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ORIGINAL RESEARCH

Phosphorus species, fractions, and leaching risk in vermicompost-amended calcareous sandy loam soil

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Abstract

Purpose Organic matter has significant effects on phosphorus (P) retention in soil. Applying vermicompost (VC) as an organic amendment is an eco-friendly approach to increase sustainability in agriculture. There is a high potential of P loss by leaching or surface runoff from coarse-textured soils. Column leaching experiments were conducted to determine the effect of VC on P mobility in a P fertilized sandy loam soil.

Method Soil columns were amended with different VC dosages (2% VC, 3% VC, and 5% VC w/w) and leached with distilled water for 31 days. Phosphorus, base cations and anions concentration, EC, and pH were analyzed in leachates and P species, leaching rate, and fractions in amended soils were determined, too.

Results The HPO_4^{-2} and $MgHPO_4$ (aq) were the dominant species in the leachates and their highest total concentration was observed in 5% VC-amended columns. Vermicompost increased P leaching and its leaching rate ranged from 0.41 mg $kg^{-1}day^{-1}$ for control to 0.59 mg $kg^{-1}day^{-1}$ for 5% VC-amended columns. With increasing VC dosage Res–P, NaOH–P, and KCl–P fractions decreased, but the HCl-P fraction increased.

Conclusion Results indicate that the VC with increasing moderately labile P fraction (HCl-P) and HPO_4^{-2} and $MgHPO_4$ (aq) species can enhance P leaching from sandy loam soil.

Keywords Coarse-textured soil, Vermicompost, Phosphorus fraction, Leaching

Introduction

Applying chemical fertilizer and intensive crop production affect the fertility status and physicochemical properties of most agricultural soils (Sharpley et al. 1994; Zhao et al. 2013). Using organic materials in soils has become a common environmental practice for increasing soil organic matter (SOM) and improving soil physicochemical properties. It is also a feasible approach to alleviate nutrients deficiency such as phosphorus (P) (Owamah et al. 2014; Shu et al. 2016; Kouakou et al. 2018; Naeem et al. 2018; Ahmed et al. 2019; Zhou et al. 2019; Choudhary et al. 2019; Ahadi et al. 2020; Ansari et al. 2020). However, improper use of organic materials may lead to P losses in the environment, surface water eutrophication, and groundwater contamination (Eghball 2003; Yan et al. 2013). Surface runoff and erosion have been known as the main pathway for P loss from soils and freshwater eutrophication (Sharpley et al. 1994; Abdi et al. 2012). However, soil column studies show that significant quantities of P can be leached from soils (Le and Marschner 2018; Eslamian et al. 2020). Some field-scale exper-

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iments have demonstrated P accumulation in subsoil (Rubæk et al. 2013).

Some studies have reported low P adsorption potential and high P leaching risk in soils amended with organic materials (McGechan et al. 2005; Ghosh et al. 2011; Yan et al. 2017). Shaheen and Tsadilas (2013) reported the positive effect of SOM on P availability in soils with high P retention capacity. Furthermore, P leaching has been reported in some P-rich, structured clay or coarse- texture soils (McGechan et al. 2005; Zhang 2008; Qin et al. 2010). Soil physical and chemical properties, such as soil texture, SOM, Al/Fe oxide-oxyhydroxides, and carbonate content, could affect P leaching (Parfitt 1979; Sanyal and De Datta 1991; Matar et al. 1992). Competition between negatively charged organic molecules originated from organic materials with P ions for the sorption sites (Regelink et al. 2015), and high molecular weight compounds such as humic and fulvic acids (Delgado et al. 2002) can reduce the P adsorption and increase P availability. The formation of organic–metal (mainly Fe) compounds also can increase P availability (Ohno and Crannell 1996).

Vermicompost (VC) is the product of the decomposition of organic wastes using certain species of earthworms (Uz and Tavali 2014). The application of VC is an appropriate decision for the developing of sustainable agriculture (Srivastava et al. 2020). Positive effects of VC on the soil’s physicochemical, and biological properties have been reported by several studies (Adhikary 2012; Joshi et al. 2013; Aksakal et al. 2016).

Most of Iran’s country regions (more than 85%) are arid and semi-arid (Khosravi et al. 2014). In arid soils, the SOM content is relatively low (Hajabbasi and Hemmat 2000) and farmers are encouraged to use organic amendments such as VC in farms to increase soil productivity (Ansari et al. 2020).Coarse-textured soils are sensitive soil for pollution of environments (Zhang 2008) and due to low P sorption capacity are often subjected to high P loss by leaching or surface runoff (Sims et al. 1998; Reed et al. 2006; Ukwattage et al. 2020). Thus, there is P leaching risk and groundwater enrichment with P.

Organic residue application can change the quantity and distribution of various P fractions (Sharpley et al. 1984). There are few studies on how effective VC application dosage is in P losses and fractions in coarse -textured soils. Therefore, column leaching experiments in the laboratory were carried out to assess the effect of VC application on P leaching rate, species, and fractions in sandy loam soil with coarse texture.

Materials and methods

Sampling and analysis of soil

One composite soil sample (0-30 cm) was collected from a field under long-term vineyard management of the Namazghah series (34° 14′ 44″N latitude and 48° 43′ 54″ E longitude, Typic Calcixerolic Xerochrept) in Malayer county of Hamadan province, west of Iran. Historically the soil received triple superphosphate (TSP) (200 kg ha^{-1} y^{-1}) and represented a typical coarse textured soil in the Namazghah region. The studied region has a semi-arid climate with a mean annual precipitation of 300 mm and a mean annual air temperature of 10°C (Sabziparvar 2003).

The soil sample was air-dried and sieved (≤ 2 mm).The pH (Thomas 1996) and electrical conductivity (EC) (Rhoades 1996) were measured in 1:5 w/v soil/water suspension; particle size distribution was analyzed using the hydrometer method (Bouyoucos 1962), the calcium carbonate ($CaCO_3$)-equivalent (CCE), was determined by titration with acid (Allison and Moodie 1965). SOM was analyzed using dichromate oxidation (Nelson and Sommers 1983). The cation exchange capacity (CEC) was determined by the saturation of the soil with 1 M NH_4OAc at pH 7 (Rowell 1994). Soil available P content was extracted according to the method proposed by (Olsen 1954) and P concentration was measured by spectrometry method (Murphy and Riley 1962). Oxalate extractable Fe and Al content (amorphous Fe and Al oxides) were extracted using Mehra and Jackson (2013) method and measured by atomic absorption spectrophotometry (AAS) and UV–vis spectrophotometer, respectively.

Single-point P sorption index (PSI_2 (mmol kg^{-1}/µmol L^{-1})) can be used as a parameter to evaluate P loss from agricultural soils and it depends on the clay and organic matter (OM) content of the soil (Nair et al. 2004). It was calculated as the difference between the initial (50 mmol P kg^{-1}) and the equilibrium P concentration (Andersson et al. 2013). The PSI_2 was calculated using the following equation (Bache and Williams 1971):

$$PSI_2 = X / \log c \qquad (1)$$

where X is the amount of P adsorbed by the soil (mmol kg^{-1} soil) at equilibrium and C is the equilibrium P concentration in the solution (µmol L^{-1}).

By dividing the extractable P (Olsen P) by the PSI_2 (with all concentrations on a molar basis), the degree of P saturation (DPS) was estimated using the following equation (Börling et al. 2004):

$$DPS = (Olsen\ P / PSI_2)\ 100 \qquad (2)$$

Chemical cementing agents (organic matter, carbonates and free iron forms) were removed prior to the separation of the clay fraction according to Kunze and Dixon (1986). X-ray diffraction (XRD) was performed in a GNR, APD-2000 X-ray diffractometer at room temperature, with Cu-Kα (λ= 0.154 nm) radiation operating at 40 kV and 40 mA, a step width of 0.02°. The XRD patterns were recorded in the 2θ range of 3º–26º. The following treatments were performed: Mg and K saturation and ethylene glycol (EG) solvation and heating for 2 h at 550 °C on Mg and K treatments, respectively (Moore and Reynolds 1989).

Vermicompost (VC)

The VC was produced from farmyard manure and it was provided by a local company, dried at 60°C, and sieved (≤ 0.5 mm) before use. The dried, ground sample was analyzed for total N by Kjeldahl digestion, as described by Sparks et al. (2020), and organic carbon by the loss-on-ignition procedure (Rowell 1994). The pH and EC were determined after extraction in distilled water (1:10 w/v), shaking at 150 rpm for 1 h (Fernández-Gómez et al. 2011). Samples were digested in nitric acid (Sakala et al. 2004), and the total P content of the digest was measured by the molybdenum blue method, the total Ca^{2+} and Mg^{2+}content were measured by titration and total K^+, and Na^+ contents by flame photometry (Rowell 1994). Fourier transform infrared (FT-IR) spectroscopy (Spectrometer Perkin Elmer Spectrum 65) was used to determine surface functional groups of VC. A mass of 0.1 g of finely ground biomass was pelleted with 1 g of KBr (Sigma) to prepare translucent sample disks. The FT-IR spectra were recorded over the wavenumber range of 400-4000 cm^{-1} with 10 scans at a resolution of 4 cm^{-1}.

Soil columns set up

A glass column leaching procedure (4.8 cm internal diameter and 30 cm length) was designed to study the effect of VC on P leaching. Columns were packed with soils that thoroughly mixed with 2, 3, and 5% of VC, (on an oven-dried basis, equal to 28, 41, and 67.5 ton ha^{-1}, respectively). The higher application dosage of VC was included to test the effects of excessive P application.

Soil columns were prepared by manually filling to a height of 10 cm by uniform tapping with a wooden rod to achieve an approximate bulk density of 1.35 g cm^{-3} (based on soil density, the weight of soil was 244.17g). Whatman No. 42 filter paper and nylon meshes were placed at the bottom of the leaching columns to avoid the movement of particles into the leachate. A filter paper was placed on the soil surface to minimize the soil disturbance. A total of 8 soil columns with two replications were set up at room temperature (22–25^{0}C), including control without VC addition and soil columns mixed with 2, 3, and 5% of VC.

Columns were saturated with distilled water and, after 24 h, were leached with 50 mL of distilled water every day for 31 days (when blocking occurs). Soil columns were covered to minimize water loss through evaporation during leaching experiments. Distilled water represents the relatively low-salinity precipitation received from rainfall or snowmelt in arid and semi-arid regions (Al-Wabel et al. 2002). The total amount of water applied to each column from the 31 leaching events was 1550 mL, which is equivalent to 857 mm of rainfall or irrigation in the Hamadan area (the mean annual rainfall of the study area is 300 mm). More water was added to the columns to maximize P leaching. Leachate samples were collected after every leaching, and their volume was recorded. The leachates were analyzed for pH and EC. The dissolved P concentration as total reactive P (TRP) was measured colorimetrically by the molybdate blue method (Murphy and Riley 1962). Leachates on the first,16th, and 31st day were analyzed for K^+, Na^+, Ca^{2+}, and Mg^{2+} (base cations), SO_4^-, Cl^-, and HCO_3^- according to Rowell (1994) method. The P species and saturation indices (SI) in the first,16th, and 31st leachates were calculated using the geochemical speciation model Visual MINTEQ (version3.0) (Allison et al. 1991). Total analyses were made within 24 h after collection. The cumulative leachate P was calculated for each treatment using the concentrations of P and the volume of the leachate fraction.

Once leaching was completed, the remaining soil in leached columns was collected, air-dried, mixed, sieved (≤ 2mm), and subjected to sequential P extraction by a modified method of Hedley et al. (1982) procedure (Ann et al. 1999). One gram of soil samples was sequentially extracted by end-over-end shaking at 150 rpm with 40 mL 2 M KCl for 2 h (as soluble and exchangeable P (KCl-P), 40 mL 0.1 M NaOH for 17 h (as Fe and Al-bound P (NaOH-P)), 0.5 M HCl for 24 h (as Ca-bound P (HCl-P)), and 5:2 mixture of concentrated HNO_3 and $HClO_4$ (as residual P (Res-P)).The amount of P in all extractions was determined with Murphy and Riley (1962) method.

Phosphorus leaching rate

To describe the P leaching rate a power model was used:

$$y = ax^b \tag{3}$$

Where Y is the cumulative leached P (mg kg^{-1}), a is the initial available P in the soil before leaching (mg kg^{-1}), and b is the rate of leaching (day^{-1}). The parameters were obtained by fitting experimental data to the model using the nonlinear procedure with the Sigma plot statistical software package (version 10.0).

Results and discussion

Soil and VC characteristics

The soil properties with a sandy loam texture (11% clay and 79% silt) included a natural pH of 7 and EC 0.16 dS m^{-1}. The Olsen-P, SOM, and CCE were 21 mg kg^{-1}, 0.5%, and 13.8%, respectively. Soil CEC and oxalate extractable Fe and Al content were 8.2 cmol$_c$ kg^{-1},310.73 mg kg^{-1}, 30.3 mg kg^{-1}, respectively.

Soil PSI_2 and DPS ratios were 1.26 mmol kg^{-1}/µmol L^{-1} and 53.76 µmol L^{-1}, respectively. The high DPS ratio can be attributed to frequent inputs of P fertilizers and high Olsen-P amounts. Andersson et al. (2013) reported that PSI_2 and DPS ratio in sandy soils range between 1 to 4.6 mmol $kg^{-1}/\mu mol\ L^{-1}$ and 4.2 to 76 µmol L^{-1}, respectively. They reported higher PSI_2 and lower DPS ratios for clay soils than sandy soils. They also found that sandy soils with a more significant presence of both Fe and Al oxides had higher P sorption capacity (PSI_2). According to Heckrath et al. (1995) and Eghball et al. (1996), in soils with a low amount of PSI, when they become only partly saturated with phosphorus due to excess fertilization, leaching of P may occur. The XRD showed that the soil is composed primarily of mica, chlorite, and smectite (Fig. 1). Phosphorus fixation by 1:1 minerals is more significant than by 2:1 minerals because of the higher amount of Al/Fe oxides associated with 1:1 minerals and the large number of exposed OH groups in the Al layer that can exchange with P (Halvin et al. 2005).

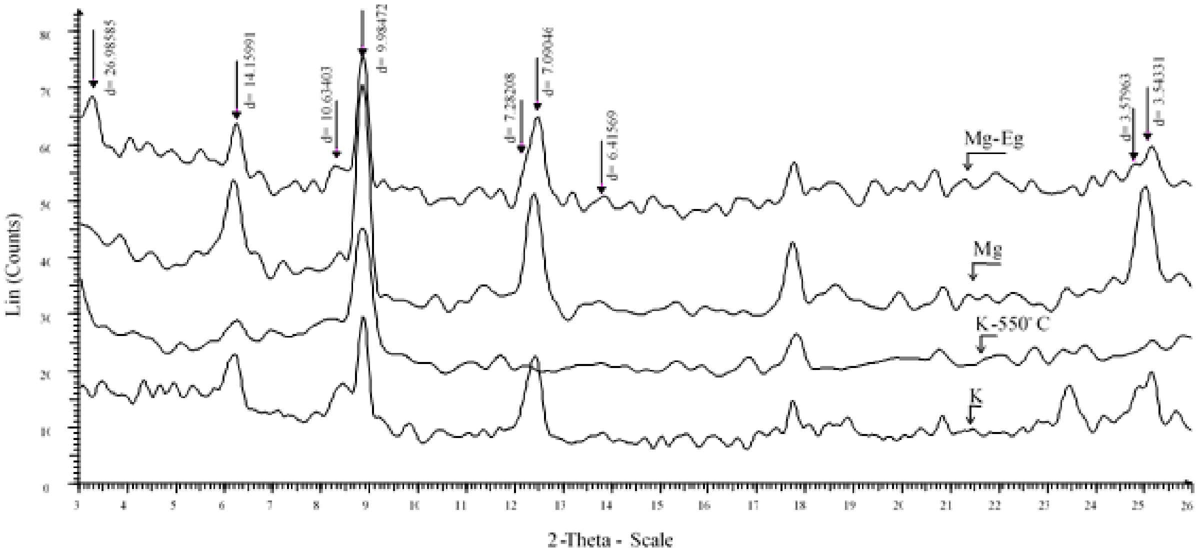


Fig. 1 X-ray diffraction (XRD) patterns of Mg, Mg-ethylene glycol (Mg-Eg), K saturated and K-550◦C treatments in the soil

Vermicompost had a pH and EC of 7.64 and 1.12 dS m^{-1}, respectively, and C/N ratio and OM content of 21.25 and 56.8%, respectively. The total content of phosphorus, potassium, calcium, and magnesium were 0.42, 0.4, 2.73 and 0.95%, respectively. About 3.8% of the total P in VC, was extractable by $NaHCO_3$ solution, which is a loosely bound fraction of P, and thus easily available for crop uptake and leaching. The FTIR Spectra of the VC was reported previously by Hamedi et al. (2021) (Fig. 2). The FTIR Spectra exhibited a broad and intense absorption peak at 3419.86 cm^{-1} with stretching vibration at 1028.52 cm^{-1} that was attributed to alcohol and phenols groups (O-H). The band at 1653.83 cm^{-1} and 873.16 cm^{-1} could be related to the stretching C=O vibration. The band at 1427.61 cm^{-1} with stretching vibration at 2925.26 cm^{-1} could be related to C=C stretching vibration of aromatic rings (Oliveira et al. 2016).

Leachate EC and pH

The first EC of leachate from amended columns was higher than the control column. The increase in EC values of soils amended with VC (VC-amended) depended on the basic materials used for vermicomposting and their salinity (Atiyeh et al. 2002). The most significant increase in EC was obtained in 5% VC-amended columns. In the first leachate of 3% and 5% VC-amended columns, EC values were more significant than the usual EC range for irrigation water 0.0–3.0 dS m^{-1}, (Ayers and Westcot 1985). After that, there was a sharp decrease, and then similar to the control column, low variations with time were observed (figures not shown). A similar trend was observed by Wang et al. (2020) in sandy soil treated with phosphate fertilizers. The soil pH has an important role in P reactions in soil (Zheng et al. 2014).There was little to no change in soil pH during and at the end of the leaching procedure (figures not shown). Leachates pH ranged from 7.93 (control) to 8.19 (3% VC-amended column) at the beginning of the experiment. The difference between the leachate pH at first and the end of the experiment was 0.03 to 0.56 units for control and amended columns. The limited effect of VC on soil pH could be attributed to the presence of calcium carbonate in the soil (13.8%) and its effect on soil pH-buffering capacity (Eslamian et al. 2020).

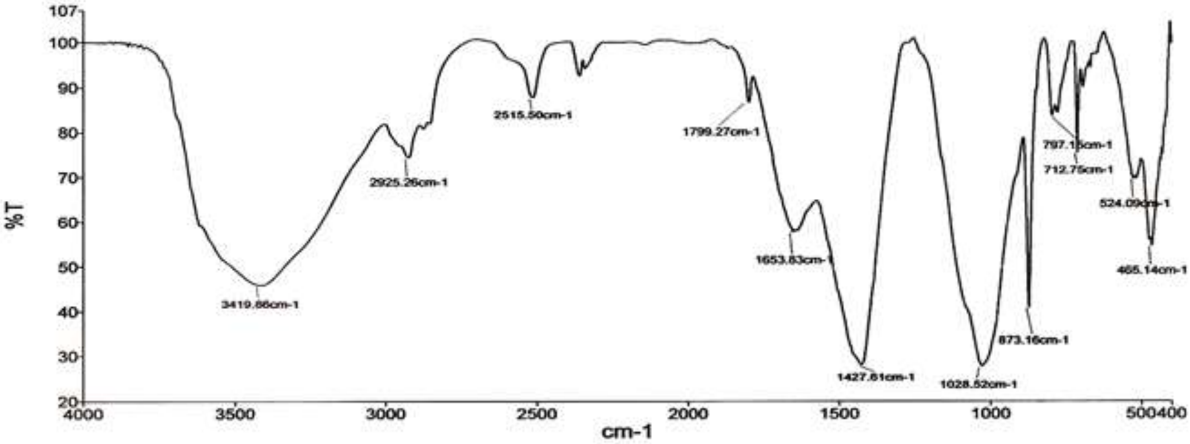


Fig. 2 Infrared spectroscopy of the vermicompost (VC) (Hamedi et al. 2021)

Phosphorus leaching and Cumulative P leached

Fig. 3 shows the P concentration in the leachate from the control and amended columns leached with distilled water. With an input of 50 mL at each leaching event, on average, 42.5 ± 3 mL leachate was collected from the columns. The P concentration in the first leachate from the amended columns was higher than the control column (≥ 6 mg L^{-1}). Leaching of P from all columns generally decreased with time and stabilized after 6 days. At the end of the leaching experiment, the P concentration in the leachate from amended columns fluctuated between 0.41 to 0.78 mg L^{-1}. The P concentration in the last leachate of control and all columns was higher than 0.10 mg P L^{-1}. Concentration of 0.10 mg L^{-1} is an environmental upper limit for P in shallow groundwater in the Netherlands (Breeuwsma et al. 1995).

Jalali and Jalali (2017) studied P leaching with distilled water for four days in 51 native soils with a wide range of physicochemical properties and reported that the P concentrations in the leachate ranged from 0.08 to 9.26 mg L^{-1}, with an average of 2.06 mg L^{-1}. Jalali and Karamnejad (2011) reported that leachate P concentrations were in the range of 0.39 to 2.3 mg L^{-1} during 45 days of leaching, in sandy loam calcareous soil amended with wheat residues.

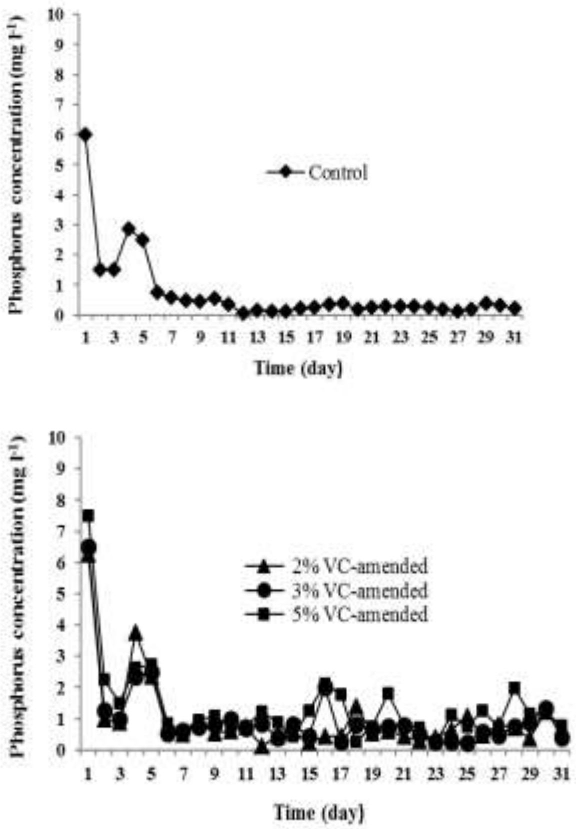


Fig. 3 Phosphorus (P) concentration in leachates of the control and amended columns

Fig. 4 shows the cumulative P leached against time. The control soil generally exhibited lower cumulative P leaching (3.6 mg kg^{-1}) compared to all the amended columns. The highest cumulative P leached was observed from the 5% VC-amended column (7.3 mg kg^{-1}). The cumulative P leached from the amended columns was as follows: 5%VC>3%VC >2%VC. Jalali and Jalali (2017) reported that the cumulative P leached from soil column leached with distilled water ranged from 0.17 to 18.5 mg kg^{-1} and from coarse- textured was more than from fine- textured soils. Brock et al. (2007) concluded that in the fields with a long-term history of dairy and poultry manure application, P losses was more than 0.21 kg P ha^{-1}. Higher P leaching from the amended columns could be related to VC interaction with soil components. Daly et al. (2001) and Bolan et al. (1994) have reported a negative correlation between SOM and P sorption. Other studies have also reported a high risk of P losses in soils fertilized with chemical and organic fertilizers for a long time (Syers and Springett 1984; Pizzeghello et al. 2011). The organic residue consists of different organic compounds such as humic and fulvic acids, amines, polysaccharides, low molecular weight organic acids, and numerous other carbon compounds (Schiffman et al. 2001; Moral et al. 2005).

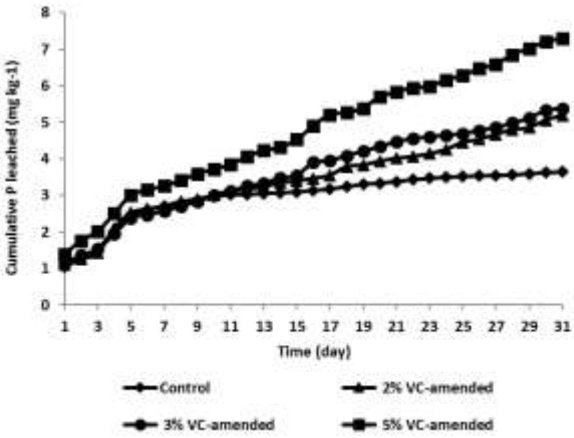


Fig. 4 Cumulative phosphorus (P) leached (mg kg^{-1}) from the control and amended columns

Formation of organophosphate complexes, competition of organic anions with P for adsorption sites, organic anion replacement of $H_2PO_4^-$ and increased negative charge on the soil surface, that can inhibit P adsorption, coating of Al/Fe oxides, and increasing the P mobility and availability and leachability (Halvin et al. 2005; Yadav et al. 2019). Similarly, Guppy et al. (2005) and Moghimi et al. (2018) attribute the increase in P availability to VC's great organic acids and their competition with orthophosphates for binding sites and complexes with metals.

High fixation and limited downward transport of P in soils with high amounts of amorphous Fe oxides and $CaCO_3$ have been reported (Zhang 2008). Tonello et al. (2020) reported that poorly crystalized iron oxides, clay minerals like chlorite, and 2:1 clay minerals with hydroxy-aluminum interlayered minerals present high P adsorption capacity. Lack of P sorption sites in the soil particles can cause P movement in the soil column (Ukwattage et al. 2020). As P adsorption by 1:1 minerals is greater than by 2:1 minerals (Halvin et al. 2005) in studied soil presence of mica, chlorite, and smectite minerals with low P adsorption potential and low amount of amorphous Fe oxides can cause more P leaching from VC-amended soil.

Base cations and anion leaching and P species in leachate

Vermicompost addition increased the leachate concentration of base cations (except for Mg^{2+}) and anions from the columns. Ion concentration in leachate followed the sequence: first day>16th day>31st day and was affected by the VC dosage (Fig. 5). Ions concentration in amended columns was higher than control. On the 16th, and 31st days of leaching, significant reductions in Na^+ and SO_4^{-2} concentrations were detected. The effect of VC on the mobility of ions over time may be related to the presence of nutrients, such as P, soluble K^+, exchangeable Mg^{2+} and Ca^{2+} in plant-available forms in VC (Tiwari et al. 1989). The availability and storage of these cations in the soil are closely related to soil chemical properties such as cation exchange capacity, where studied soil has low CEC (8.2 $cmol_c\ kg^{-1}$).

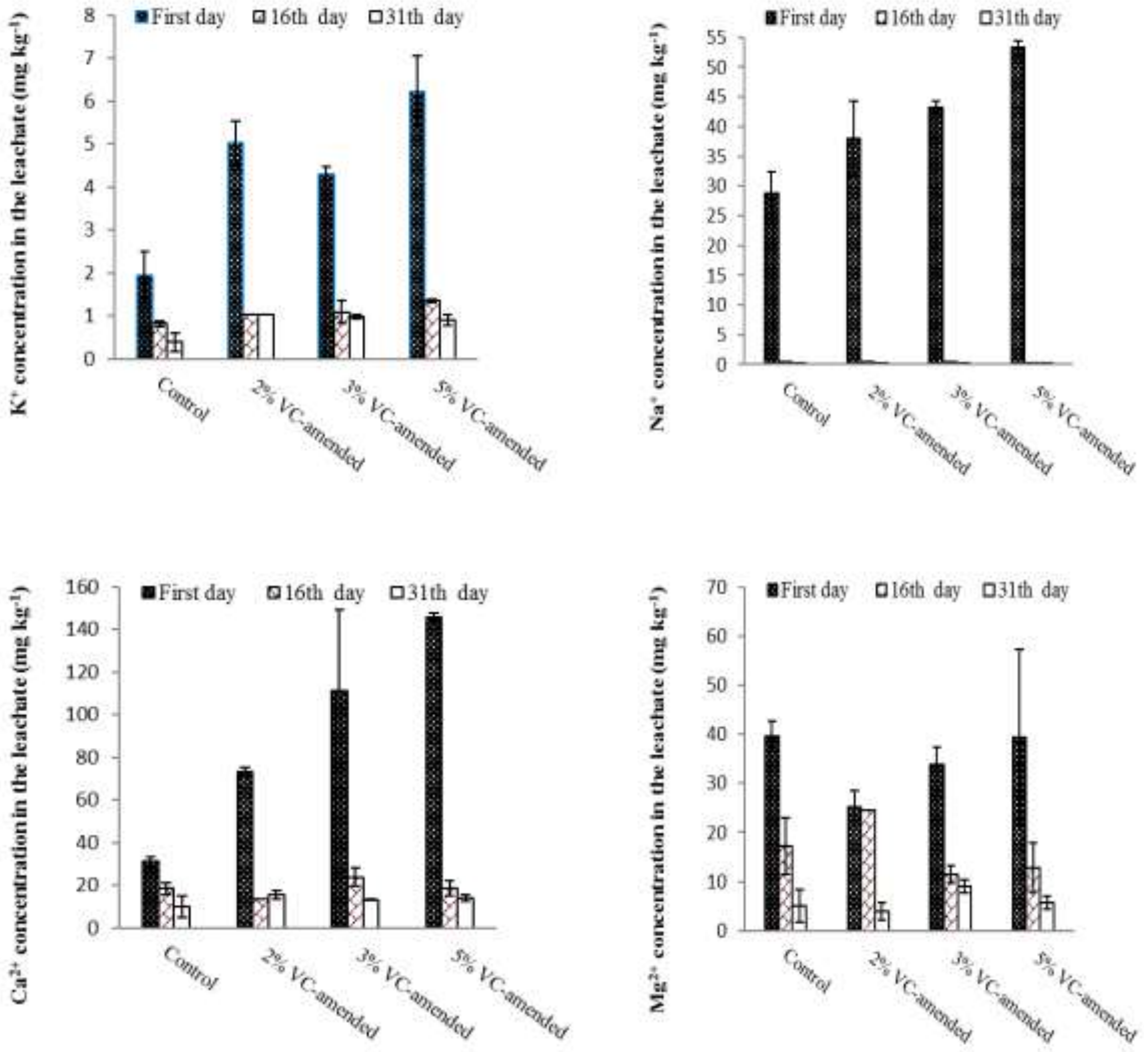
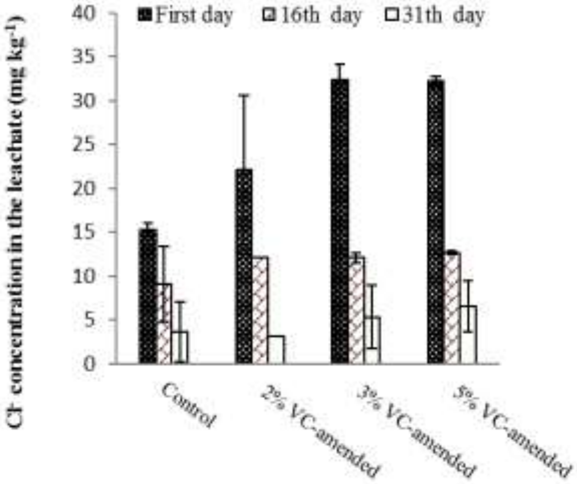
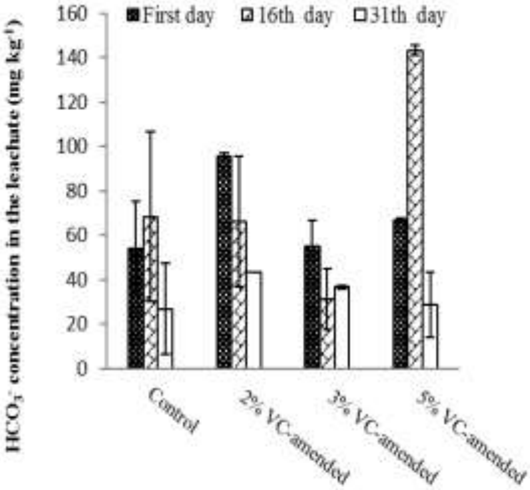
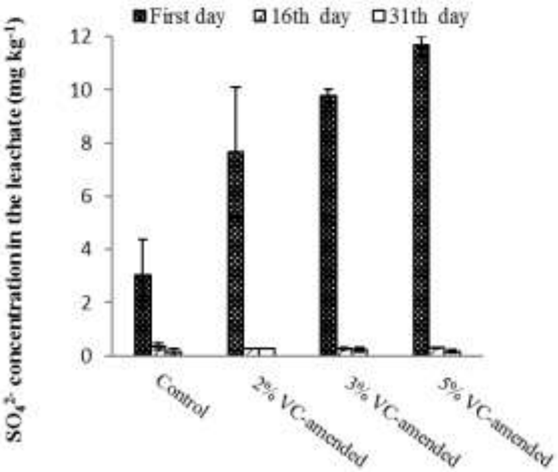


Fig. 5 Change in base cations and anions concentration (mg kg^{-1}) in leachate from the control and amended columns

Bars indicate standard error of the means (n=2).







Continued Fig. 5 Change in base cations and anions concentration (mg kg^{-1}) in leachate from the control and amended columns

Bars indicate standard error of the means (n=2).

The major chemical P species in the amended columns solution were as follows: HPO_4^{2-} > $MgHPO_4$ (aq) > $CaHPO_4$ (aq) > $H_2PO_4^{-1}$ (Table 1). The total percentage of $CaHPO_4$ (aq) and $MgHPO_4$ (aq) species in 2% and 3% VC-amended columns solution were more than the total percentage of HPO_4^{2-} and $H_2PO_4^{-1}$ species. $CaHPO_4$ (aq) and $MgHPO_4$ (aq) as ion pairs consist of a positive ions (Ca^{2+} and $Mg^{2+)}$ and negative ion (HPO_4^{2-}) temporarily bonded together by the electrostatic attraction form an electrically neutral substance, and it can be easily leached from soils. The high amount of soluble Ca^{2+} and more formation of $CaHPO_4$ (aq) and $MgHPO_4$ (aq) species in the solution can increase P leaching from the amended columns. The concentration of equilibrium P in leached solution, through the leaching experiments, was controlled by the dissolution rate of hydroxyapatite (HA, $Ca_5(PO_4)_3OH$), b-tri-Ca phosphate (b-TCP, $Ca_3(PO_4)_2$), and octa-Ca phosphate (OCP, $Ca_4H(PO_4)_3$ $2.5H_2O$) minerals. Similarly, other studies have reported that HA, b-TCP, and OCP minerals as solid phase control the equilibrium P solution concentrations in manure-amended calcareous soils (Hansen and Strawn 2003; Jalali and Arfania 2010; Jalali and Karamnejad 2011).

Phosphorus leaching rate and fractions

Equation 3 satisfactorily modeled cumulative P leaching in different treatments, and the model constants are presented in Table 2. Phosphorus leaching rate (a*b) ranged from 0.41 mg kg^{-1} day^{-1} for the control column to 0.59 mg kg^{-1} day^{-1} for the 5% VC-amended column. Phosphorus leaching rate from 5% VC-amended column was significantly higher than other columns ($P \leq 0.05$). Jalali and Karamnejad (2011) reported that the P leaching rate from a sandy loam soil treated with potato residue was higher than the control. The phosphorus leaching rate from a sandy loam calcareous soil with simulated acid rain was between 0.032 to 0.041 mg P kg^{-1} day^{-1} (Jalali and Naderi 2012). With increasing in VC dosage, the P leaching rate increased from 0.47 to 5.9 mg P kg^{-1} day^{-1}. The higher leaching rate from amended columns could be related to low CEC and clay content (11%), clay type, and the presence of $MgHPO_4$ (aq) species in the studied soil.

Before leaching in control soils, P fractions decreased as Res–P (63.35%) > HCl -P (28.96%) > NaOH–P (6.75%) > KCl–P (0.92%) and after leaching, KCl-P, NaOH-P and Res-P fractions of control soil decreased while the HCl-P fraction increased (Table 3). KCl-P could replace P in solution as a labile fraction and the moderately labile P (HCl-P) and Res-P contribute to the long-term P release and seem to act as slow-release P sources (Silveira et al. 2006). Phosphorus fractions (%) in amended columns at the end of the leaching experiment are represented in Table 3. The KCl-P, NaOH-P, and Res-P fractions in amended columns were lower than leached control columns. Similarly, Yan et al. (2017) reported Res-P reduction in a subtropical paddy soil amended with swine manure.

After leaching, in the amended columns, the HCl-P fraction was higher than unleached and leached control soil, indicating that the VC application enhanced the P mobilization and suggesting that P preferred Ca-bound compared to the other fractions. Some released P entered in the HCl–P fractions during the leaching procedure. The HCl-P fraction increased with increasing VC dosage in the amended columns.

Table 1 The major chemical percentage of phosphorus (P) species in leached from the control and amended columns

	Treatment	Control	Amended		
			2% VC	3% VC	5% VC
	Species				
First day					
	$H_2PO_4^{1-}$	3.66	2.45	2.27	2.22
	HPO_4^{2-}	33.38	36.42	37.56	32.23
	$CaHPO_4$ (aq)	14.34	21.55	16.27	14.07
	$MgHPO_4$ (aq)	42.91	27.37	33.74	43.18
16th day					
	$H_2PO_4^{1-}$	1.15	-*	3.32	1.09
	HPO_4^{2-}	36.65	36.45	38.92	36.14
	$CaHPO_4$ (aq)	13.68	18.85	18.66	7.87
	$MgHPO_4$ (aq)	29.95	17.08	31.62	45.82
31st day					
	$H_2PO_4^{1-}$	1.67	1.98	2.29	5.93
	HPO_4^{2-}	44.45	46.93	46.07	51.10
	$CaHPO_4$ (aq)	17.84	17.29	16.63	20.39
	$MgHPO_4$ (aq)	19.42	19.44	23.29	16.20

*: not detected

Table 2 Parameters of the Power model ($y = ax^b$) used to describe cumulative phosphorus (P) leached in the control and amended columns

Treatment	a mg kg^{-1}	b day^{-1}	a*b mg P $kg^{-1}day^{-1}$	r^2	SE
Control	1.41	0.29	0.41^b	0.93	0.18
Amended					
2% VC	1.06	0.45	0.47^b	0.98	0.16
3% VC	0.98	0.49	0.48^b	0.99	0.09
5% VC	1.10	0.54	0.59^a	0.99	0.16

Means followed by the same letter do not differ at $P \leq 0.05$

Table 3 Mean percentages of sequential extractable phosphorus (P) in the control and amended columns after 31 leaching events

Treatment	KCl-P	NaOH-P	HCl-P	Res-P
		%		
Control- before leaching	0.92	6.75	28.96	63.35
Control- after leaching	0.50	5.74	33.39	60.35
Amended				
2% VC	0.45	5.04	40.50	54.00
3% VC	0.47	5.09	46.68	47.74
5% VC	0.49	4.94	46.31	48.24

Thus, the effect of VC application on the increment of HCl–P fraction as moderately labile P in coarse texture soil in terms of P availability and environmental impact needs to be considered. Different studies confirmed that applying organic residue increased labile P fractions and decreased Res-P fraction (Qaswar et al. 2020; Qian et al. 2004). The portion of NaOH- P that is mainly the part of the P strongly binding to the surfaces of the Fe and Al oxides via chemisorption (Zhang et al. 2020) showed no distinct changes with VC dosage. Similar results reported by Ashjaei et al. (2010)

Conclusion

The use of VC in sustainable agriculture is emphasized. Still, the results showed that VC addition to sandy loam soil with a low amount of PSI_2 (that estimates the number of free sorption sites) and 1:1 clays could produce a significant quantity of leachable P. The HCl-P fraction increase in the amended columns indicates that the VC application enhanced the P mobilization and suggests that P preferred Ca-bound. Some of the released P entered the HCl–P fractions during the leaching procedure. Vermicompost addition increased $MgHPO_4$ (aq) species, with low affinity to sorption on the soil surface, which can also cause intensive P leaching losses from amended columns. However, it must be mentioned that this leaching study was completed under no cropping conditions. As P leaching from soils is affected by the plant, further field observations are needed to verify the method and application dosage of VC.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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