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Reducing phosphorus excretion and loss potential by using a soluble supplement source for swine and poultry

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ABSTRACT

Animal diets are often over-supplemented with low bioavailability phosphorus (P) sources in China, resulting in unnecessary excretion and loss of P to the environment. The effect of reducing dietary P supplementation and using a highly available P supplement for swine and poultry was determined. Manure collected in feeding trials involving the use of dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP) that were < 1 or 17% water soluble, respectively, to increase dietary total P to amounts ranging from approximately 0.39 to 0.68% was analyzed for total P as well as different forms of P (H_2O-, $NaHCO_3$-, NaOH-, HCl- and residue-P). Manure total P varied with the amount of P supplemented, ranging from 14.5 to 22.3 g kg^{-1} for pigs, 4.7–13.6 g kg^{-1} for broilers and ducks, and 8.0–23.5 g kg^{-1} for layers. Determined using manure from pigs and birds receiving the highest supplemental amounts, MDCP reduced manure total P by up to 12.1% and H_2O–P by up to 18.4% compared to DCP. Manure P extracted by weak NaOH and HCl was up to 9.4% higher for MDCP than DCP. Thus, using MDCP resulted in manure P that was lower in labile fractions than DCP. Soil leaching studies showed that dissolved P collected in leachate from manure was 9.4–32.6% lower when MDCP replaced DCP in the diet of pigs, broilers, ducks, and layers, confirming that MDCP reduced labile P in manure. Minimizing dietary P supplementation and using highly available MDCP as the supplemental source for pigs, broilers, ducks, and layers reduced P excretion and loss potential to the environment.

1. Introduction

Phosphorus (P) is an essential element for animals. Phosphorus is involved in many aspects of physiology, including reproduction (DNA), energy metabolism (ATP), and body structure (bones, teeth) (Knowlton et al., 2004; Scholz et al., 2013). Because of the vital roles P plays, inorganic P is often included in animal diets to ensure sufficient intakes (Penn et al., 2004; Stein et al., 2008). However, overfeeding of P is highly problematic. High dietary P reduces the efficiency of P utilization, resulting in increased P excretion (Wang et al., 2011; Bai et al., 2015). Phosphorus contained in manure is prone to running off and leaching from cropland that receives manure application, contributing to eutrophication of freshwater and marine ecosystems (Strokal et al., 2016). Over-supplementation of P is also costly, and can accelerate the depletion of phosphate resources that are nonrenewable (Cordell et al., 2009; Sattaria et al., 2012; Scholz et al., 2013). It is estimated that 383,000 tons of phosphate rock is used annually by the animal industry in China alone (Steiner et al., 2015), and the world's inorganic P reserves could be depleted within the next 30–100 years (Cooper et al., 2011; Cordell et al., 2013; Cordell and Neset, 2014).

China is the largest pork and egg production country in the world (FAO, 2017), and proper use of P is important. The amount of dietary P recommended by the Chinese feeding standards is 0.43–0.74% for pigs, 0.35–0.45% for broilers, 0.35–0.42% for ducks,

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and 0.32–0.40% for layers (Xiong, 2010), all higher than the recommendations of 0.43–0.70, 0.30–0.35, 0.30–0.40, and 0.21–0.31% for these animals or poultry species, respectively, by feeding standards of the United States (Guo et al., 2018). There is a great need to control the use of P in diets for swine and poultry in China.

Grains constitue the main part of the diet for swine and poultry (Leytem and Thacker, 2008; Abbasi et al., 2019). However, most of the P contained in grains, usually cereals for swine and poultry, exists in the form of phytate that is indigestible because swine and poultry are lacking in phytase, the enzyme that is needed to release P from phytates. To utilize P in cereals, exogenous phytase has been added to swine and poultry diets in recent years (Zyła et al., 2001; Almeida and Stein, 2012), and the digestibility of P has been increased 40–65% (Spencer et al., 2000; Maguire et al., 2005; Fritts and Waldroup, 2006). However, there are issues associated with phytase supplementation in relation to product variation, pH sensitivity, and enzymatic activity (Adeola and Cowieson, 2011; Kumar et al., 2015). Moreover, although increased utilization of P in grains due to the use of phytase can reduce the amount of phosphates needed in diet, P still needs to be supplemented in order to fully meet the animal's requirements (Zyła et al., 2001; McGrath et al., 2005; Petersen and Stein, 2006; Casteel et al., 2011). Dicalcium phosphate ($CaHPO_4$, DCP) is the most commoly used supplements, usually included in the diet at 0.34–1.70% for swine and 0.05–1.80% for poultry (Applegate et al., 2003; Vadas et al., 2004; Petersen and Stein, 2006; Powers et al., 2006; Stein et al., 2008; Ajith et al., 2018; Hamdi et al., 2018; Liu et al., 2018). A problem with DCP is low solubility (<1%) and thus low bioavailability (Casteel et al., 2011).

A more soluble product that has beome commercially available in China is a specialty mono-dicalcium phosphate (MDCP) product manufactured by Yuntianhua Group (Kunming, Yunnan, China). This product is an eutectic blend of calcium dihydrogen phosphate [$Ca(H_2PO_4)_2$, MCP] and DCP. It contains 17% soluble P, which is 82% of its total P content (Zhang, 2008). Li et al. (2016), Lv et al. (2018), and Wan et al. (2018) reported 93.6, 76.7, 62.3, and 70.5% P apparent digestibilities for pigs, broilers, ducks, and layers, respectively, when supplemented with MDCP. Pigs and birds were also found to gain in bone mineralization and phosphorus retention. However, how this highly water soluble supplement affects manure P vulnerability and leaching potential of manure application is undetermined.

The form of P contained in manure is an important factor affecting P vulnerability and loss potential. Baxter et al. (2003) suggested that the form is more sensitive than total P (TP) as an indicator of how much manure P is available to crops and how much could be lost from the soil. Phosphorus is lost from the soil mainly in dissolved forms, dependent on ration formulations, P concentrations, and whether exogenous phytase is used in the diet (Smith et al., 2004; Wienhold and Miller, 2004; Toor et al., 2005; Powers et al., 2006).

Studies have been conducted in China to fractionate manure P. Du et al. (2011) extracted P using H_2O and $NaHCO_3$ in manure of dairy cows, pigs, sheep, chickens, and ducks collected from Huaihe River Basin, and Li et al. (2014a) and Yan et al. (2015) did similar analyses using samples collected from Beijing and Shandong province. These studies have provided a general analysis of the characteristics of manure P for these animals. The objective of this study was to determine: (i) changes of manure P in the amount and form when pigs and poultry were supplemented with different amounts and sources of inorganic P varying in solubility, and (ii) the effect of substituting MDCP for DCP in animal and poultry diets on P runoff.

2. Materials and methods

2.1. Feeding trials

This study was part of a project that involved conducting animal feeding trials and analyzing manure. The feeding trials were conducted in 2016 in Beijing, Gansu, and Shaanxi, China, and have been reported by Li et al. (2016). Each of the feeding trials concerned supplementing a basal diet with different amounts of DCP (Bejing Chemical Plant, Beijing, China) or MDCP (specialty feed grade, Yuntianhua Group, Kunming, Yunnan, China) (Table 1) for pigs (*Sus scrofa domesticus*), broilers (*Gallus gallus domesticus*), ducks (*Anatinae domesticus*), or layers (*Gallus gallus domesticus*).

Currently, DCP is the most commonly used P supplement in China, but the specialty MDCP product used in these trials is more soluble and contains less heavy metals. The basal diets (Table S1) were soybean-corn-based, containing 0.37, 0.36, 0.43, and 0.34% TP for pigs, broilers, ducks, and layers, respectively. Dietary treatments were formed by adding DCP or MDCP to the basal diets, each to provide supplemental P at 0.05, 0.10, 0.15, and 0.20% for pigs, 0.05, 0.10, 0.15, 0.20, and 0.25% for broilers and ducks, and 0.05, 0.10, 0.15, 0.20, 0.25, and 0.30% for layers (Table S1). Diets did not contain phytase supplements. The final TP content, including contributions from the basal formulation and supplementation, of the dietary treatments for both supplemental DCP and MDCP was 0.42, 0.47, 0.52, and 0.57% for pigs, 0.41, 0.46, 0.51, 0.56, and 0.61% for broilers, 0.48, 0.53, 0.58, 0.63, and 0.68% for ducks, and 0.39, 0.44, 0.49, 0.54, 0.59, and 0.64% for layers (Table S2).

Each treatment used 6 replicates (pens or cages) of 8 animals for pigs, 16 birds for broilers, 16 birds for ducks, or 9 birds for layers. The experiments were conducted during days 30–60 of age for pigs, days 0–20 for broilers and ducks, and days 259–280 for layers. Feed intake, fecal output, dry matter apparent digestibility, P apparent digestibility, and growth or production of animals or birds were reported by Li et al. (2016) and summarized in Table S3.

2.2. Manure

Manure was collected during the feeding trials conducted in 2016.

For pigs, manure collection was done between days 30–40 of animal age. Three pigs weighing 20 ± 2.3 kg were randomly selected from each treatment and moved to stainless steel metabolism crates equipped with wire mesh and pans to separate feces and urine. Pigs were fed at 08:00, 14:00, and 20:00, with free access to drinking water all day. After a 5-day adaptation, feces were totally collected at 08:00 for 5 days, weighed, and stored at 4 °C. Samples were composited within animal across days, dried at 65 °C for 2 days to constant weight, and ground to pass a 2-mm screen.

Three cages of birds were randomly selected from each

Table 1
Analyses of dicalcium phosphate (DCP) and mono-dicalcium phosphates (MDCP)[a].

Item	DCP	MDCP
Ca (%)	≥22.8	≥14.5
Total P (%)	17.0	21.4
Water soluble P (%)	0.00	17.50
pH	7.2–8.0	3.5–4.5
Acid binding capacity	546	20
F (%)	≤0.18	≤0.13
As (%)	≤0.003	≤0.001
Pb (%)	≤0.003	≤0.002
Cd (%)	≤0.001	≤0.000

[a] Provided by Beijing Chemical Factory (Beijing, China) for DCP and Yuntianhua Group (Kunming, Yunnan, China) for MDCP.

treatment in each experiment. Bird excreta were collected at 08:00 on days 18–20 of age for broilers and ducks, and days 268–270 for layers. Collected manure was weighed each day, stored at 4 °C, and pooled within cages at the end of the collection. Samples were later dried at 65 °C for 2 days and ground to pass a 2-mm screen.

2.3. Fractionation of manure P

Manure P was fractionated sequentially using the procedure described by Dou et al. (2000). Briefly, 0.3 g of ground samples (2 mm) was weighed into 50 mL screw-cap centrifuge tubes, and added with 30 mL of deionized water. Tubes were shaken on a reciprocal shaker at 200 rpm for 1 h, and centrifuged at 10000 rpm for 10 min at the room temperature. Extracts were filtered through a 0.45 μm nitrocellulose membrane with vacuum, and analyzed for inorganic P and total P using the molybdate-blue method (Murphy and Riley, 1962). Aliquots of the filtrate were also extracted sequentially with 0.5 M $NaHCO_3$ (pH 8.5), 0.1 M NaOH, and 1.0 M HCl, and extracts were analyzed for P content. Extraction residues were digested with H_2SO_4–H_2O_2 at 380 °C for 3 h and analyzed for P.

2.4. Leaching studies

Leaching studies were conducted in 2017. This simulation study using pure sand and 12 sources of manure in a completely randomized block design with three replications. Sand was used to take its advantage of no interference of other elements (Bould and Parfitt, 1973; Perez-Lopez et al., 2007; Wei et al., 2018). Sand was sterilized with 1.5 M HCl for 24 h, rinsed with water to pH 7.0, and dried at 30 ± 5 °C (equal to air dry) to 1.3 g cm^{-3}, conditions typically seen in Northern China. Dried and sterilized sand was put into polyvinyl columns of 20 cm length and 10 cm inner diameter, innerlined with filter paper to prevent side leaking. The manure sources were pigs fed diets containing DCP or MDCP at 0.05, 0.10, or 0.20%, and broilers, ducks, and layers that received the highest amount of DCP or MDCP in the feeding trials. Manure was spread on the surface 0.50 mm sand of the columns at a rate equivalent to 260 kg P ha^{-1}, a level commonly used in Northern China (Anzai et al., 2016; Zhao et al., 2017). Columns were irrigated with 200 mL water every other day. The rate for these columns that had a surface area of 78.5 cm^2 was a simulation of the annual rainfall in Northern China that averaged 330 mm, from storms of 80 mm h^{-1}, 20 min, on average (Zhang, 2012). Leachate was collected, filtered (0.45 μm), digested with alkaline potassium persulfate (0.2 M $K_2S_2O_8$), and analyzed for dissolved P (Murphy and Riley, 1962).

2.5. Statistical analysis

Data on manure TP, P extracted by H_2O (H_2O–P), $NaHCO_3$ ($NaHCO_3$–P), NaOH (NaOH–P), and HCl (HCl–P), and extraction residue P (RP) were analyzed for one-way ANOVA using SPSS 20.0 (SPSS Inc., Chicago, IL, USA). Differences among treatments in manure P were determined using the Duncan (D) test at $P < 0.05$. For the leaching studies, the effect of the source and amount of supplemental P fed on manure dissolved P was assessed by the Univariate General Linear Model for swine, and by independent *t*-test for poultry.

3. Results

3.1. Total P excretion

Fecal TP for pigs ranged from 14.5 to 22.3 g kg^{-1} or 810–1438 mg day^{-1} (Fig. 1, Fig. S1). The concentration increased as the amount of P supplemented increased (Fig. 1a). The concentration was lower for MDCP than DCP, especially at 0.15 and 0.20% additions. Similarly, the amount of TP excreted was 15.6% lower when MDCP was used as the supplemental source rather than DCP.

The concentration of manure TP ranged from 4.7 to 9.0 g kg^{-1} for broilers, 4.9–13.6 g kg^{-1} for ducks, and 8.0–23.5 g kg^{-1} for layers (Fig. 1). The highest concentration occurred at the highest supplemental amount for broilers and ducks. Similar to pigs, manure TP concentration was lower for MDCP than DCP (Fig. 1b, d). At the highest supplemental amount, manure TP concentration was 7.2, 17.3, and 11.7% lower for MDCP than DCP for broilers, ducks, and layers, respectively. Likewise, the amount of TP excreted was 32.2, 8.5, and 25.3% lower for MDCP than DCP for these birds respectively (Fig. S1). Interestingly, manure TP content was similar for ducks receiving 0.25% P from MDCP and 0.20% P from DCP (Fig. 1c), and for layers receiving 0.25% P from MDCP and 0.20% P from DCP (Fig. 1d).

3.2. Manure P fractions

Determined using samples of manure excreted when the highest amount of supplemental P was fed in each experiment, MDCP, compared to DCP, decreased H_2O–P and $NaHCO_3$–P concentrations by up to 25.8, 12.6, 12.0, and 23.3% for pigs, broilers, ducks, and layers, respectively (Fig. 2). In the meantime, the concentrations for HCl–P and NaOH–P increased for MDCP. Among these fractions, H_2O–P had the highest concentration for both DCP and MDCP, followed by NaOH–P or HCl–P for broilers, ducks, and layers receiving DCP (Fig. 2). The concentration of RP was not affected by the source of supplemental P. Supplemental MDCP also reduced excretion of H_2O–P and $NaHCO_3$–P for broilers, ducks, and layers (Fig. S2).

3.3. Proportion of total P as H_2O–P and $NaHCO_3$–P

Water soluble P accounted for 56.0–64.9%, and $NaHCO_3$–P 15.1–28.2%, of TP in pig manure (Figs. 3a and 4a). The proportion of TP accounted for by H_2O–P and $NaHCO_3$–P was larger for DCP than for MDCP, by 13.7 and 38.2% on average respectively. The amount of P supplemented affected the proportions slightly.

Water soluble P accounted for 16.4–30.5% of TP for broilers, 14.5–37.8% for ducks, and 27.7–44.4% for layers, depending on the source and amount of supplemental P (Fig. 3b, c, d). Similar to pigs, the proportions of TP as H_2O–P and $NaHCO_3$–P were lower for MDCP than DCP for these birds. The difference for H_2O–P was 12.8% for broilers, 12.5% for ducks, and 15.1% for layers. The difference for $NaHCO_3$–P was even bigger, 28.2, 16.5 and 9.9% for broilers, ducks, and layers, respectively. Similarly, the amount of supplemental P did not affect the proportions.

3.4. Proportion of total P as NaOH–P, HCl–P, and residue-P

The NaOH–P fraction accounted for 7.2–15.1, 20.0–40.9, 23.8–34.8, and 12.9–31.5% of TP for pigs, broilers, ducks, and layers, respectively (Fig. 5). Using MDCP as the supplemental source increased the proportion of TP as NaOH–P in all trials except the one that used broilers, compared to DCP. The effect of the supplemental amount varied among different animals. The highest percentage of TP accounted for by NaOH–P was observed at the highest supplementation for pigs and layers, but at the lowest supplementation for broilers.

The fraction of HCl–P accounted for 4.2–10.9, 18.4–34.5, 23.7–36.3, and 25.6–35.8% of TP for pigs, broilers, ducks, and layers, respectively (Fig. 6). Supplementation of P at 0.20, 0.25, 0.05, and 0.05% resulted in the largest percentages of HCl–P for pigs, broilers, ducks, and layers, respectively. Similar to NaOH–P, the

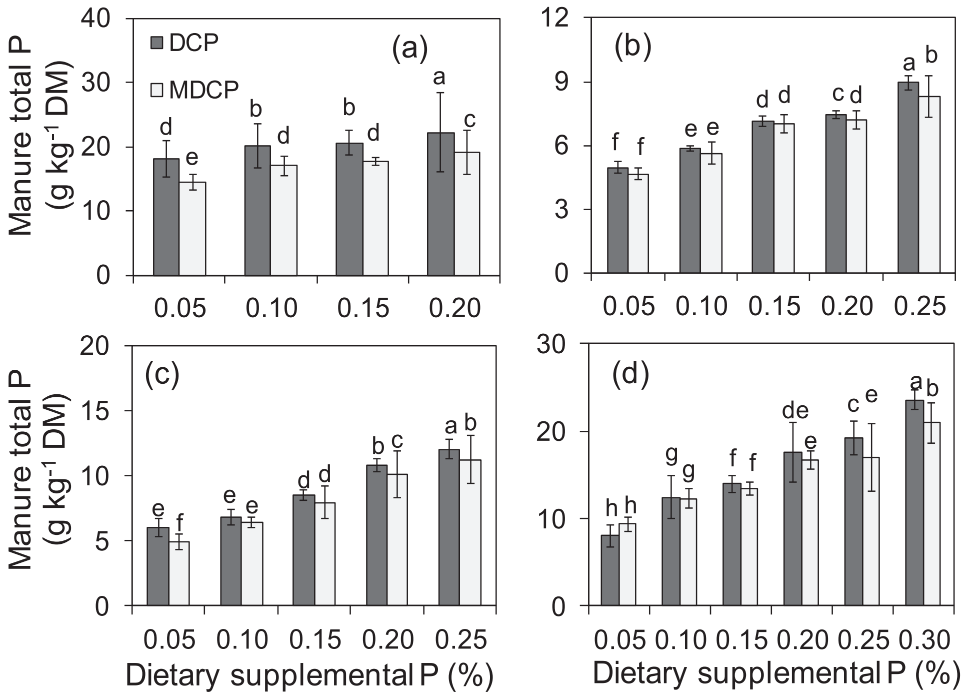

Fig. 1. Concentration of total P in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets supplemented with different amounts of P using dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Concentrations shown in bars topped with different letters differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

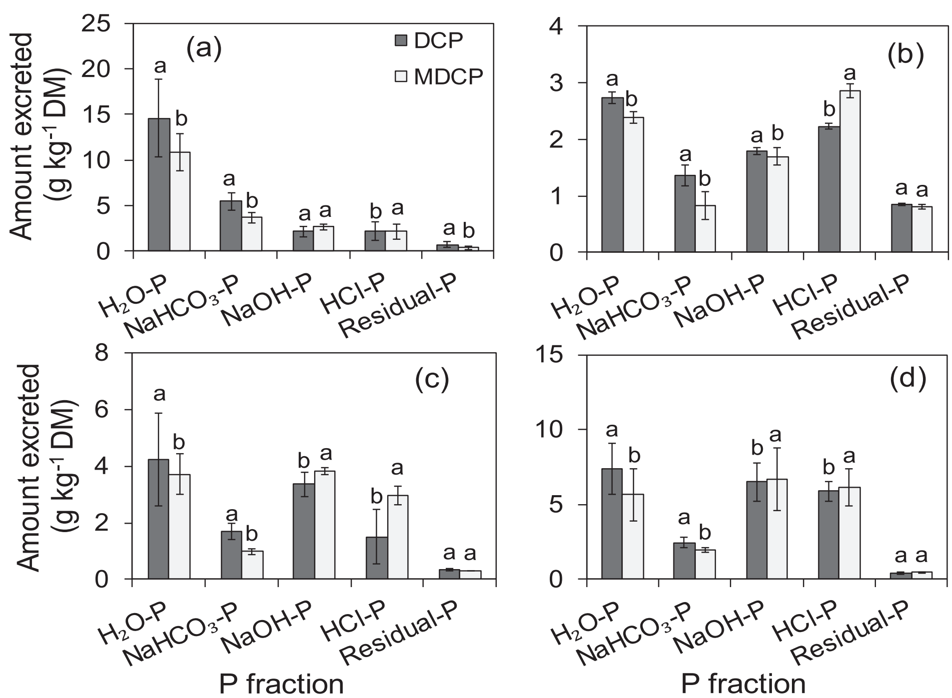

Fig. 2. Manure P extracted sequentially by water (H_2O−P), 0.5 M sodium bicarbonate ($NaHCO_3$−P), 0.1 M sodium hydroxide (NaOH−P), and 1.0 M hydrochloric acid (HCl−P), and extraction residue P (RP) in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets containing the highest amount of supplemental P (0.20, 0.25, 0.25, and 0.30% for pigs, broilers, ducks, and layers, respectively) used in the experiments from dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Concentrations shown in bars topped with different letters within a fraction differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

proportion of TP accounted for by HCl−P was increased by MDCP.

Only a small proportion of P was extracted by H_2SO_4−H_2O_2 (Fig. 7). The residue-P varied with the source and amount of supplemental P, with the largest percentages found with 0.05% supplementation for poultry. However, the source of supplemental P did not affect the proportion of residue-P.

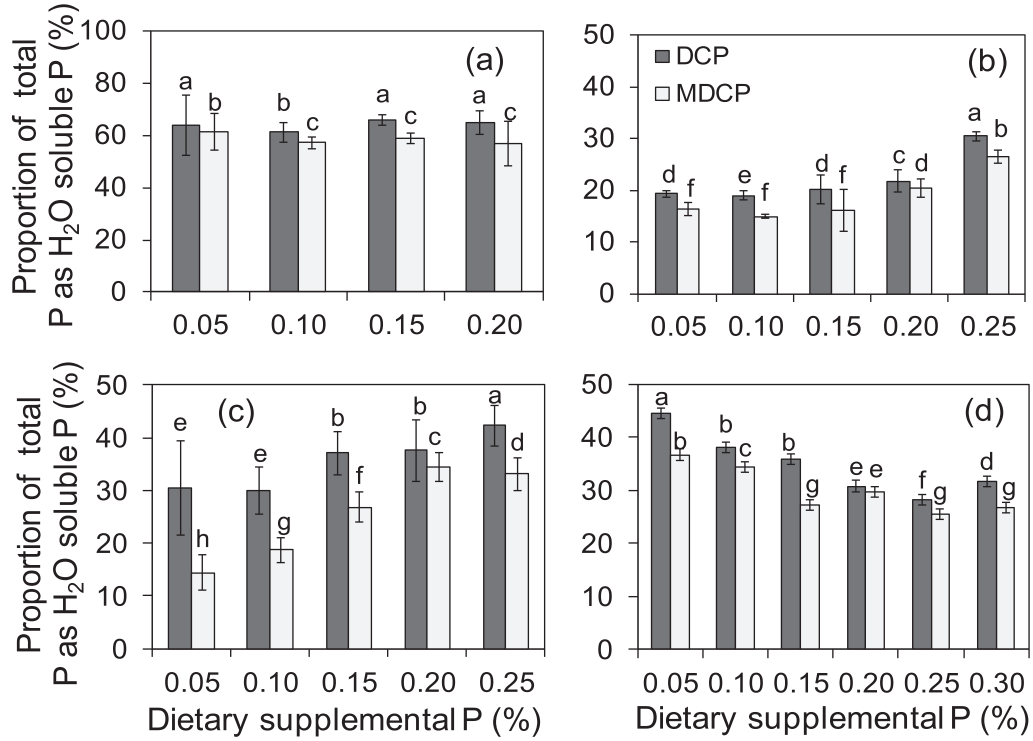

Fig. 3. Proportion of total P as H_2O soluble P in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets supplemented with different amounts of P using dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Proportions shown in bars topped with different letters within a fraction differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

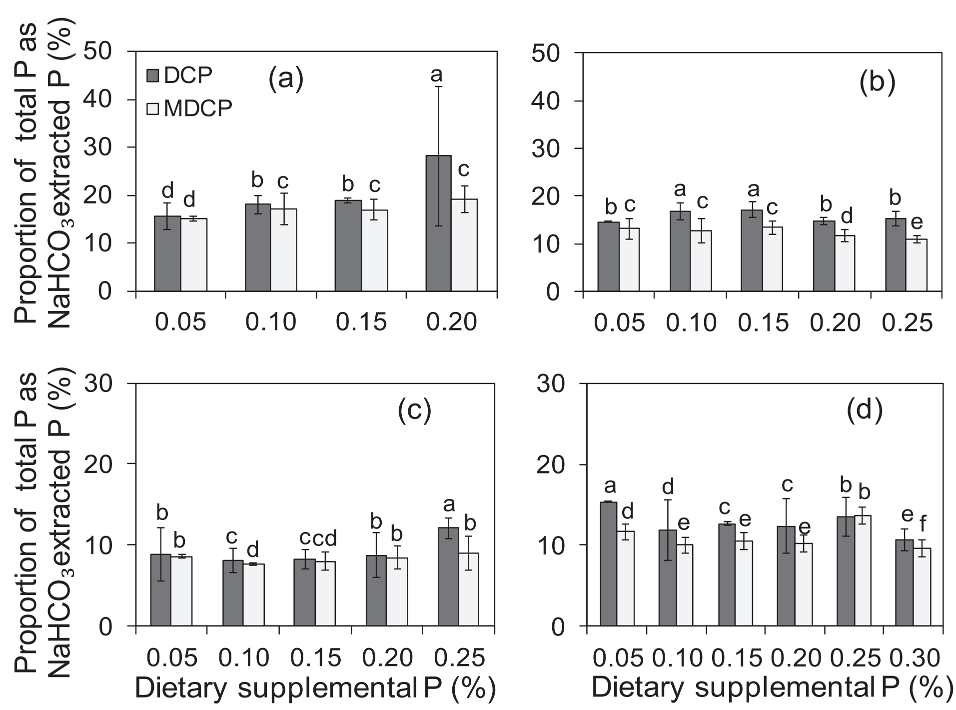

Fig. 4. Proportion of total P dissolved in 0.5 M $NaHCO_3$ in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets supplemented with different amounts of P using dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Proportions shown in bars topped with different letters within a fraction differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

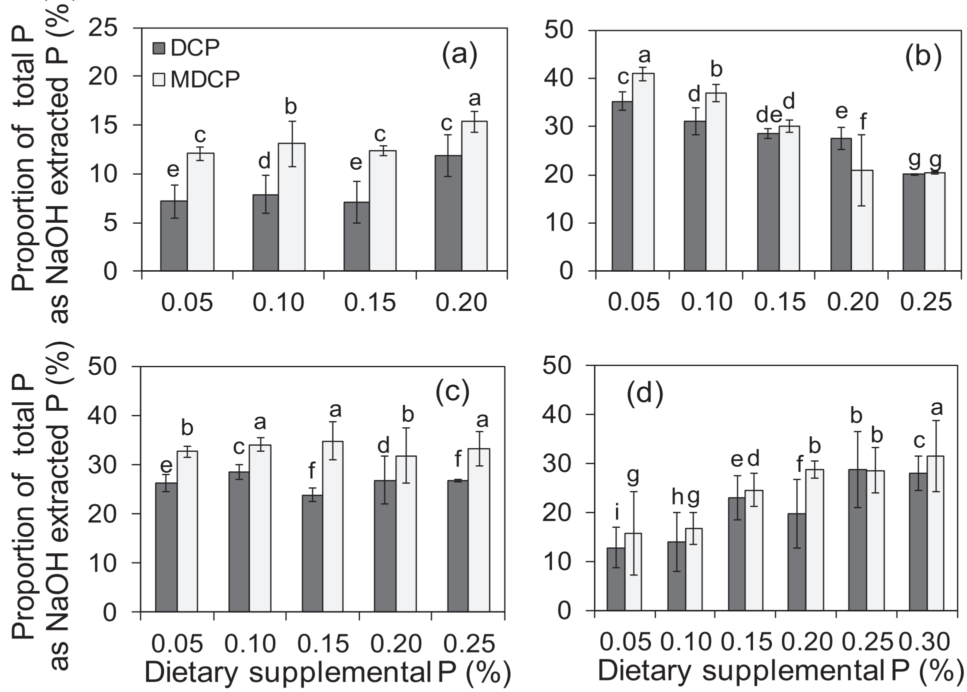

Fig. 5. Proportion of total P dissolved in 0.1 M NaOH in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets supplemented with different amounts of P using dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Proportions shown in bars topped with different letters within a fraction differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

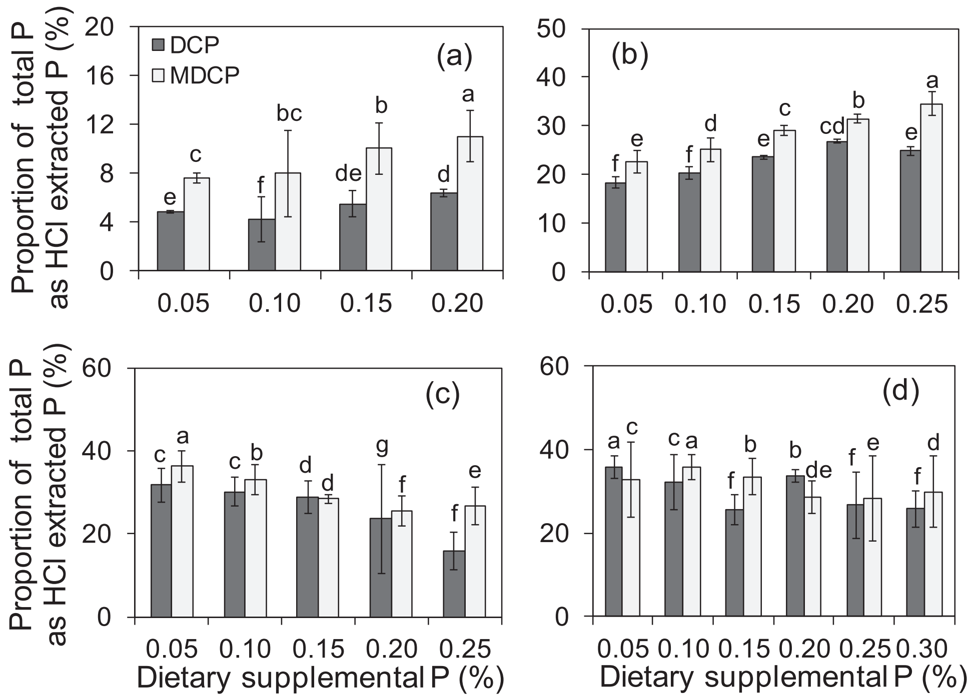

Fig. 6. Proportion of total P dissolved in 1.0 M HCl in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets supplemented with different amounts of P using dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Proportions shown in bars topped with different letters within a fraction differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

3.5. Dissolved P in leachate

The rainfall simulation was conducted to further explore the effect of the source and amount of P supplementation on the loss potential of manure P. The mean concentration of dissolved P in the leachate was 31.3–36.1 mg L^{-1} for pig manure, and 5.8–14.1 mg L^{-1} for poultry manure (Fig. 8). The source and amount of supplemental P significantly influenced manure P leaching. The concentration of

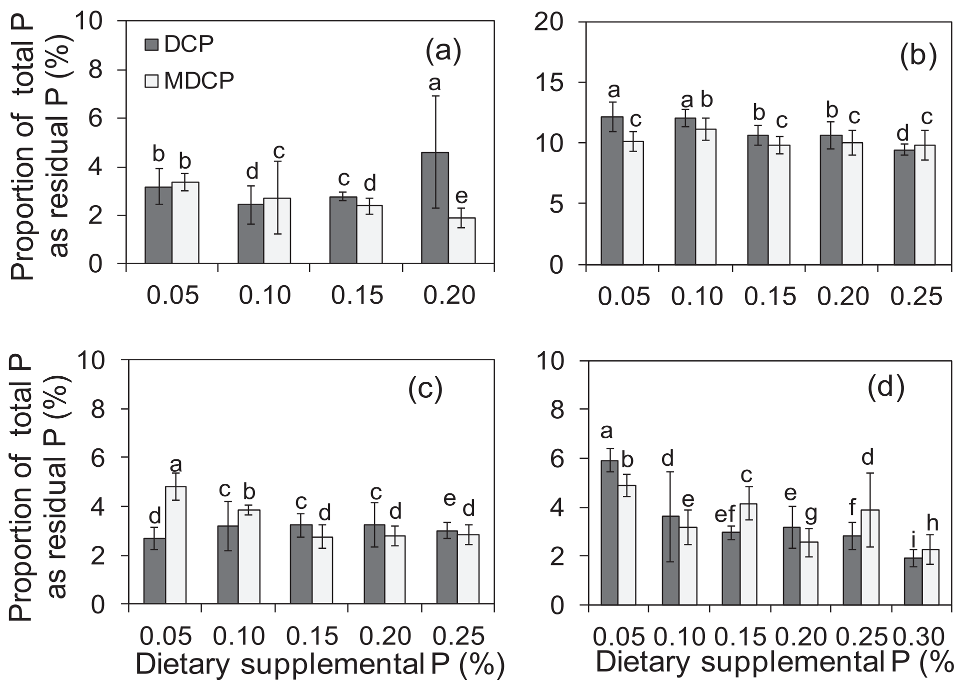

Fig. 7. Proportion of total P as extraction residual P in manure of pigs (a), broilers (b), ducks (c), and layers (d) fed diets supplemented with different amounts of P using dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Proportions shown in bars topped with different letters within a fraction differed at $P < 0.05$. Error bars represent standard error (±) of the mean.

dissolved P in pig manure increased as the amount of supplemental P fed increased. The concentration of dissolved P was lower for MDCP than for DCP, and the reduction was 13.5, 45.0, 25.8, and 47.2% for manure of pigs, broilers, ducks, and layers, respectively.

4. Discussion

It is desirable to minimize P excretion by animals without affecting animal growth. Extensive research has been conducted to study relationships between the source and amount of P fed and P excretion. In the United States, Dou et al. (2000), Petersen and Stein (2006) and Stein et al. (2008) examined changes in P excretion when dicalcium phosphate, monosodium phosphate, or monocalcium phosphate were included in the diet for dairy cows and pigs. However, little has been known for changes in the form of manure P under different feeding conditions, especially when diets are supplemented with inorganic P. This study was designed to examine changes of manure P in the form and amount when swine and poultry diets were supplemented with different amounts of DCP or MDCP that are distinctly different in solubility. The major finding was that substituting MDCP for DCP increased P digestibility (Table S3.), and reduced total P excretion by 15.6, 4.6, 9.1, 11.1%, and soluble P by 25.8, 12.6, 12.0, and 23.3% for pigs, broilers, ducks, and layers, respectively.

4.1. Total and soluble P

While little is known about MDCP, many data on DCP are available in the literature. Manure TP concentrations for pigs receiving DCP ranged from 18.1 to 22.3 g kg^{-1} in the present study, similar to those reported by Song et al. (2008) and Yan et al. (2015) for China. The values were also similar to those reported for the Europe (17.4–31.4 g kg^{-1}) and the United States (17.2–33.6 g kg^{-1}) (Wienhold and Miller, 2004; Angel et al., 2005; Pagliari and Laboski, 2012). The P concentration in swine manure in China has been higher than those observed for some developed countries (Li et al., 2014a; Yan et al., 2015), and the lower values observed in this study apparently resulted from reduced use of P supplements from traditional amounts in China (Guo et al., 2018).

The high solubility of P in MDCP (Table S3) resulted in lower manure TP concentrations than for DCP. In particular, the concentration for MDCP was 4.9–11.3 g kg^{-1} for laying hens, compared to 6.0–13.6 g kg^{-1} for DCP. The latter was more similar to values of 8.5–28.7 g kg^{-1} reported for the United States (Dou et al., 2000; Plumstead et al., 2007). Similar comparisons can also be made for broilers, pigs, and ducks.

Determined using samples of excreta of animals or birds receiving the highest supplemental P amounts used in the feeding trials, manure H_2O–P concentrations for pigs and ducks supplemented with DCP were similar to those observed in some earlier studies (Baxter et al., 2003; Wienhold and Miller, 2004), but higher than those reported by others (Li et al., 2014a; Wu et al., 2015). The concentrations of manure H_2O–P for broilers and layers were similar to those reported by Dou et al. (2000), Li et al. (2014a) and Yan et al. (2015). Manure was collected as excreted in our study that would minimize H_2O–P losses, whereas samples were obtained from storage tanks in some of the other studies, contributing to some of the differences. Animal growth stages and dietary composition and P content may have also contributed to study variations. Yan et al. (2015) reported that manure P increased as ducks became more mature. Lower concentrations for MDCP than DCP suggested that more P was absorbed from MDCP as a result of its high solubility.

4.2. MDCP versus DCP

The MDCP reduced TP, H_2O–P, and $NaHCO_3$–P, but increased NaOH–P and HCl–P in manure of pigs, broilers, ducks, and layers,

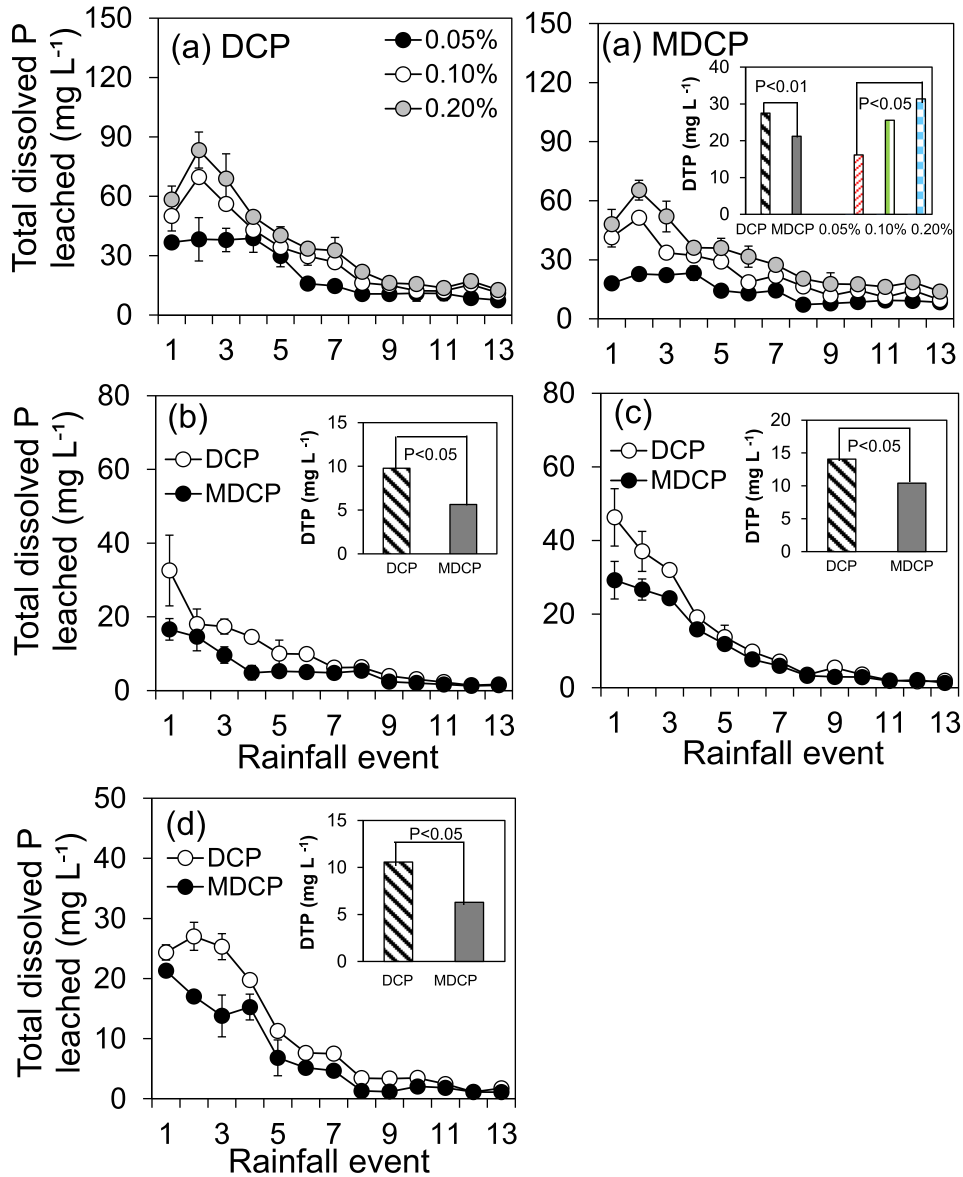

Fig. 8. Leaching of dissolved P (DTP) during consecutive rainfall events from manure of pigs (a) fed diets containing 0.05, 0.10, or 0.20% supplemental P, and from manure of broilers (b), ducks (c), and layers (d) fed diets containing the highest amount of supplemental P (0.25, 0.25, and 0.30% for broilers, ducks, and layers, respectively) used in feeding trials. The supplemental P was provided from dicalcium phosphate (DCP) or mono-dicalcium phosphates (MDCP). Error bars represent standard error (±) of the mean.

as compared to DCP, a reflection of changed digestibility (Table S3). In addition to solubility (17.5% vs. < 1%), a known factor that affects phosphate availability in the digestive tract of animals or poultry (NRC, 2001), Khattak et al. (2016) suggested that manufacturing conditions employed in the production of DCP and MDCP can lead to subtle changes in product chemical and physical properties that could affect P absorption. Tu and Huo (1997) and Zhang (2008) reported that optimized Ca to P ratios increased P digestibility, and Almeida and Stein (2012) and Rojas and Stein (2012) showed lowered Ca to digestible P ratios associated with increased P availabilities in swine. The specialty MDCP product used in this project has a Ca to P ratio (1.3:1) that is closer to animals' requirement (1.5–2.0:1) than the ratio (0.7:1) for DCP (Table 1), and showed higher absorption of P (Table S3) that consequently resulted in reduced Ca to digestible P ratios (Table S2). The product also has a lower pH (3.5–4.5 vs. 7.5–8.0) or acid binding capacity (20 vs. 546) than DCP (Table 1), and would release H^+ in the small intestine where pH is typically 7–8, an activity that would facilitate P absorption (Li et al., 2014b). Moreover, the product contains a larger proportion of α-calcium phosphate (Tu and Huo, 1997) and less heavy metals (Pb, As, Hg, Cd, F) (Table 1) than DCP, properties that would contribute to low excretion of TP, H_2O–P, and $NaHCO_3$–P (Casartelli et al., 2005; Leytem and Thacker, 2008; Westendorf and Williams, 2015). These observations suggest that the MDCP product used in this study may have structural or chemical advantages that facilitate the absorption of P, especially H_2O–P and $NaHCO_3$–P. As excretion of H_2O–P and $NaHCO_3$–P decreased, the proportion of NaOH–P and HCl–P in manure would increase. Finally, Leytem et al. (2004) suggested that there might be transformation of stable P to water soluble P taking place in the hindgut of animals fed DCP. In any event, reduced H_2O–P and $NaHCO_3$–P and increased NaOH–P and HCl–P indicated that manure P was reduced in mobility when animals and chickens were fed MDCP rather than DCP.

Reduced dissolved P in manure for MDCP compared to DCP observed in the leaching studies (Fig. 2) confirmed the observation that MDCP reduced the mobility of P in manure based on analysis of forms. Baxter et al. (2003), Smith et al. (2004), McGrath et al. (2005), and Jokela et al. (2012) suggested that manure P leaching could be controlled by careful selection of supplemental P sources to be used in diets. Results suggested that the MDCP product used in this study is more environmentally friendly than DCP as a dietary supplement.

4.3. Implications for managing P for animals

Over-supplementation of P is a common practice in swine and poultry production in China. Reducing supplemental P for pigs, broilers, ducks, and layers reduced P excretion in this study, consistent with other studies (Penn et al., 2004; Smith et al., 2004; McGrath et al., 2005; Toor and Sims, 2016). However, the current study showed that reducing the supplemental amount to 0.05% resulted in animal deaths and reduced growth or production (Table S3). Clearly, P supplementation needs to be limited, but is still necessary.

Using high water soluble P supplements such as MDCP rather than traditional supplements for animals can reduce manure TP content and P loss potential. It has been estimated that such a replacement can reduce TP and H_2O-P excretion by up to 32% for pigs and 57% for broilers. The feeding trials in this project showed that P digestibility and feed efficiency increased when MDCP was used as compared to DCP (Table S3). As efficiencies increase, less supplementation would be needed to meet animal's requirements for absorbable P. Guo (2017) estimated that 18–30% of phosphate rock could be saved if MDCP replaced DCP for swine and poultry in China.

5. Conclusions

The use of P in animal diets needs to be minimized to control loss of P to the environment. However, animal diets are often over-supplemented with low bioavailability P sources in China. This study showed that reducing supplemental P for pigs, broilers, ducks, and layers to amounts that did not affect production and using a specialty MDCP product rather than DCP as the supplemental source reduced total P excretion and the proportion of environmentally labile fractions of manure P.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117654.

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