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From sewage sludge ash to a recycled feed phosphate – digestibility of precipitated calcium phosphate in broiler chickens and growing pigs

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ABSTRACT

Today, EU is largely (∼92%) dependent on the import of phosphates as most mines are located outside Europe. Because of the limited availability, phosphorus **(P)** is included on the list of Critical Raw Materials. Precipitated calcium phosphate **(PCP)** recovered from sewage sludge ash is a novel and sustainable option to replace mined P as raw material in feed phosphates, e.g. monocalcium phosphate **(MCP)** or dicalcium phosphate, but the digestibility has not yet been tested in vivo. The aim was therefore to determine PCP and MCP apparent ileal digestibility **(AID)** of P in broiler chickens and apparent **(ATTD)** and true **(TTTD)** total tract digestibility of P in growing pigs. A chicken study comprised 240 Ross 308 chickens that were housed in groups of eight from day 21 to day 28. Five diets were used, a basal diet and two test diets, which contributed either 0.075% (low) or 0.150% (high) additional P for each of the test sources (MCP and PCP). The basal and test diets were composed to achieve increasing levels of P and AID was calculated with regression analysis. In the pig study, eight individually housed pigs were used in a change-over study with two experimental periods. The pigs were fed a basal P-free diet in a preperiod to be able to estimate endogenous P losses and then two different diets in two periods using a change-over design, where MCP and PCP were the only P source, providing in total 0.33 (basal diet), 4.42 (MCP) and 3.53 (PCP) g kg^{-1}P, respectively. The AID of P in PCP and MCP for chickens was 58.4 and 75.1% (P = 0.166). The ATTD and TTTD of P in PCP for pigs were 58.4 and 67.2%, respectively, which was lower (P < 0.001) than the corresponding values for MCP (82.1 and 89.1%), respectively. The digestibility of calcium **(Ca)** did not differ in the chicken diets with high inclusion levels of PCP and MCP (54.7 and 55.3%, respectively, P = 0.535), but was lower for PCP than MCP in the pig study (57.8 and 70.8% respectively, P = 0.001). In conclusion, the digestibility of P in PCP for chickens did not differ from conventional MCP, whereas for pigs, it was lower, but could be a viable alternative to other common sources of P.

Implications

The transition to circular economy is crucial in building a sustainable society. In this context, phosphorus is a key factor. Today, the EU is largely dependent on import as most mines are located outside Europe. The large ecological footprint from mining and long transports makes safe recycling of phosphorus substantial to strengthen the EU food value chain. Precipitated calcium phosphate recovered from sewage sludge ash has the potential to be used as an alternative feed phosphate, and this study provides in vivo digestibility of phosphorus and calcium of this alternative feed phosphate in poultry and pigs. Recycled phosphorus in animal feed aligns with EU's green deal and farm-to-fork strategy, securing domestic supply and saving significant amounts of CO_2 emissions.

Introduction

The transition to a circular economy is crucial in building a sustainable society. Today, almost half of our climate impact and 90% of water scarcity issues are linked to the way we extract resources and produce goods and food (IRP, 2019). In this context, phosphorus **(P)** has a key function. Clearly, fertilisers are vital for global food production (Ritchie, 2021). In addition, the geopolitical instability leads to problems with sourcing fertilisers and P to make fertilisers. The EU's fertiliser and animal food industries, as well as other industry sectors using P compounds, are highly reliant on imports of phosphate rock with a large ecological footprint.

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Today, EU is largely (92%) dependent on import as most mines are located outside Europe, mainly in Morocco and Russia (Brownlie et al., 2022). P is non-substitutable in fertilisers and feed and, therefore, is included on EU's list of Critical Raw Materials (EC, 2020) and with increased demand for resource efficiency and more sustainable value chains, the use of recycled P will be unavoidable in the future society. P can be recovered from sewage sludge by precipitation, which has shown high bioavailability of P for plants (Shiba and Ntuli, 2017).

Within pig and poultry production, P is added in the feed. The amount of the added P that animals can utilise differs between different feedstuffs (Jongbloed and Kemme, 1990). The P that is not digested by the animal is excreted in faeces and urine and contributes to the leakage of nutrients and the environmental burden. To avoid this, the correct amount of P with a high digestibility should be added to the feed. In feed formulation, this requires that the digestibility of the feed ingredients is known. EasyMining, a Swedish innovation company, Uppsala, Sweden, dedicated to closing nutrient cycles, has invented a process that recovers P from sewage sludge ash (EasyMining, 2022) to produce a precipitated calcium phosphate **(PCP)**. The PCP is a pure product that fulfils quality demands in feed legislation (EU, 2002, 2003, and 2006) (Table 1). The main benefit with using recycled calcium phosphate such as PCP is closing of the P cycle, resulting in reduced need for rock phosphate and imports from outside Europe by having domestic production of phosphates with decreasing CO_2 emissions (Johansson, 2020). The PCP have a potential to be used as a feed ingredient, but to be so, the P digestibility in monogastric animals such as chickens and pigs need to be determined and tested in vivo.

The aim of this project was therefore to determine the P digestibility of PCP in growing chickens and pigs. The hypothesis was that PCP should have a comparable P digestibility for both chickens and pigs as conventional monocalcium phosphate **(MCP)** and dicalcium phosphate **(DCP)**.

Material and methods

Test sources monocalcium phosphate and precipitated calcium phosphate

The P source in MCP used was a commercial (MCP BOLIFOR®, MCP-F, YARA). P in PCP was efficiently recovered from incinerated sewage sludge according to the Ash2®Phos-process. The process consisted of three steps that allow to separate elements of interest and detoxify the products; a first acidic step, a second alkaline step (where intermediate products are produced), and a final conversion step where the intermediates are processed into final products. The main inputs of the process were ash from incinerated sewage sludge, acid (hydrochloric acid) and lime (EasyMining, 2022). The PCP fulfilled the quality demands in the feed legislation with lower values than the legal limits for fluorine, cadmium, arsenic, mercury, lead, dioxins and polychlorinated biphenyl (EU, 2002, 2003, and 2006) (Table 1). Limit values for aluminium and nickel are not listed in the EU legislation on undesirable substances in animal feed, but levels for toxicity can be found for the total intake of feed. The dietary inclusion level of PCP was 0.45, 0.91 and 2.23% in the chicken (Table 2) and pig (Table 3) diets, and the values of aluminium and nickel in the diets corresponded to 7.7, 15.5 and 37.9 mg kg^{-1} and were below toxicity for chickens and pigs according to NRC (2005) and EFSA (2015). The solubility of P in 2% citric acid was tested in both MCP and PCP according to the procedure described by IFP (2023). The solubility test was done in duplicates and average dissolution degrees were calculated and the result for PCP and MCP is shown in Table 1.

Table 1
Analysed solubility in 2% citric acid, mineral, trace mineral and content of dioxins and polychlorinated biphenyl in MCP and PCP used in the pig and chicken feed.

Item	MCP[1]	PCP
Chemical formula	$Ca(H_2PO_4)_2 \times H_2O$	$Ca_5(PO_4)_3OH$
Solubility in 2% citric acid, %	86	87
Ca, g/kg	165	350
P, g/kg	249	175
Mg, g/kg	10	4.1
F, g/kg	2	14
Fe, g/kg	.	1.4
Al, g/kg	.	1.7
As, mg/kg	<10	1.4
Cd, mg/kg	<10	<0.1
Pb, mg/kg	<15	3.6
Hg, mg/kg	<0.1	<0.1
Cu, mg/kg	.	5
Cr, mg/kg	.	1.7
Co, mg/kg	.	0.7
Ni, mg/kg	.	2.5
Dioxins, mg/kg	.	<0.1
Polychlorinated biphenyl, mg/kg	.	<0.1

Abbreviations: MCP = monocalcium phosphate, PCP = precipitated calcium phosphate.
[1] BOLIFOR®, MCP-F, YARA, Pocklington York, UK. Indicates that data are not available.

Experimental design and housing – chicken study

The chicken study was performed at the Swedish Livestock Research Centre, SLU, Uppsala. A total of 240 one-day-old chicks (Ross 308) was divided into 30 groups with eight chickens/group. The chickens were housed in pens raised from the floor with solid floor covered by wood shavings, with free access to feed and water throughout the experiment. From days 1–21, the chickens were fed a commercial poultry feed based on wheat and soybean meal (Johan Hansson AB, Sweden), all feed were free from coccidostats. On day 21, the actual digestibility study started. The digestibility study included five experimental diets, a basal diet composed to fulfil the protocol requirements stated in WPSA (2013; Table 2). In addition, two experimental diets were used to determine the P digestibility of the test sources, PCP and MCP (Bolifor MCP-F, Yara, Sweden). These were supplemented at two levels; 0.075 (low) and 0.15% (high), in order to achieve an increase in the total P level in the diet compared to the basal diet (Table 2) and perform regression analysis with the slope being the digestible coefficient. Titanium dioxide **(TiO_2)** was added with 5 g kg^{-1} to all diets as an indigestible marker. The Ca:P ratio was optimised to be maintained at 1.3 for all diets, and other nutrients such as vitamins, minerals and trace elements were optimised to be provided in adequate amounts and to not differ between the experimental diets. All ingredients were milled through a hammer mill with a 3-mm screen before mixed and steam pelleted (conditioning temperature 75 °C) through a 3-mm die; the temperature of the feed after pelleting was 83.6 °C.

The chickens were weighed weekly, and dietary treatments were distributed to get similar starting weight for all treatments. The average weight of the chickens on day 21 was 1016.2 g ± 186 g, and there was no difference (P = 0.998) in start weight between the treatments. The chickens were fed the experimental diets between day 21 and day 28, the amount of feed given and feed residues as well as BW were registered on pen basis weekly. Between days 0 and 21, the feed intake was 1351.3 ± 70.61 g/chicken and the feed conversion ratio was 1.39 ± 0.086. On day 28, the chickens were killed by an intravenous injection of sodium pentobarbital through the wing vein. The digestive tract was removed, and the gut content from ileum identified as the part from Meckel's Diverticulum to the ileo-caecal-colonic junction was collected. Samples from birds in the same pen were pooled and stored at −20 °C and freeze-dried before analysis.

Table 2
Ingredient composition of experimental diets used to determine P digestibility of monocalcium phosphate (MCP) and precipitated calcium phosphate (PCP) when supplemented at two levels in chickens, and its optimised and analysed chemical composition.

Item	Basal	MCP Low	MCP High	PCP Low	PCP High
Ingredients, %					
Corn	40.00	40.00	40.00	40.00	40.00
Wheat	23.31	23.33	23.35	23.61	23.32
Soybean meal	15.00	15.00	15.00	15.00	15.00
Wheat starch	10.85	10.07	9.29	10.06	9.82
Potato protein	7.45	7.45	7.46	7.41	7.46
Soybean Oil	0.62	0.94	1.25	0.86	1.04
Limestone	0.79	0.90	1.01	0.64	0.47
Titanium dioxide	0.50	0.50	0.50	0.50	0.50
PCP	0	0	0	0.45	0.91
MCP	0	0.33	0.66	0	0
Premix[1]	0.51	0.51	0.51	0.51	0.51
Sodium bicarbonate	0.24	0.24	0.24	0.24	0.24
Methionine	0.22	0.22	0.22	0.22	0.22
NaCl	0.20	0.20	0.20	0.20	0.20
Choline Chloride	0.12	0.12	0.12	0.12	0.12
L-Lysine	0.12	0.12	0.12	0.12	0.12
L-Arginine	0.09	0.09	0.09	0.09	0.09
Optimised chemical composition					
DM	873.6	874.5	875.3	874.2	874.7
Calcium, g kg^{-1} DM	4.61	5.72	6.83	5.72	6.84
Phosphorus, g kg^{-1} DM	3.55	4.40	5.26	4.40	5.26
Ca/P	1.30	1.30	1.30	1.30	1.30
Analysed chemical composition					
DM	912.8	914.8	911.3	913.9	915.4
Ash, g kg^{-1} DM	43.80	48.30	46.10	48.20	45.30
Calcium, g kg^{-1} DM	5.35	6.28	7.33	6.14	7.19
Phosphorus, g kg^{-1} DM	3.89	4.25	5.05	4.20	4.89
Ca/P	1.38	1.48	1.45	1.46	1.47

[1] The premix provided (per kg feed): Vitamin A (retinyl acetate): 9 900 IE; Vitamin D3 (cholecalciferol) 2 475 IE; Vitamin E (alpha-tocopheryl acetate): 64.4 mg; Vitamin B1 (thiamine mononitrate): 2.0 mg; Vitamin B2: 6.0 mg; Niacin: 30 mg; Vitamin B5 (calcium-D-pantothenate): 15 mg; Vitamin B6 (pyridoxine hydrochloride): 6 mg; Biotin: 0.2 mg; Vitamin B9 (folic acid): 1.6 mg; Vitamin B12 (cyanocobalamin): 0.02 mg; Vitamin K3 (menadione nicotinamide bisulphite): 3.09 mg; Fe (iron sulphate): 52.5; Zn (zinc sulphate):82.5 mg; Cu (copper sulphate):15 mg; I (calcium iodate): 1.05; Mn (manganese sulphate): 127.5 mg; Se (sodium celite): 0.3 mg.

Experimental design and housing – pig study

The study was performed at the Centre of Veterinary Medicine and Animal Science at the Swedish University of Agricultural Sciences, Uppsala in May and June 2021. Eight pigs (Yorkshire × Hampshire) were used in the study and were 9 weeks old at the start of the experiment with and average weight of 24. 9 ± 3.19 kg. All pigs were gilts from two litters, and the experimental diets were randomly distributed within litter. The pigs were fed a basal P-free diet (0.33 g/kg^{-1} DM) in a preperiod (fed prior to the test diets) to be able to estimate endogenous P losses **(ELP)**. Two test diets with different test sources of phosphorus, PCP and MCP, with similar P and Ca levels, were then fed to the pigs in two periods using a change-over design. The MCP and PCP diets provided in total of 4.42 and 3.53 g kg^{-1} DM of P and 7.51 and 7.35 g kg^{-1} DM of Ca, respectively. TiO_2 was added with 2.5 g kg^{-1} to all diets as an indigestible marker. All diets are shown in Table 3. The pigs were kept in individual pens with nose contact with the neighbouring pig. They did not have access to straw, but the pens were equipped with a rubber mat, and the pigs had access to plastic and rubber toys to enable explorative behaviour. The basal-diet and the experimental diets were fed to the pigs during 11 days in each period (preperiod, period 1 and period 2), consisting of 7 days of adjustment to the diet, followed by 4 days of faeces collection. The feed allowance was 4% of the pig BW, divided into two equal meals. The diets were meal feed and water was added and mixed with the feed prior to each feeding in a ratio of 2:1. Faeces were collected after the pigs had defecated, from carefully cleaned floors. A pooled sample from the four days of faecal sampling was used for analysis. The samples were stored in freezer −20 °C and were freeze-dried before analysis.

Chemical analyses and calculations

The digesta and faeces were freeze-dried before analysis. Feed and digesta were analysed for DM, CP, TiO_2, Ca and P. The feed, ileal digesta and faecal samples were analysed for DM by drying at 103 °C for 16 h and for ash after ignition at 550 °C for 3 h. TiO_2 in feed ileal digesta and faecal samples was analysed according to Short et al. (1996) on 0.1 g samples of ileal and faecal samples and 0.5 g of feed samples and was used as an indigestible marker for calculations of AID and ATTD coefficients. Ca and P were analysed according to Swedish standard (Svensk Standard SS 02 83 11) with some minor modifications. Briefly, 1 g sample was weighed in and 20 mL 7 M HNO_3 was added and boiled for 1 h with mixing after 15 and 45 min. The samples were cooled, and deionised water was added to reach a total volume of 100 mL before mixing. The samples were thereafter diluted, mixed and centrifuged, and the Ca and P level was measured with a Spectro Blue ICP Spectrometer, Spectro Ametek, Kleve, Germany.

The ileal apparent digestibility **(IAD)** and apparent total tract digestibility **(ATTD)** for the diets were calculated using the indicator technique (Sauer et al. 2000) according to the equation:

$$\mathrm{IAD/ATTD}\ (\%) = 100 - [100 \times (\mathrm{TiO}_{2\mathrm{D}} \times \mathrm{PC}_{\mathrm{Dig/F}})/(\mathrm{TiO}_{2\mathrm{Dig/F}} \times \mathrm{PC}_{\mathrm{D}})]$$

where TiO_{2D} is the TiO_2 concentration in diet (g kg^{-1} DM), $PC_{Dig/F}$ is the P concentration (g kg^{-1} DM) in digesta/faeces, $TiO_{2Dig/F}$ is the TiO_2 concentration (g kg^{-1} DM) in digesta/faeces and PC_D is the P concentration (g kg^{-1} DM) in diet.

The content of precaecal digestible P **(pcdP)** in the chicken diet was calculated according to WPSA (2013) as:

$$\mathrm{pcdP}\ (\mathrm{g\ kg^{-1}\ DM}) = \mathrm{IAD}\ (\%) \times \mathrm{PC_D}/100$$

Table 3
Ingredient composition of a basal diet to determine endogenous P losses (ELP) and two experimental diets used to determine the P digestibility of monocalcium phosphate (MCP) and precipitated calcium phosphate (PCP) in the pig study, and its optimised and analysed chemical composition in g kg^{-1} DM.

Item	Basal	MCP	PCP
Ingredient (%)			
Corn starch	50.87	49.99	50.56
Dextrose	18.00	18.00	18.00
Potatao protein	18.00	18.00	18.00
Rape seed oil	5.00	5.00	5.00
Cellulose	4.00	4.00	4.00
Limestone	1.92	1.18	0
MCP	0	1.62	0
PCP	0	0	2.23
Sodium bicarbonate	0.40	0.40	0.40
NaCl	0.39	0.39	0.39
Lysine-HCl	0.35	0.35	0.35
Premix	0.320	0.320	0.320
Methionine-DL	0.27	0.27	0.27
Titanium dioxide	0.25	0.25	0.25
Magnesium oxide	0.10	0.10	0.10
Threonine	0.05	0.05	0.05
Tryptophan	0.057	0.057	0.057
Zinc sulphate	0.021	0.021	0.021
Sodium selenite	0.001	0.001	0.001
Optimised chemical composition[1]			
DM	916.5	917.3	916.5
Calcium, g kg^{-1} DM	7.84	7.84	8.81
Phosphorus, g kg^{-1} DM	0.59	4.60	4.60
Ca/P	13.3	1.70	1.92
Magnesium, g kg^{-1} DM	0.88	0.96	0.73
Potassium, g kg^{-1} DM	1.16	1.16	1.14
Chloride, g kg^{-1} DM	3.67	3.67	3.67
Sodium, g kg^{-1} DM	2.97	2.97	2.95
Iron, mg kg^{-1} DM	212.4	232.0	132.7
Copper, mg kg^{-1} DM	19.2	19.2	19.2
Manganese, mg kg^{-1} DM	52.1	46.9	24.5
Zinc, mg kg^{-1} DM	86.7	87.6	85.7
Analysed chemical composition			
DM	934.0	929.3	930.8
Ash, g kg^{-1} DM	31.7	41.4	36.9
Calcium, g kg^{-1} DM	6.84	7.51	7.35
Phosphorus, g kg^{-1} DM	0.33	4.42	3.53
Ca/P	20.7	1.70	2.08

[1] The diet provided (mg kg^{-1}): Pantothenic acid 12.24; Choline 45.0; Vitamin B3 Niacin 20.4; Vitamin E 61.2; Vitamin B1 2.04; Vitamin B12 0.02; Vitamin B2 4.08; Vitamin B6 3.06 and (IE kg^{-1}): Vitamin D3 510; Vitamin A 5 100.

where IAD is the ileal apparent digestibility for the diet and PC_D is the P concentration (g kg^{-1} DM) in diet.

The ELP that is referred to the basal diet free of P was estimated as described by Mariscal-Landín and Reis de Souza (2006) according to the following equation:

$$ELP\ (g\ kg^{-1}\ DMI) = (PC_F \times (TiO_{2B}/TiO_{2F})) \times DMI_B$$

where PC_F is the P concentration in faeces (g kg^{-1} DM), TiO_{2B} is the TiO_2 concentration in the basal diet (g kg^{-1} DM), TiO_{2F} is the TiO_2 concentration in faeces (g kg^{-1} DM) and DMI_B is the DM intake of the basal diet (kg day^{-1}).

To calculate the true total tract digestibility **(TTTD)** of P, the equation by Furuya and Kaji (1991) was used:

$$TTTD\ (\%) = ATTD + (ELP/PC_D) \times 100$$

where ATTD is the apparent total tract digestibility of P (%) in the diet, ELP is the endogenous losses of P (g kg^{-1} DMI) and PC_D is the P concentration (g kg^{-1} DM) in the diet.

Statistical analyses

In the chicken study, one value was classified as an outlier since the IAD of P was two SD from the treatment mean, and excluded from the statistical analysis. In the pig study, one pig was excluded from the statistical analysis due to values that were classified as outliers since the ATTD of Ca and TTTD of P was two SD from the treatment mean. The statistical analysis was performed with the Mixed procedure in SAS® 9.4 (SAS Institute Inc., 2021) to determine treatment effects by ANOVA. For the chicken study, the model included diet as a fixed factor, and pen as a random factor. Pen served as experimental unit. In the pig study, diet and period were used as fixed factors and pig as random factor. *P*-values <0.05 were considered significant. To estimate the digestibility of PCP and MCP in the chicken study, a multiple regression analysis with a common intercept was performed in the GLM procedure between the total P contents and the pcdP in the diets, where the slope is the digestibility of the P source.

Results

Chicken study

The BW on day 28 was 1701.3 ± 135.58 g (mean ± SD), the feed intake between day 21 - day 28 was 895.6 ± 102.38 (mean ± SD) and feed conversion ratio between days 21 and day 28 was 1.34 ± 0.088 (mean ± SD). None of these parameters differed between the diets. The IAD of organic matter and Ca did not differ between diets, whereas the IAD of P was higher in the MCP high diet than in the other diets (P = 0.022) and pcdP were higher in both PCP and MCP high diets compared with PCP and MCP low (P = 0.001) (Table 4). The linear relationship between the total P content in the diet and pcdP is shown in Table 5. The IAD of P in MCP was estimated to 75.1% and in PCP to 58.4% (P = 0.166). The amount of P in MCP and PCP was 227 and 165 g kg^{-1}; thus, the amount of digestible P was 170.5 g kg^{-1} for MCP and 96.4 g kg^{-1} for PCP.

Pig study

For pig start and final weights as well as growth rate, there were no effects of diet. Although, as expected, an effect of period was found and the final weight was 30.1 ± 4.97 and 35.6 ± 1.27 kg (mean ± SD) for period I and period II, respectively. The ATTD of organic matter did not differ between the MCP and PCP diets, but a diet effect was found for the ATTD of Ca and P with higher digestibility of both Ca and P for MCP compared with PCP (P = 0.001). The estimated ELP ranged between 270 and 363 (average 309) mg kg^{-1} DMI, and the TTTD of P corrected for endogenous losses were correspondingly higher than the values for ATTD of P (Table 6) but showed a diet effect with higher TTTD for MCP compared with PCP (P = 0.001). Period had no effect on either ATTD or TTTD of OM, Ca or P. The amount of P in MCP and PCP was 227 and 165 g kg^{-1}. Using the ATTD, the amount of digestible P was 186.4 g kg^{-1} for MCP and 96.4 g kg^{-1} for PCP. The corresponding digestible P based on the TTTD were 202.3 g kg^{-1} for MCP and 110.9 g kg^{-1} for PCP.

Discussion

The PCP recovered from incinerated sewage sludge demonstrate a pure product showing lower levels than the legal limits for fluorine, cadmium, arsenic, mercury, lead, dioxins and polychlorinated biphenyl. The level of aluminium and nickel in the diets was also below-recommended toxicity levels for chicken and pigs (NRC, 2005; EFSA, 2015). In both the chicken and pig study, the growth performance was within the expected range and did not differ between diets. The feed intake and growth rate of the chickens were within 10% deviation from expected growth performance of

Table 4
Ileal apparent digestibility (%) of organic matter, Ca and P as well as the pcdP (g kg^{-1} DM) of MCP and PCP when supplemented at two levels (low and high) in chickens.

Item	Basal	PCP Low	MCP Low	PCP High	MCP High	SEM	*P*-value
Organic matter	73.43	73.73	74.41	75.76	75.60	0.770	0.150
Ca	59.03	55.13	58.13	54.71	55.34	2.196	0.535
P	41.91[ab]	40.28[b]	42.64[ab]	44.16[ab]	48.27[a]	2.007	0.022
PcdP	1.61[b]	1.67[b]	1.79[b]	2.16[a]	2.43[a]	0.094	0.001

Abbreviations: MCP = monocalcium phosphate, PCP = precipitated calcium phosphate, pcdP = precaecal digestible P.
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$.

Table 5
Linear relationship between precaecal digestible P content (g kg^{-1} DM) and total P of monocalcium phosphate (MCP) and precipitated calcium phosphate (PCP) in chickens.

Item	Regression equation	SE of slope	SE intercept	R^2	Ileal digestibility, %	*P*-value Test source
MCP	Y = 0.751X – 0.638	0.142	0.620	0.770	75.1	0.166
PCP	Y = 0.584X – 0.603	0.110	0.475	0.770	58.4	

Table 6
ATTD (%) of organic matter, Ca and P and TTTD (%) of MCP and PCP in pigs.

Item	MCP	PCP	SEM	*P*-value
ATTD of organic matter	94.2	94.0	0.24	0.348
ATTD of Ca	71.3	58.5	2.29	0.001
ATTD of P	82.1	58.4	2.02	0.001
TTTD of P	89.1	67.2	2.00	0.001

Abbreviations: MCP = monocalcium phosphate, PCP = precipitated calcium phosphate, ATTD = apparent total tract digestibility, TTTD = true total tract digestibility.

Ross 308 (Aviagen, 2019), which is one of the criteria of the WPSA (2013) protocol. A higher BW was observed for period I than period II in the pig study and was expected, as the pigs were older in period II. Since the pigs were given a restricted amount of feed, the pigs were not expected to reach their maximal genetic growth potential and the results should therefore not be compared to growth studies.

We hypothesised that PCP should have a similar P digestibility as MCP for both chickens and pigs. The obtained results could however not fully support this and lower P digestibility of PCP than MCP was found in pigs and although not significantly different, numerically lower values were observed also in chickens. According to our knowledge, this is the first time the digestibility of PCP is determined in vivo, whereas previous research has evaluated the digestibility of other feed phosphates, e.g. MCP, DCP, monodicalcium phosphate, defluorinated phosphate, monosodium phosphate and tricalcium phosphate. According to previous results (summarised in Table 7), the reported P digestibility of MCP in the present studies is judged to be within expected range. The tested PCP had lower digestibility compared to MCP in general, but show similar P digestibility as DCP and monodicalcium phosphate for chickens.

By using a P-free basal diet, the P that is excreted by the animal is of endogenous origin, and the basal endogenous losses of P can be estimated (Petersen and Stein 2006). Correction for the basal ELP from the ATTD allows for the determination of true total tract digestibility (TTTD), which can be assumed as an accurate estimation of the bioavailable P (Petersen et al. 2011; Baker et al. 2013). In the present study, a P-free diet was used, which made it possible to determine ELP and TTAD of the MCP and PCP. However, the ELP in the present study were higher (average 309 mg kg^{-1} DM) than previously reported values of 210 and 139 mg kg^{-1} of DMI (Ajakaiye et al. 2003; Petersen and Stein 2006). On the other hand, losses of endogenous P have been ranging between 70 mg kg^{-1} of DMI (Dilger and Adeola 2006; Pettey et al. 2006) and 670 mg kg^{-1} of DMI (Shen et al. 2002). The higher values might be a result of using different estimation procedures, such as the regression procedure (Dilger and Adeola 2006) or that digestibility measurements are used with different techniques, for example the use of and indigestible marker or total faecal collection in metabolism cages. Also, dietary factors in diets containing commonly used feed ingredients

Table 7
Comparison between IAD, ATTD, STTD and TTTD (%) of P of different feed phosphates for chickens and pigs in the present study and previous research.

Item	PCP	MCP	DCP	MDCP	DFP	MSP	TCP	Reference
Chicken								
IAD		78.3	59.0	70.7	31.5			Bikker et al. (2016)
		64.6	69.3	60.2				Trairatapiwan et al. (2018)
	58.4	75.1						Present study
Pig								
ATTD		84.0[1]						Lopez Diaz (2020)
		88.0[2]						
		83.0–88.0	81.0					Petersen and Stein (2006)
		85.9	78.4	78.0		87.3	65.2	Kwon and Kim (2017)
	58.4	82.1	–	–	–	–	–	Present study
STTD	–	93.0	87.0	86.5	-	94.9	71.3	Kwon and Kim (2017)
TTTD	–	88.6–94.9[3]	81.5	–	–	98.2	–	Petersen and Stein (2006)
	67.2	89.1						Present study

Abbreviations: IAD = ileal apparent digestibility; ATTD = apparent total tract digestibility; STTD = standardised total tract digestibility; TTTD = true total tract digestibility; PCP = precipitated calcium phosphate, MCP = monocalcium phosphate, DCP = dicalcium phosphate; MDCP = monodicalcium phosphate; DFP = defluorinated phosphate; MSP = monosodium phosphate; TCP = tricalcium phosphate.
[1] Volcanic MCP.
[2] Non-volcanic MCP.
[3] In MCP with 50–100% MCP.

that may make specific diet-dependent endogenous losses and higher total endogenous losses. In the present study, however, the P-free basal diet was based on corn starch and could be assumed to be comparable with that of Petersen and Stein (2006). The estimated TTTD of P in PCP and MCP in the present study were higher than the ATTD, which is in agreement with the results of Petersen and Stein (2006). However, both the ATTD and TTTD of P in PCP were lower compared with the other tested feed phosphates in the literature (Table 7). Large variations in P digestibility both among and between different P sources have however been reported by others and are likely due to both differences in experimental set-up and quality of P-sources (Bikker et al., 2016; Rodehutscord et al., 2017; Trairatapiwan et al., 2018). Therefore, it has been suggested that comparisons between sources mainly should be made within studies (Rodehutscord et al., 2017).

Due to diet composition, it was not possible to estimate the Ca-digestibility for the individual P sources MCP and PCP, only for the complete diets in the present study. The present chicken study showed no difference in Ca-digestibility between the diets with MCP and PCP inclusion. The basal diet in the chicken study without the addition of MCP and PCP had an IAD of Ca of 59% and the diets with MCP and PCP inclusion ranged between 54.7 and 58.1%. In comparison, Bikker et al. (2016) estimated IAD of Ca to 67% in their low P basal diet and to 66%, 60%, 64% and 37% for diets with MCP, DCP, monodicalcium phosphate and defluorinated phosphate, respectively. However, many factors such as Ca-source, particle size and Ca-level might affect Ca digestibility (Kim et al., 2018) which makes it hard to make direct comparisons between studies.

The ATTD of Ca for pigs was lower in the PCP than MCP diet (58.5 vs 71.3%). For pig studies, the ATTD of Ca in diets used by Lopez Diaz (2020) was 52% for volcanic MCP and 60% for non-volcanic which is similar to the ATTD of Ca of 58.5% in the PCP diet in the present study. The majority (96.8%) of Ca in the PCP diet originated from PCP and the diet digestibility is therefore likely a good estimation of the ATTD of Ca in PCP. The Ca-digestibility of 71.3% for pigs on the MCP diet in the present study is slightly higher than Lopez Diaz et al. (2020) reported, but is on the other hand slightly lower than 76% that is reported for MCP by Kwon and Kim (2017). In comparison, Kwon and Kim (2017) also reported ATTD of Ca in DCP to 74%, monodicalcium phosphate to 72%, monosodium phosphate to 67% and tricalcium phosphate to 64%.

Conclusion

In conclusion, this study shows that recycling of a clean and safe phosphorus product can be used as a feed phosphate in diets to monogastric animals. The amount of digestible P in PCP for chickens do not differ from conventional MCP, whereas for pigs, it was lower than reported for conventional MCP, however, in the same range as literature data for conventional DCP and tricalcium phosphate. The use of a recycled P source has the potential to be used as a viable alternative to other common sources of P.

Ethics approval

The study was approved by the Uppsala Ethics Committee on Animal Research (ethics approval numbers 5.8.18-10572/2019 for the chicken study and 5.8.18-03495/2021 for the pig study), which is in compliance with EC Directive 86/609/EEC on animal studies.

Data and model availability statement

Data are deposited in an official repository at SLU, Dept. of Animal Nutrition and Management, Swedish University of Agricultural Sciences, Box 7024, 750 07 Uppsala, Sweden. Access rights to data and processes are available to reviewers upon request.

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Declaration of interest

The authors report no conflict of interest.

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