

Full Length Research Paper

# The result of water-dispersible colloids in manure on the transfer of dissolved and colloidal phosphorus by the medium of a soil column

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To investigate the effect of water-dispersible colloids derived from swine manure on the potential risks of phosphorus (P), migration behavior of P in saturated-flow columns was compared in the presence and absence of water-dispersible colloids of manure in influent. It was found that dissolved phosphorus (DP) accounted for a majority of total P (65-98%) in the effluent with deionized water treatments, while contributed between 21 and 45% to total P leaching with the manure colloid treatments. In manured soils, with the inflow of manure colloidal suspension, colloidal P in the effluent were 26.7 times higher than that of deionized water treatment ( $P_{M+W}$ ) and 1.9 times more than that of unamended soil treated with manure colloid ( $P_{0+M}$ ) in the end of the leaching experiment. Despite the initial reduction of DP concentrations in the effluent with the presence of manure colloid, the DP concentrations still increased smoothly and continued to transport with the effluent throughout the breakthrough experiment. This suggested that P sorption sites of the soil and the added manure colloid in the column were fastly saturated during initial stage of the experiment. In manure colloid treatments, higher colloidal P concentrations in leachate were related to larger P contents of leached colloids, which were in sorption equilibrium with larger concentrations of dissolved P. Furthermore, in deionized water treatments, good linear correlation between colloidal P and colloidal Fe indicated that Fe hydroxides could be served as a main medium for the transportation of colloidal P.

**Key words:** Dissolved P, colloidal P, water-dispersible colloids, manure, degree of phosphorus saturation (DPS).

## INTRODUCTION

Phosphorus (P) is an important element, which has significant impact on the global environment and water quality. It is well accepted that manure application at high rates will elevate P levels in the soil profile, which can result in the increase of colloidal and dissolved P in surface water and ground water (Zhang et al., 2003; Lehmann et al., 2005; Dunne et al., 2006; Koopmans et al., 2007; Li et al., 2010). Animal wastes could offer a cheap alternative source of soil fertility (Mubarak et al., 2009). Large amount of manure, wash water, and storm water runoff were produced by concentrated animal

feeding operations (CAFOs). As manure was dissolved in water, microorganisms and other nutrients would be released along with manure colloid, which is composed of a complex mixture of partially digested organic matter and microbial biomass (Bradford et al., 2006). They reported that higher effluent concentrations of *Giardia* (one type of pathogenic protozoan parasite) was facilitated in soil column experiments due to the filling of straining sites by manure colloidal suspension. Recently, the complex interactions between manure colloidal suspension and specific microorganisms have been widely studied during surface and subsurface transportation (Andrey et al., 2007). However, till date, there are few reports on the investigation of P transportation in soil triggered by water-dispersible colloids derived from manure. Furthermore, it is noted that water-dispersible

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**Table 1.** Selected chemical properties of the soil in P<sub>0</sub> and P<sub>M</sub> soil.

Properties	P <sub>M</sub> soil	P <sub>0</sub> soil
pH	7.32±0.05	7.15±0.03
Bulk density, g cm <sup>-3</sup>	1.52±0.02	1.56±0.04
Organic carbon, g kg <sup>-1</sup>	25.57±0.22	21.09±0.17
TP, mg kg <sup>-1</sup>	1726.45±7.65	933.32±55.93
Olsen P, mg kg <sup>-1</sup>	127.75±5.35	47.03±2.80
Fe <sub>ox</sub> <sup>a)</sup> , g kg <sup>-1</sup>	5.81±0.25	6.61±0.34
Al <sub>ox</sub> <sup>a)</sup> , g kg <sup>-1</sup>	1.20±0.14	1.27±0.08
P <sub>ox</sub> <sup>a)</sup> , mg kg <sup>-1</sup>	895.99±9.52	518.86±5.73
Degree of phosphorus saturation(DPS) <sup>b)</sup> , %	39.01±0.56	20.28±0.39

a) Acid ammonium oxalate-extractable P, Fe, and Al (mg kg<sup>-1</sup>). b) Expressed as a %.

colloids of manure not only contained different sizes of colloids, but also carry much more P compared to water-dispersible soil colloid, which will greatly affect the transportation of P.

So far, it remains a great challenge to determine whether particulate P (colloidal P) constitutes the majority of P in leaching waters (de Jonge et al., 2004; Motoshita et al., 2003; Heathwaite et al., 2005). Recently, Siemens et al. (2008) reported that accumulation of P in soils increased the risk of colloid-facilitated leaching of P when large volumes of electrolyte passed through the soil matrix, especially when the total concentration of electrolyte was low and the addition of P exceeded the soil's sorption capacity (Siemens et al., 2004; Ilg et al., 2008). In recent years, the deionized water and artificial water were widely used as the inflow in the column experiments (Ilg et al., 2008; Makris et al., 2006). And the results indicated that suspended colloids acted as carriers in soil whatever manure colloid and soil colloid has been considered (Laubel et al., 1999; McCarthy and McKay, 2004). Makris et al. (2006) suggested that water-dispersible soil colloid were important carriers for P via subsurface water flow, such as molybdate-reactive phosphorus (molybdate-reactive phosphorous was part of dissolved P) in long-term manure application field. It is noted that leaching of dissolved P was an unnegligible long-term environmental problem in areas with excessive manure application.

Furthermore, it is reported that the transportation of colloidal P were found to be strongly affected by many factors, such as ionic strength, pH, and water flow dynamics (DeNovio et al., 2004; de Jonge et al., 2004; Simard et al., 2000). The amorphous iron (Fe) and aluminum (Al) in the water-dispersible colloid fraction of a soil have significant effect on the transportation of P (Seta and Karathanasis, 1996; Haygarth et al., 1997; Hens and Merckx, 2001; Siemens et al., 2004). Therefore, it is highly desired to know more about water-dispersible colloids of manure effects on the transportation of P and the factors mentioned earlier.

We hypothesized that: 1) water-dispersible colloids in

manure facilitated and enhanced vertical P movement through soil; 2) high DPS not only causes high concentration of dissolved P, but also enhances the release and leaching of colloidal P. To test these hypotheses, migration behavior with or without inflow of manure colloidal suspension was compared in saturated-flow columns packed with aggregate-sand mixture materials. Furthermore, the possible mechanism of dissolved P and colloidal P transportation was proposed.

## MATERIALS AND METHODS

### Soil preparation

Two geologically similar soils were used in this study. Both soils were sampled (0-15 cm depth) from Jiaxing (JX) Agricultural Research Station (120° 40' E, 30° 50' N) in the southeast part of the TaiHu region of China in May 2007. The JX soil was a gleyed paddy soil (clay loam, mixed, mesic Mollic Endoaquepts), having high clay content (38.8%). In this Agricultural Research Station, field experiments were performed during two rotations of rice (*Triticum aestivum* L.)–rapeseed (*Brassica napus* L.) growth since May 2005. The applications were performed twice each year (applied for rice and rapeseed, respectively). The manure were broadcast and incorporated into the topsoil to a depth of 50 mm. Manured soil (P<sub>M</sub>) in this study was sampled from the plot that applied swine manure (application rates is 210 kg ha<sup>-1</sup> per year). Unamended soil (P<sub>0</sub>) was sampled from the plot without application of manure. The application rates in the history were calculated according to Total P. Furthermore, all of the plots were planted with vegetable for 5 years before rice-rapeseed rotation cultivation. Therefore, the concentration of P in both of the sampled soils was relatively high before this study (Table 1). Both soils were air-dried and passed through a 2-mm sieve. The basic soil properties are shown in Table 1.

### Water-dispersible colloids of manure preparation

Swine manure was collected from Jiaxing (JX) Shuangqiao farm. Samples were placed in sealable plastic bags and stored under refrigeration at 4°C with 80-90% RH. Water-dispersible colloids were fractionated from bulk samples of swine manure which was added into deionized water to obtain water-manure suspension of 12.5 g L<sup>-1</sup> in plastic centrifuge bottles. The slurry was mixed using a reciprocating shaker for 16 h at 100 rpm and centrifuged at 5000

**Table 2.** The properties of suspension of water-dispersible colloids of manure.

Properties	Manure colloid
pH	7.74±0.02
Electrical conductivity, mS cm <sup>-1</sup>	0.524±0.15
Optical density	0.249±0.12
Average size, nm	325±36
Zeta potential, mV	-25.1±0.3
Total P, mg L <sup>-1</sup>	6.282±0.13
Total dissolve P (mg L <sup>-1</sup> )	3.639±0.09
Colloidal P (mg L <sup>-1</sup> )	2.643±0.22
Total Fe (mg L <sup>-1</sup> )	0.195±0.006
Total dissolve Fe (mg L <sup>-1</sup> )	0.155±0.004
Colloidal Fe (mg L <sup>-1</sup> )	0.040±0.01

rpm for 8 min (Biofuge Stratos, Heraeus Instr., UK). After that, the colloid particles <1 µm remaining in suspension were decanted and saved as a stock solution. The analysis methods were introduced in the part of Chemical methods. The properties of suspension of water-dispersible colloids of manure were shown in Table 2.

### Column transport experimental design

Four soil column treatments in this study were designed as follows: manured soil treated with manure colloidal suspension (P<sub>M</sub>+M), unamended soil treated with manure colloidal suspension (P<sub>0</sub>+M), manured soil treated with deionized water (P<sub>M</sub>+W) and unamended soil treated with deionized water (P<sub>0</sub>+W).

The soil columns were prepared similar to the technique of the mixture soil system as described by Stutter et al. (2007). According to Stutter et al. (2007), the aggregate-sand mixture do not only enhance flow velocities and dispersive flow around soil aggregates, which could maximize the interaction between macro- and micropore flow regions, but also maintain flow over extended periods without the risk of blockages often associated with experimentally induced flow through intact soil. Therefore, the aggregate-sand mixture system provided a greater saturated hydraulic conductivity than intact soil column. Briefly, acid-washed quartz sand (35 g, 0.30-0.71 mm diameter) and two air-dried aggregate soils (35 g) mentioned previously were mixed gently and thoroughly, respectively, and then packed this mixture into glass chromatography columns with overall dimensions of 15 cm length and 2.6 cm inner diameter. Columns were packed with aggregate-sand mixture to eliminate the structural heterogeneities of intact soil. This design provide a greater saturated hydraulic conductivity than an equivalent column depth of intact soil in order to enhance flow velocities and dispersive flow around the clay soil aggregates, thereby it could maximize the interaction between macro- and micropore flow regions. Columns containing soil aggregates (embedded within a sand matrix) provided an experimental system in which both convective and diffusive processes contributed to phosphorus leaching. To avoid any possible contamination from the preceding experiment, a new column containing fresh aggregate-sand mixture was used for each experiment. The experiments were repeated twice in their entirety for reproducibility.

During the experiment, the soil columns were set up vertically, dry-packed homogeneously, and separately filled with the differently treated soils. The packed aggregate-sand mixture was tapped to settle an approximate depth of 15 cm, then gently compressed with the upper flow adaptor as the columns were sealed. The columns were oriented vertically and saturated from the bottom at a flow rate

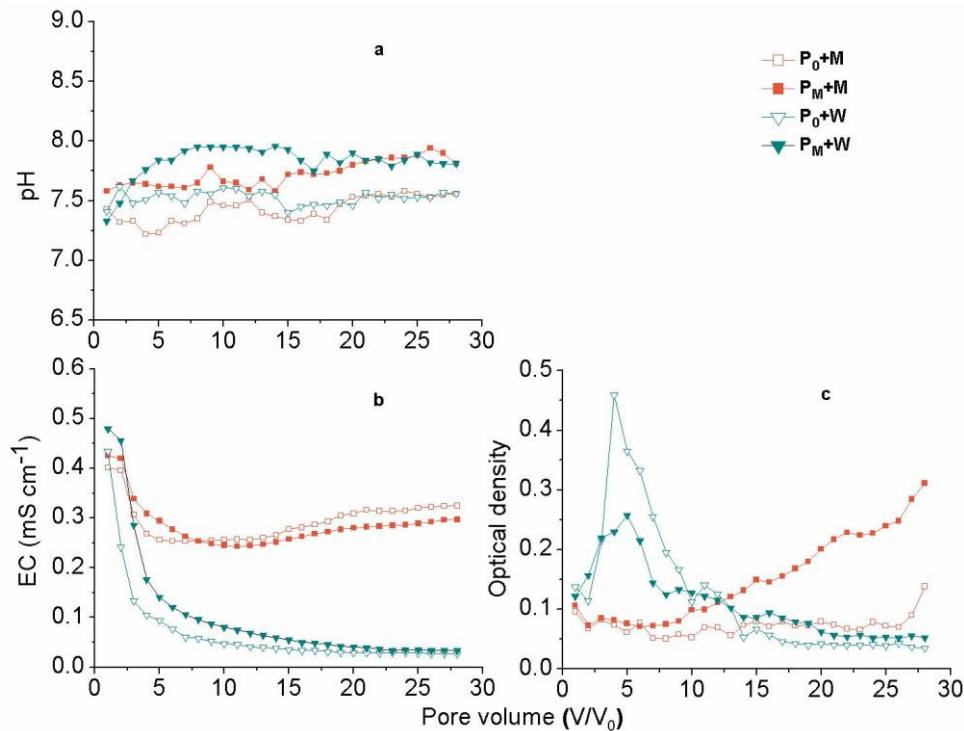
of 30 cm<sup>3</sup> h<sup>-1</sup> with 1 pore volume (PV, 1 pore volume ≈ 30 ml) of deionized water to remove air pockets followed by stabilization for 24 h before leaching experiment. Once the columns were saturated from the bottom, the following leaching sequence was applied with manure colloid suspension and deionized water (downward). Then, continuous solute flows (manure colloid suspension and deionized water, respectively) were injected at the column entrance at a steady-rate of 0.5 ml min<sup>-1</sup> (30 cm<sup>3</sup> h<sup>-1</sup>). Effluent samples were collected in glass test tubes using an autosampler at intervals of 1 pore volume, and a subsample was immediately filtered (< 0.1 µm) and stored at 4°C in the dark along with unfiltered samples. The analytical procedures were outlined below.

### Chemical methods

Total P and Olsen P of soil samples were determined according to Hooda et al. (2001) and Olsen et al. (1982), respectively. Total Al, Fe, and P in the acid ammonium oxalate extracts (Zhang et al., 2005) were analyzed by inductively coupled plasma spectrometry, and the percent degree of phosphorus saturation (DPS) was calculated as (m mol kg<sup>-1</sup> P/0.5[m mol kg<sup>-1</sup> Al + Fe]) using the method of McDowell et al. (2001).

In the laboratory, the effluent samples were first analyzed for optical density, pH, and EC. The optical density of the suspension of the effluent samples was measured at 540 nm using a Unico UV-2000 spectrophotometer (United Products and Instruments, Dayton, USA). The pH and the electrical conductivity (EC) of water suspension were determined according to Lu (1999). Particle-size distribution information and Zeta potential for water-dispersible soil colloid of soils in the column was determined using ZetaSizer Nano ZS90 (Malvern Instrument, Worcs, UK). Further, the unfiltered samples and filtered sample (< 0.1 µm) were analyzed colorimetrically (Murphy et al., 1962) after a Kjeldahl digestion (Taylor, 2000) before analyzing for total P (TP) and dissolved P (DP). And then, fractions defined as colloidal P were calculated as the difference of TP and DP. Both of Total Fe and dissolved Fe in the unfiltered samples and filtered samples (< 0.1 µm) were analyzed. They were measured with atomic absorption spectroscopy equipped with a graphite furnace attachment (GFAAS) after acidification of the effluent. And then, colloidal Fe was calculated as the difference between total Fe and dissolved Fe (filtered 0.1 µm) (Lienemann et al., 1999).

Differences within one soil between the two treatments (manure colloid and water) and differences within one treatment between manured and unamended soil were tested using an independent samples t-test at the 95% significance level ( $P = 0.05$ ). All statistical



**Figure 1.** Dynamics of pH, EC and optical density of effluent in different treatments.

**Table 3.** Significance (*P* values) of differences between deionized water and manure colloid and between  $P_M$  soil column and  $P_0$  soil column.

Measured variable	Deionized water - manure colloid		$P_M$ soil - $P_0$ soil	
	$P_M$ soil	$P_0$ soil	Deionized water	Manure colloid
pH	0.913 <sup>a</sup>	<0.001 * <sup>b</sup>	0.047 <sup>c</sup>	0.877
Electrical conductivity	0.011*	0.219	0.218	0.670
Optical density	0.129	<0.001 *	0.016*	**
TP	0.857	<0.001 *	**	0.438
DP	0.015 *	<0.001 *	**	0.683
Colloidal P	<0.001 *	<0.001 *	**	0.091
Total Fe	<0.001 *	<0.001 *	0.223	0.036 *
Dissolved Fe	0.024 *	0.004 *	0.026 *	0.442
Colloidal Fe	<0.001 *	<0.001 *	0.318	0.064

<sup>a</sup>Differences within one soil between the two treatments (manure colloid and water) were tested using an independent samples t-test at the 95% significance level ( $P = 0.05$ ); \* significant values at  $P < 0.05$ ; <sup>c</sup>differences within one treatment between  $P_M$  and  $P_0$  soils were tested using an independent samples t-test at the 95% significance level ( $P = 0.05$ ).

analyses were performed with a SPSS version 17.0 software program at  $P < 0.05$  (\*).

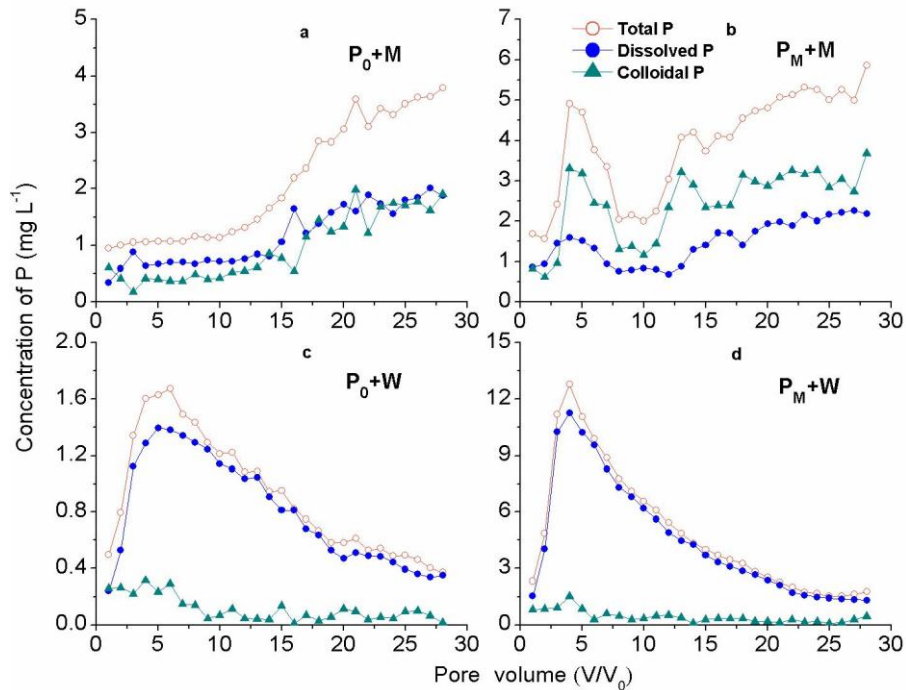
## RESULTS AND DISCUSSION

### The properties of the effluent and soil

The pH values of the effluents for all treatments were found to be in the range from 7 to 8 during the leaching experiments (Figure 1a). The pH values of leachates from

both of  $P_M$  ( $7.7 \pm 0.2$ ) treatments were higher than that of the  $P_0+W$  ( $7.5 \pm 0.1$ ) treatment ( $P < 0.05$ ), but not significant higher than  $P_M+W$  treatment, which indicated that the little increasing pH were related to the addition of colloid and the higher pH of the  $P_M$  soil itself (Table 3).

The values of EC in the effluents, which were the indicator of ionic strength, were analyzed in this study (Simón et al., 1999). The EC values decreased sharply with leaching in both  $P_M$  and  $P_0$  treatments throughout the experiment in water treatments (Figure 1b). In contrast,



**Figure 2.** Breakthrough curves for total P, dissolved P and colloidal P transport in different treatments.

both of the degressive EC values in colloid treatments ( $P_M+M$ ,  $P_0+M$ ) began to increase gradually after 10 pore volumes. The elevated EC values with colloid treatments were probably caused by the continuous addition of manure colloid, which was in the range from 0.2 to 0.5  $\text{mS cm}^{-1}$  in the effluent. Their following raise of P and Fe in turn was more clearly associated with increasing ionic strength of the effluent (Figures 2b and 3b). Accordingly, before the starting of leaching experiments, the values of EC of water-dispersible soil colloid of  $P_M$ -sand and  $P_0$ -sand mixture soils were 0.148 and 0.123  $\text{mS cm}^{-1}$ , respectively (data not shown in tables). After the transport experiment, in the  $P_M+M$  treatment, the EC of the water-dispersible soil colloid of topsoil from the column decreased to 0.0853  $\text{mS cm}^{-1}$  and the subsurface soil decreased to 0.0735  $\text{mS cm}^{-1}$ . In the  $P_0+M$  treatment, EC of topsoil and subsurface soil decreased to 0.0647 and 0.0635  $\text{mS cm}^{-1}$ , respectively. These observations indicated that ionic strength of the soil colloid reduced accordingly corresponding to concentration of exchangeable ions from soil colloid, which was transported vertically to the effluent.

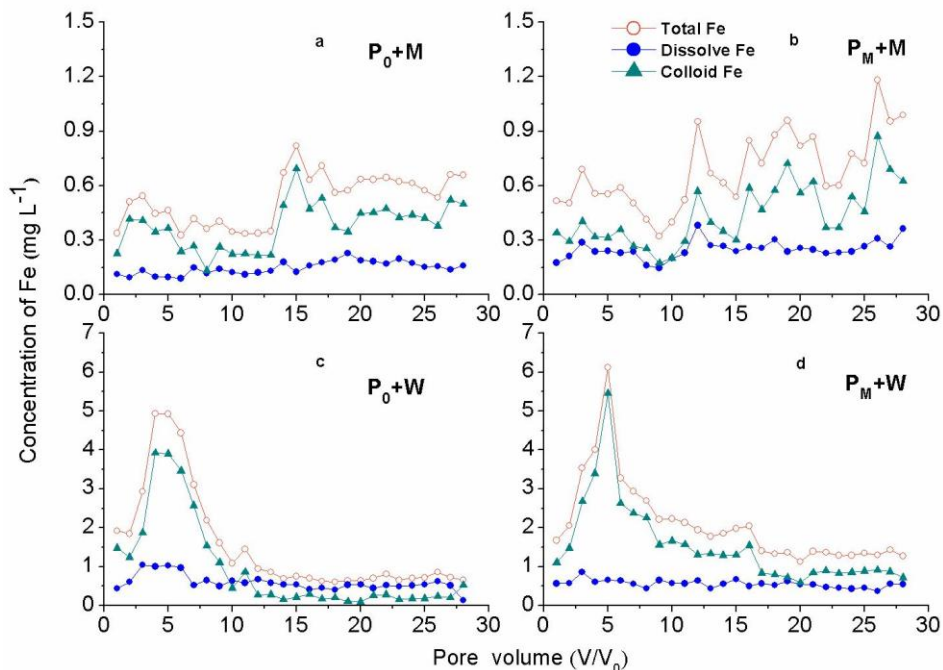
The dynamics of optical density (colloid concentration) and EC of the effluent for the four treatments are shown in Figure 1c. The optical density of the effluents from both of  $P_M+W$  and  $P_0+W$  treatments were characterized by increasing concentrations until the peak at the 4<sup>th</sup> PV, after which optical density were declined smoothly. Contrast to the water treatments, the variation of colloid concentration in  $P_0+M$  treatment was relatively low, while

colloid concentration in  $P_M+M$  ascended slowly. The size of the particles in the effluent of  $P_M+M$  treatment was estimated to 300-500 nm (data not shown in tables), which is closed to the size of manure colloid. However, most of colloidal P in the effluent with the water treatments mainly exists as small particle size less than 100 nm. This finding also confirmed that manure colloid was transported with the effluent.

The average zeta potential of water-dispersible soil colloid in  $P_M$  soil with manure colloid treatment decreased from -26.3 to -30.3 mV before and after the leaching experiment, respectively. An increasing risk of colloid mobilization and transport has been assumed to trigger the release of P-containing Fe oxides from negatively charged quartz sand matrices when zeta potential value below -20 mV was measured in the supernatant (Siemens et al., 2008; Ilg et al., 2008).

### Leaching of colloidal P with the effluent

Figure 2 showed the breakthrough curves of DP, colloidal P, and total P in effluent of four different treatments. The total amounts of colloidal P in effluent were as follows:  $P_M+M > P_0+M > P_M+W > P_0+W$ . In the  $P_M+M$  treatment, colloidal P concentration was significantly increased with the increasing pore volumes when manure colloids were introduced into the  $P_M$  soil, reaching a highest value of 3.31  $\text{mg L}^{-1}$ , as shown in Figure 2b. And then, there was a sharp decrease until the appearance of a change point



**Figure 3.** Breakthrough curves for transport of Total Fe, Dissolved Fe and Colloidal Fe in different treatments.

at 10<sup>th</sup> pore volume, but still significantly higher than that of P<sub>M</sub>+W treatment, indicating that P was facilitated by manure colloid compared with P<sub>M</sub>+W treatment (Figure 2d, Table 3). More specifically, colloidal P concentrations were initially low (1.17 mg L<sup>-1</sup>) at 10<sup>th</sup> pore volume and gradually increased to 3.68 mg L<sup>-1</sup>. Moreover, colloidal P in the effluent exceeded the colloidal P in manure suspension itself (2.64 mg L<sup>-1</sup>) after 10<sup>th</sup> pore volume, suggesting colloidal P in the effluent was extracted from soil gradually. By the end of the leaching experiment, colloidal P concentrations in the effluent with the P<sub>M</sub>+M treatment were 26.7 times higher than that of the deionized water treatment (P<sub>M</sub>+W) and 1.9 times more than that of the P<sub>0</sub>+M.

With the inflow of deionized water, the increasing concentrations of colloidal P in effluent also reached 1.52 mg L<sup>-1</sup> in P<sub>M</sub>+W and 0.32 mg L<sup>-1</sup> in P<sub>0</sub>+W at 4<sup>th</sup> PV, respectively (Figure 2c, Figure 2d). Then their concentrations gradually tailed off, and reached a lower values less than 0.02 mg L<sup>-1</sup>. The peak effluent colloid concentration right after breakthrough followed by a decrease to a constant low level, also corresponded to previous findings of Jacobsen et al. (1997), Schelde et al. (2002), and de Jonge et al. (2004a).

Contrast to water treatments, colloid concentration in P<sub>M</sub>+M was about 6 times at the 28<sup>th</sup> pore volumes higher than that of P<sub>M</sub>+W treatment, indicating that the inflow of manure colloid could delay the vertical transport of colloid compared to water treatments (Figure 1c). According to

the reports of Schelde et al. (2006), long-term manured soils contained relatively higher ionic strength resident water than unamended soil, which might retain the vertical transport of colloid. Apparently, the breakthrough curves of colloidal P were corresponding to the optical density in all of the treatments. These strong linear correlations between colloidal P and colloid concentrations ( $R^2 > 0.75$ ,  $P < 0.05$ ) indicated that colloids played an important role in P transport in the saturated soil columns.

Concentrations of dissolved Fe, colloidal Fe, and total Fe in effluent were presented in Figure 3. The distribution of colloidal Fe and dissolved Fe were coherent to the change of P in these treatments, and most of the fractions existed as colloidal Fe. More significantly, colloidal P had significant linear correlation with the colloidal Fe ( $R^2 = 0.27$ ,  $P < 0.05$ ). As for the P<sub>0</sub>+M treatment, colloidal P accounted for 25-64% of total P. Especially, most of the ratio could reach as high as 40% after the 10<sup>th</sup> pore volume. In both of P<sub>M</sub>+W and P<sub>0</sub>+W treatments, primary leaching P was DP (more than 65% of total P). However, dominant fraction of Fe existed as colloidal Fe in these two treatments can reach to the peak point 5.45 and 3.93 mg L<sup>-1</sup>, respectively. There was still good linear correlation between colloidal P and colloidal Fe in the P<sub>0</sub>+W treatment ( $R^2 = 0.66$ ,  $P < 0.05$ ) and P<sub>M</sub>+W treatment ( $R^2 = 0.45$ ,  $P < 0.05$ ), respectively. Therefore, it can conclude that Fe hydroxide was the main medium for the transportation of colloidal P with treatments.

### Leaching of dissolved P with the effluent

As shown in Figure 1, although there was still a peak at about the 4<sup>th</sup> pore volume, concentrations of DP in manure colloid treatments were much less than that of the deionized water treatments. Unlike the P<sub>M</sub>+M treatment, DP in the P<sub>0</sub>+M increased slightly during the first 10 pore volumes and no obvious peaks turned up. Subsequently, it climbed smoothly and did not reach a plateau even at the end of the experiment, also indicating non-equilibrium and consecutive DP release from the soil matrix. After then, the DP concentration elevated gradually closed to DP concentration of the manure colloid suspension itself (3.64 mg L<sup>-1</sup>) in both of the P<sub>M</sub> and P<sub>0</sub> soils. It is obvious that the addition of manure colloid prevented part of the mobility of DP in the first 10 pore volumes. However, the inflows of manure colloid were inadequate to retain the release of DP with the increasing pore volumes (Figure 2a and b).

With the increasing pore volumes, the effluent concentrations and particle size distribution with manure colloid treatments also became closer to the influent manure colloid. The independent samples t-test suggested that no differences of the P fractions and Fe fractions were observed between P<sub>M</sub>+M and P<sub>0</sub>+M treatments (Table 3), indicating that manure colloid was a significant P resource in the leachate. In both of P<sub>M</sub>+W and P<sub>0</sub>+W treatments, primary leaching P was the DP (accounted for 65%-98% of total P) in the effluent (Figure 1). And DP increased rapidly within the first 4 pore volumes and then decreased smoothly with further water inflow. The total quantities of DP with P<sub>M</sub>+W treatment were 5.6 times higher than that of P<sub>0</sub>+W treatment, which also indicated that the transported water-soluble components of manure were composed mostly of inorganic P, posing a potential risk to ground water.

According to the results, excessive import of manure colloid facilitated the transportation of both colloidal P and DP from soil columns. One explanation for this phenomenon was the interaction of soil with manure suspension. DP in aqueous mobile phase, which is transported from topsoil to the subsoil along with the introduction of manure colloid, was desorbed from the soil matrix and resorbed to the manure colloid. It was proposed that some component of manure colloid (such as hydroxyapatite) could be major P sorbent that can influence P vertical movement (Makris et al., 2006). This point has been further proved by Burwell et al. (1974) and Sharply et al. (1981). They also draw a conclusion that mobile P could be re-adsorbed by solid material during transport. This suggested that P sorption sites of the soil and the added manure colloid in the column were fastly saturated during initial stage of the experiment with the continuously inflow of manure colloid suspension. Thus, DP was retained in soil column before the saturation of P sorption sites of the manure colloid, and was extracted with effluent slower than in deionized water treatment

during the first 10 pore volumes. As a result, soil columns have been weaker to retain colloidal P than to retain DP as the interaction of soil with manure suspension.

### Relating DPS to dissolved and colloidal P

As a result of long-term application of manure, the DPS (39.1%) of P<sub>M</sub> soil was higher than that of P<sub>0</sub> soil before the starting of the experiment (Table 1). According to the investigations of Nair et al. (2004) and Siemens et al.

(2004), high DPS could be seen as "facilitator" for a potential leaching of P. Between the P<sub>M</sub> and P<sub>0</sub> soil, it is well known that the most obvious different property was DPS, which was an environmental indicator to estimate the P release from soil (Zhang et al., 2005). The DPS value in P<sub>M</sub> soil was significantly higher than the critical value of 25% (van der Zee and de Haan, 1994). Thereafter, dissolved P in the effluent would increase sharply and then transfer downward. Meanwhile, orthophosphate sorption-desorption processes were hypothesized to play an important role in colloid-facilitated transport (Laegdsmand et al., 2004; de Jonge et al., 2004). An increasing P concentration of colloidal particles might be the consequence of increasing dissolved P concentrations and sorption equilibrium with manure application. Therefore, it was obvious that high DPS do not only caused significant high dissolved P loss, but also enhanced the release and leaching of colloid and colloidal P from soils (Figure 1c and d).

### Conclusion

In the present work, migration behavior of P in the presence and absence of water-dispersible colloids of manure in influent was compared in different DPS of soils, which indicated that the water-dispersible manure suspension can facilitate DP and colloidal P leaching. Despite the initial reduction of DP concentrations in the effluent with addition of manure colloid during initial stage of the experiment, the DP levels in the effluent of P<sub>M</sub> soil increased smoothly and continued to transport with the effluent throughout the following experiment due to the fastly saturation of soil column. The good linear correlation between colloidal P and colloidal Fe demonstrated that Fe hydroxides could be served as a main medium for the transportation of colloidal P in all of the treatments. Moreover, the increase in colloidal P concentrations was accompanied by a detectable increase of colloid concentration. These results indicated that P-associated colloids from manure can not only act as a contaminant source of P, but also carriers of P transportation. Furthermore, the results found out that higher concentrations of DP and colloidal P were released from soil with higher DPS.

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