Blake & Hess, 2014

Annex 3 Composition micro nutrients

Type	B	Co	Cu	Fe	Mn	Mo	Zn	Se	Al	As	Cd	Cr	Hg	Ni	Pb	Counts	Reference
Broiler			772		891		733									12	Chastain et al, 2012
PLA			43.1	4300	1600		600			15.0	0.4			14.8	6.0	1	Codling, 2002
ELMA			352	7680	1.3		1300		9.1	10.9						1	Codling, 2013
BLA			1502	8440	2.5		1542		15.4	12.9						1	Codling, 2013
PLA			335		1393		1080									1	Faridullah et al, 2009a
Chicken litter ash (900°C)			421		1773		1073							134.0	79.3	1	Faridullah et al, 2009b
Duck litter ash (900°C)			282		1160		613							94.6	64.7	1	Faridullah et al, 2009b
ELMA			127		1114		1173		nd							1	Komiyama et al, 2013
ELMA			87		950		795		0.0							1	Komiyama et al, 2013
Broiler			309		2238		1652		0.1							1	Komiyama et al, 2013
chicken litter ash (700°C)			52.4		1400		9500			30.4	6.6			19.3	8.5	1	Yusiharni et al, 2007
Turkey manure ash			420				1000									1	Pagliari et al, 2010a
PLA			335		1393		1080							74.0		1	Faridullah et al, 2013
BLA	270	8.8	290	6500	4200	79.0	3800	12.0								1	Lynch et al, 2013
Fibrophos®	150	10.0	500	4000	2500	30.0	2000	5.0								*	Lynch et al, 2013
PLA	1250		120	3010	770	*	750									1	McClurg et al, 1971
PLA	*	*	1700	5900	2100		1400	2.4	6.3	52.0	0.8	34.0	0.1		4.4	1	Blake & Hess, 2014

Annex 4 Apparent recovery and fertiliser replacement values of P, crop

Source (1)	Reference fertiliser	Soil	Crop	ARE	PFRV	Reference	Remark
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Phacelia	7.8	123	Bachman & Eichler-Löbermann, 2010	
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Buckwheat	4.3	66	Bachman & Eichler-Löbermann, 2010	
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Ryegrass (2 cuts)	4.7	36	Bachman & Eichler-Löbermann, 2010	
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Oil radish	15.8	73	Bachman & Eichler-Löbermann, 2010	
BLA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	0.7	27	Codling, 2013	
BLA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	0.5	27	Codling, 2013	
ELMA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	1.6	64	Codling, 2013	
ELMA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	1.2	61	Codling, 2013	
BLA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	0.8	28	Codling, 2013	
BLA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	0.9	38	Codling, 2013	
ELMA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	1.8	65	Codling, 2013	
ELMA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	1.8	78	Codling, 2013	
BLA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	1.1	31	Codling, 2013	
BLA-high rate 80	$Ca(H_2PO4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	1.3	47	Codling, 2013	
ELMA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	2.1	60	Codling, 2013	
ELMA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	2.1	75	Codling, 2013	
PLA-low rate39 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam	Wheat boot stage	0.2	*	Codling e.a., 2002	2
PLA-high rate 78 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam	Wheat boot stage	0.5	*	Codling e.a., 2002	2
PLA-low rate39 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam, limed	Wheat boot stage	4.1	*	Codling e.a., 2002	2
PLA-high rate 78 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam, limed	Wheat boot stage	2.6	*	Codling e.a., 2002	2
PLA	KH_2PO_4	not specified, probably loamy sand	Phacelia	7.8	141	Eichler-Loebermann et al, 2008	
PLA	KH_2PO_4	not specified, probably loamy sand	Buckwheat	4.3	75	Eichler-Loebermann et al, 2008	
PLA	KH_2PO_4	not specified, probably loamy sand	Ryegrass, 2 months, one cut	4.7	50	Eichler-Loebermann et al, 2008	
PLA	KH_2PO_4	not specified, probably loamy sand	Oil radish	15.8	84	Eichler-Loebermann et al, 2008	

Source (1)	Reference fertiliser	Soil	Crop	ARE	PFRV	Reference	Remark
PLA	no reference	loamy sand (Masa)	maize, 2 months	1.3	*	Faridullah et al, 2013	
PLA	no reference	loamy sand (Masa)	maize, 2 months	1.1	*	Faridullah et al, 2013	
PLA	no reference	loamy sand (Masa)	maize, 2 months	1.7	*	Faridullah et al, 2013	
PLA	no reference	sand dune soil	maize, 2 months	0.8	*	Faridullah et al, 2013	
PLA	no reference	sand dune soil	maize, 2 months	0.7	*	Faridullah et al, 2013	
PLA	no reference	sand dune soil	maize, 2 months	1.0	*	Faridullah et al, 2013	
CLA 0° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	5.4	*	Faridullah et al, 2009	
CLA 200° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	10.2	*	Faridullah et al, 2009	
CLA 400° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	15.6	*	Faridullah et al, 2009	
CLA 600° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	10.4	*	Faridullah et al, 2009	
CLA 800° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	10.3	*	Faridullah et al, 2009	
CLA 900° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	12.2	*	Faridullah et al, 2009	
DLA 0° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	6.2	*	Faridullah et al, 2009	
DLA 200° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	10.8	*	Faridullah et al, 2009	
DLA 400° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	13.1	*	Faridullah et al, 2009	
DLA 600° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	6.2	*	Faridullah et al, 2009	
DLA 800° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	5.1	*	Faridullah et al, 2009	
DLA 900° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	7.2	*	Faridullah et al, 2009	
PLA	Triple superphosphate	loamy sand	Ryegrass, 2 cuts	4.8	81.4	Lopez et al, 2009	
PLA	Triple superphosphate	loamy sand	Oil radish	7.3	68.9	Lopez et al, 2009	
TMA	Triple superphosphate	loam (mesic aquic hapludol)	Maize, 52 DAE	55.5	75.1	Pagliari et al, 2010b	
TMA	Triple superphosphate	loam (mesic aquic hapludol)	Maize, 52 DAE	52.9	90.5	Pagliari et al, 2010b	
TMA	Triple superphosphate	loam (mesic aquic hapludol)	Maize, 52 DAE	44.4	84.6	Pagliari et al, 2010b	
TMA	Triple superphosphate	loam (mesic aquic hapludol)	Maize, 52 DAE	44.4	99.6	Pagliari et al, 2010b	
TMA	Triple superphosphate	loam (mesic aquic hapludol)	Maize, 52 DAE	41.6	93.8	Pagliari et al, 2010b	
PLA (=CMA) 0% acidified-200° C	Triple superphosphate	loam	Maize, 1 month	2.5	37.2	Siegel et al, 1977	
PLA (=CMA) 0% acidified-400° C	Triple superphosphate	loam	Maize, 1 month	1.8	34.3	Siegel et al, 1977	
PLA (=CMA) 0% acidified-800° C	Triple superphosphate	loam	Maize, 1 month	1.3	33.2	Siegel et al, 1977	
PLA (=CMA) 0% acidified-1200° C	Triple superphosphate	loam	Maize, 1 month	1.1	33.0	Siegel et al, 1977	
PLA 50% acidified-200° C	Triple superphosphate	loam	Maize, 1 month	2.7	39.8	Siegel et al, 1977	

Source (1)	Reference fertiliser	Soil	Crop	ARE	PFRV	Reference	Remark
PLA 50% acidified-400° C	Triple superphosphate	loam	Maize, 1 month	2.8	52.8	Siegel et al, 1977	
PLA 50% acidified-800° C	Triple superphosphate	loam	Maize, 1 month	2.1	54.7	Siegel et al, 1977	
PLA 50% acidified-1200° C	Triple superphosphate	loam	Maize, 1 month	2.1	59.6	Siegel et al, 1977	
PLA 100% acidified-200° C	Triple superphosphate	loam	Maize, 1 month	4.0	59.0	Siegel et al, 1977	
PLA 100% acidified-400° C	Triple superphosphate	loam	Maize, 1 month	3.2	60.6	Siegel et al, 1977	
PLA 100% acidified-800° C	Triple superphosphate	loam	Maize, 1 month	2.3	60.5	Siegel et al, 1977	
PLA 100% acidified-1200° C	Triple superphosphate	loam	Maize, 1 month	2.3	67.1	Siegel et al, 1977	
CLAT	monocalciumphosphate	Lateric gravel	Ryegrass, 1th cut	*	*	Yusiharni et al, 2007	3
CLAT	monocalciumphosphate	Lateric gravel	Ryegrass, 2nd cut	*	*	Yusiharni et al, 2007	4
PLA-80	Triple superphosphate	not specified, high pH 8.2	Ryegrass, 4th cut	10.3	112.5	Richardson, 1994	5
PLA-160	Triple superphosphate	not specified, high pH 8.2	Ryegrass, 4th cut	10.3	105.9	Richardson, 1994	5
PLA-80	Triple superphosphate	not specified, high pH 8.2	Ryegrass, 6th cut	3.4	120.0	Richardson, 1994	5
PLA-160	Triple superphosphate	not specified, high pH 8.2	Ryegrass, 6th cut	2.6	128.6	Richardson, 1994	5
PLA-80	Triple superphosphate	not specified, normal pH 6.4	Ryegrass, 4th cut	1.7	100.0	Richardson, 1994	5
PLA-160	Triple superphosphate	not specified, normal pH 6.4	Ryegrass, 4th cut	2.9	83.3	Richardson, 1994	5
PLA-80	Triple superphosphate	not specified, normal pH 6.4	Ryegrass, 6th cut	3.4	100.0	Richardson, 1994	5
PLA-160	Triple superphosphate	not specified, normal pH 6.4	Ryegrass, 6th cut	4.3	115.4	Richardson, 1994	5

1

BLA: broiler litter ash

CLA: chicken litter ash, partially burned

CLAT: chicken litter ash, fully burned

DLA: duck litter ash

ELMA: egg laying hen manure ash

TMA: turkey manure ash

Additions to these codes condition the treatments per fertiliser application rate, temperature conditions of incineration or acidification treatment of the ashes. For details see given reference.

2 PFRV unreliable

3 PFRV 7.3% based on P content

4 PFRV 21% based on P content

5 P rate estimated

Annex 5 Apparent recovery and fertiliser replacement values of P, soil

Source	Reference fertilizer	Soil	Crop	STP	ARE	PFRV	Reference
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Phacelia	Resin	1.2	52	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Buckwheat	Resin	5.5	56	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Ryegrass (2 cuts)	Resin	4.0	66	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Oil radish	Resin	2.7	89	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Phacelia	Olsen	1.2	-120	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Buckwheat	Olsen	-0.2	-31	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Ryegrass (2 cuts)	Olsen	-1.0	-25	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Oil radish	Olsen	-0.8	-7	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Phacelia	Water	1.1	45	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Buckwheat	Water	1.3	39	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Ryegrass (2 cuts)	Water	1.3	42	Bachman & Eichler-Löbermann, 2010
PLA	KH_2PO_4	loamy sand (Haplic Luvisol)	Oil radish	Water	0.9	25	Bachman & Eichler-Löbermann, 2010
BLA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	Mehlich-3	34.5	51	Codling, 2013
BLA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	Mehlich-3	28.6	47	Codling, 2013
ELMA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	Mehlich-3	36.8	107	Codling, 2013
ELMA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Corn	Mehlich-3	44.8	156	Codling, 2013
BLA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	Mehlich-3	25.5	60	Codling, 2013
BLA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	Mehlich-3	22.4	51	Codling, 2013
ELMA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	Mehlich-3	33.8	132	Codling, 2013
ELMA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Wheat after corn	Mehlich-3	30.5	136	Codling, 2013
BLA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	Mehlich-3	42.0	74	Codling, 2013
BLA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	Mehlich-3	36.9	69	Codling, 2013
ELMA-low rate 40	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	Mehlich-3	48.0	114	Codling, 2013
ELMA-high rate 80	$Ca(H_2PO_4)_2$	sandy loam (mesic typc fragiudult)	Soybean after wheat after corn	Mehlich-3	44.3	120	Codling, 2013
PLA-low rate39 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam	Wheat boot stage	Water	1.9	760	Codling e.a., 2002
PLA-high rate 78 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam	Wheat boot stage	Water	0.9	318	Codling e.a., 2002
PLA-low rate39 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam, limed	Wheat boot stage	Water	0.4	502	Codling e.a., 2002
PLA-high rate 78 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam, limed	Wheat boot stage	Water	0.3	350	Codling e.a., 2002
PLA-low rate39 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam	Wheat boot stage	Mehlich-3	11.9	171	Codling e.a., 2002
PLA-high rate 78 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam	Wheat boot stage	Mehlich-3	12.8	149	Codling e.a., 2002
PLA-low rate39 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam, limed	Wheat boot stage	Mehlich-3	7.0	160	Codling e.a., 2002
PLA-high rate 78 kg P/ha	KH_2PO_4	averaged over sandy loam and silt loam, limed	Wheat boot stage	Mehlich-3	8.1	237	Codling e.a., 2002
PLA	KH_2PO_4	not specified	Phacelia	P-DL	7.3	185	Eichler-Loebermann et al, 2008
PLA	KH_2PO_4	not specified	Buckwheat	P-DL	9.5	156	Eichler-Loebermann et al, 2008

Source	Reference fertilizer	Soil	Crop	STP	ARE	PFRV	Reference
PLA	KH_2PO_4	not specified	Ryegrass, 2 months, one cut	P-DL	9.0	138	Eichler-Loebermann et al, 2008
PLA	KH_2PO_4	not specified	Oil radish	P-DL	5.8	102	Eichler-Loebermann et al, 2008
PLA	KH_2PO_4	not specified	Phacelia	Water	0.4	51	Eichler-Loebermann et al, 2008
PLA	KH_2PO_4	not specified	Buckwheat	Water	0.5	44	Eichler-Loebermann et al, 2008
PLA	KH_2PO_4	not specified	Ryegrass, 2 months, one cut	Water	0.5	50	Eichler-Loebermann et al, 2008
PLA	KH_2PO_4	not specified	Oil radish	Water	0.4	30	Eichler-Loebermann et al, 2008
PLA	no reference	loamy sand (Masa)	maize, 2 months	1 M HNO_3	0.75	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	1 M HNO_3	0.47	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	1 M HNO_3	0.42	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.1 M HNO_3	0.76	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.1 M HNO_3	0.50	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.1 M HNO_3	0.40	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.01 M HNO_3	0.69	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.01 M HNO_3	0.45	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.01 M HNO_3	0.37	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.05 M EDTA	0.74	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.05 M EDTA	0.50	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.05 M EDTA	0.39	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.1 M NH_4OAc	0.09	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.1 M NH_4OAc	0.08	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.1 M NH_4OAc	0.09	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	1 M NH_4NO_3	0.20	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	1 M NH_4NO_3	0.16	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	1 M NH_4NO_3	0.14	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.01 M $CaCl_2$	0.03	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.01 M $CaCl_2$	0.03	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	0.01 M $CaCl_2$	0.02	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	Water	0.004	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	Water	0.004	*	Faridullah et al, 2013
PLA	no reference	loamy sand (Masa)	maize, 2 months	Water	0.003	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	1 M HNO_3	0.49	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	1 M HNO_3	0.27	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	1 M HNO_3	0.25	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.1 M HNO_3	0.53	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.1 M HNO_3	0.31	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.1 M HNO_3	0.22	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.01 M HNO_3	0.49	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.01 M HNO_3	0.25	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.01 M HNO_3	0.22	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.05 M EDTA	0.39	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.05 M EDTA	0.24	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.05 M EDTA	0.22	*	Faridullah et al, 2013

Source	Reference fertilizer	Soil	Crop	STP	ARE	PFRV	Reference
PLA	no reference	Sand dune soil	maize, 2 months	0.1 M NH_4OAc	0.03	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.1 M NH_4OAc	0.05	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.1 M NH_4OAc	0.06	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	1 M $NH4NO_3$	0.11	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	1 M $NH4NO_3$	0.09	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	1 M $NH4NO_3$	0.08	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.01 M $CaCl_2$	0.03	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.01 M $CaCl_2$	0.02	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	0.01 M $CaCl_2$	0.02	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	Water	0.007	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	Water	0.003	*	Faridullah et al, 2013
PLA	no reference	Sand dune soil	maize, 2 months	Water	0.003	*	Faridullah et al, 2013
PLA	no reference	sandy loam	Ryegras, 2 cuts	Water	1.3	*	Lopez et al, 2009
PLA	no reference	sandy loam	Ryegras, 2 cuts	P-DL	30.0	*	Lopez et al, 2009
PLA	no reference	sandy loam	Oil radish	Water	0.9	*	Lopez et al, 2009
PLA	no reference	sandy loam	Oil radish	P-DL	19.2	*	Lopez et al, 2009
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	Water	0.7	27.6	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	Water	0.7	27.6	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	Bray 1	95.0	95.0	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	Bray 1	83.3	83.3	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	FeO	17.6	67.7	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	FeO	14.7	70.0	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	Olsen	5.5	16.9	Pagiliari et al, 2010a
TMA	Triple superphosphate	loam (mesic aquic hapludol)	none, average 64 days incubation	Olsen	4.8	18.3	Pagiliari et al, 2010a
CLAT	Mono calcium phosphate (=Triple superphosphate)	Lateric gravel	Ryegrass, 20 weeks	Colwell (~Olsen)	*	45.0	Yusiharni et al, 2007

Annex 6 Apparent recovery and fertiliser replacement values of K

Source	Reference fertiliser	Soil	Crop	ARE	PFRV	Reference	Remark
CLA 0° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	5.0	*	Faridullah et al, 2009	
CLA 200° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	30.7	*	Faridullah et al, 2009	
CLA 400° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	18.6	*	Faridullah et al, 2009	
CLA 600° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	17.7	*	Faridullah et al, 2009	
CLA 800° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	4.6	*	Faridullah et al, 2009	
CLA 900° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	10.9	*	Faridullah et al, 2009	
DLA 0° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	6.8	*	Faridullah et al, 2009	
DLA 200° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	12.8	*	Faridullah et al, 2009	
DLA 400° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	29.1	*	Faridullah et al, 2009	
DLA 600° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	9.4	*	Faridullah et al, 2009	
DLA 800° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	4.1	*	Faridullah et al, 2009	
DLA 900° C	no reference	sand dune soil	Japanese mustard spinach (Brassica rap L, cv perviridis)	6.5	*	Faridullah et al, 2009	
PLA	Muriate of potash	loamy sand	Ryegrass, 2 cuts	30.0	74.3	Lopez et al 2009	
PLA	Muriate of potash	loamy sand	Oil radish	50.0	118.2	Lopez et al 2009	
PLA-80	Muriate of potash	not specified, low K	Ryegrass, 4th cut	54.2	95.2	Richardson, 1994	1
PLA-160	Muriate of potash	not specified, low K	Ryegrass, 4th cut	39.5	76.2	Richardson, 1994	1
PLA-80	Muriate of potash	not specified, low K	Ryegrass, 6th cut	11.7	114.7	Richardson, 1994	1
PLA-160	Muriate of potash	not specified, low K	Ryegrass, 6th cut	8.3	96.5	Richardson, 1994	1

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