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RESEARCH ARTICLE

Contrastive nutrient leaching from two differently textured paddy soils as influenced by biochar addition

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Abstract

Purpose The aims of the current study were to (1) examine the interactive effects of biochar addition and differently textured soils (clayey and sandy soils) on nutrient leaching and (2) identify potential mechanisms related to the leaching.

Materials and methods A repacked soil column experiment was set up to test the effects of five biochar rates added to clayey and sandy soils grown with rice (*Oryza sativa* L. ssp. japonica) for 3 months. Four leaching events were conducted to measure concentrations of ten elements in the leachate, including calcium (Ca), sodium (Na), potassium (K), magnesium (Mg), aluminum (Al), iron (Fe), manganese (Mn), ammonium nitrogen (NH_4^+), nitrate nitrogen (NO_3^-), and phosphorus (P).

Results and discussion On the sandy soil, biochar addition linearly and significantly reduced Ca concentration (by 38%), but increased Na (by 92%), K (by 292%), and P (by 411%) concentrations in the leachate, compared to the non-biochar-added soil. In contrast, on the clayey soil, biochar addition showed no obvious effect on the leaching of these elements. Biochar addition significantly reduced leaching of Al, Fe, Mn, and NH_4^-, but increased leaching of Mg. Mechanisms related to the reduced leaching of NH_4^-, Ca, Al, Fe, and Mn could be involved in the liming effect and increased nutrient holding capacity by biochar addition, and those responsible for increased leaching of Na, K, and P could be involved in co-addition of these elements with the added biochar.

Conclusions Biochar addition had contrastive effects on nutrient leaching, which was more profound on sandy soil than on clayey soil grown with rice crop.

Keywords Biochar · Nutrient leaching · Paddy soil · Soil texture

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1 Introduction

Nutrient losses through leaching from the soil surface layer may pollute groundwater, deplete soil fertility, and thus reduce soil productivity (Bronswijk et al. 1995; Lehmann and Schroth 2002). A number of factors could potentially affect nutrient leaching, including soil texture, e.g., clay content, organic matter, nutrient holding capacity, fertilizer application, rainfall, plant growth, agricultural management, hydraulic conductivity, and water holding capacity (Liu et al. 2015; King et al. 2016; Tahir and Marschner 2017; Li et al. 2018). Available nutrients, quantitatively indicated through cation exchange capacity (CEC), could be presented and retained in soil through binding to exchange sites mostly derived from clay minerals and organic matter (Parfitt et al. 1995). Soil having higher clay content may retain more nutrients, resulting in lower nutrient leaching than that having lower clay content (Tahir and Marschner 2017). Chen et al. (2006)

found that as much as 97% of P added as water-soluble fertilizer was leached from the sandy soil. At soil moisture of field capacity, up to 44% of total potassium (K) applied on a sandy soil was leached, while around 3.3% of total K applied on a clayey soil was leached (Mendes et al. 2016). As a result, an increase in either clay fraction or organic matter content would enhance nutrient holding capacity, an important feature of soil to hold nutrients, thereby reducing nutrient leaching.

Moreover, to reduce leaching, the addition of biochar to soil has been a well-studied option. Biochar is a carbon-rich substrate and is derived from plant residues. Biochar can be produced in an oxygen-limited condition for a temperature range of 300–700 °C (Lehmann and Joseph 2009; Spokas 2010). Biochar is porous, high in negative charge density, and has a large surface area (Liang et al. 2006; Laird et al. 2010). These specific features may enable biochar to adsorb and hold inorganic forms of elements, thereby reducing their leaching from the biochar-added soil. Likewise, Zheng et al. (2013) explained that NH_4^- could be absorbed on the surface of biochar through acid functional groups. On the other hand, contained in the biochar with a considerable portion, some inorganic elements such as Na, K, and P could be added to the soil with the applied biochar, facilitating leaching of these elements. With these different mechanisms, biochar addition was found to reduce leaching of N, P, K, and Si (Lehmann et al. 2003; Laird et al. 2010; Knowles et al. 2011; Sika and Hardie 2014), while increase leaching of N, Ca, Mg, K, and P (Major et al. 2012; Bu et al. 2017; Silva et al. 2017), or even both increase and decrease leaching of K, Na and Ca, Mn, P, Zn, respectively, in the same study (Novak et al. 2009). These varying results could be a consequence of numerous reasons, such as different biochar properties, experimental conditions, and soil properties. Similarly, Yao et al. (2012) concluded that nutrient leaching effect of biochar could vary with biochar and nutrient elements. Moreover, a study by Li et al. (2018) even showed that biochar addition at 1 and 4% increased, but at 2% reduced NO_3^- leaching from the sandy soil. These indicate that more studies could be in need to address the leaching of different elements as affected by varying biochar application rates.

In addition, there are limited studies from literature addressing the leaching effect of biochar on paddy differently textured soils. Although the interaction effect of biochar and soil texture on soil fertility was recently reported (El-Naggar et al. 2018), such the effect on nutrient leaching was scarcely understood (Borchard et al. 2019). The authors concluded that biochar addition to sandy soil could reduce NO_3^- leaching, but the similar result on the clayey soil was not reported. Teutscherova et al. (2018) found that biochar addition had a different effect on NH_4^+ and NO_3^- leaching from two contrasting soils. Nevertheless, the authors did not examine such the effect on leaching of other elements, such as K, Na, Ca, Mg, Al, Fe, Mn, and P, which are much different in chemical behavior from NH_4^+ and NO_3^-. Understanding water conditions such as paddy fields, nutrient leaching from the fields

added with rice residue-derived biochar is not clearly discussed, although the rice crop is cultivated for more than 161 million ha globally (Statista 2018). Moreover, due to relatively continuously flooding condition of paddy field, some mechanisms of biochar mentioned above could be modified, possibly resulting in different effects of biochar on nutrient leaching, compared to the dry and rewetting condition of other crops. A typical example could be that oxidation, a mechanism developing negative charges of biochar (Liang et al. 2006), could be weakened in an anaerobic and flooding condition, minimizing the effect of biochar on inorganic nutrients adsorption, and thus their leaching from the paddy soil. These necessitate a study to examine the effects the biochar on nutrient leaching from flooded paddy soils.

Therefore, the current study was conducted on two differently textured soils added with five biochar rates and grown with rice crop. The aims of the current study were to (1) examine the interactive effects of biochar addition and the tested soils (clayey and sandy soils) on nutrient leaching and (2) identify potential mechanisms related to the leaching. It is hypothesized that the effect of biochar on nutrient leaching on the sandy soil could be more profound than that on the clayey soil.

2 Materials and methods

2.1 Experimental materials

Soil samples were taken from two paddy fields, which were different in soil texture. The clayey soil was taken from a *Dystric Fluvisol* (FAO/UNESCO) in Long Hoa commute Can Duoc district, Long An province (106° 35′ E and 10° 34′ N) and the sandy soil was from a *Haplic Acrisols* in Xuan Thoi Son commute, Hoc Mon district, Ho Chi Minh City (106° 35′ E and 10° 52′ N), Vietnam. The clay content of the clayey soil was 61% and that of the sandy soil was 5.5%. After being taken, soil material was transferred to a laboratory at the Industrial University of Ho Chi Minh City (IUH) for pretreatment. The soil material was air-dried and ground to pass a 2-mm sieve and be ready for the experiment.

Biochar used for the current study was the ones used in our previous study (Nguyen et al. 2018). It was produced from rice husk and rice straw at temperatures from 400 to 450 °C. Because our previous results showed that the effects of the two biochar types (one derived from rice husk and the other from rice straw) on extractable nutrient concentrations of the amended soil were not obviously different (Nguyen et al. 2018), the two biochar types were mixed at 1:1 ratio (hereafter, called biochar) for the current study. Two feedstocks (rice husk and rice straw) were used to produce biochars for the current study because they are the most common agricultural residue in Vietnam, the fifth largest rice producer in Asia (FAO 2018) having over 4.5 million ha of paddy land.

2.2 Soil column experimental setup

The column leaching method used for the current study was similar to that used by Laird et al. (2010) with some modifications. The leaching column was established, using a PVC tube (diameter 17.5 cm by length 18 cm = 4329 cm³). One end of the tube was covered with a PVC cap, which was drilled to create a hole for leaching. The hole was covered with nylon mesh to prevent solid material inside from being drained out and the tube bottom was added with 200 g of coarse sand to facilitate even leaching. A small plastic pipe (diameter 5 mm, draining pipe) was used to connect the column bottom to a pre-washed plastic bottle (sampling bottle) for leachate collection. The draining pipe was attached with a controller to control the leaching rate. The sampling bottle had a lid to minimize leachate loss through evaporation. Another hole was drilled on the lid to connect with the draining pipe.

The experiment was triplicated and thirty leaching columns (2 soils × 5 biochar rates × 3 replicates) were established. Each of two air-dried ground soils was mixed with biochar at five rates, including 0, 0.5, 1, 2, and 5% (w/w). Around 4–5 kg of each biochar-soil mixture (depending on soils and biochar rates) was repacked into the leaching columns, and gentle tamps were applied to the columns along with the addition of the mixture. The height of the mixture was 14 cm and a few centimeters from the top were for standing water. The repacked columns were added with tap water to 3 cm—water depth for 10 days before rice (Oryza sativa L. ssp. japonica) seed sowing. Rice seed germination, sowing, and cultivation practices were applied following protocol applied in (Nguyen et al. 2018). Inorganic fertilizers were applied as 4.6 g urea-N, 1.7 g superphosphate-P, and 1.7 g potassium-K per 24 columns. These rates are equivalent to 80 kg N, 30 kg P, and 30 kg K per ha (Luu and Nguyen 2006). P fertilizer was applied at the same time of mixing biochar and soil; N fertilizer was applied in three splits and K fertilizer was in three splits (Luu and Nguyen 2006). Surface water depth was kept around 1–3 cm for the 3-month life cycle of the rice crop. This means that soil in the leaching columns was totally submerged for the entire experimental period. All columns were arranged in a completely randomized design.

2.3 Leaching event and chemical analysis

Four leaching events were conducted on the 29th, 39th, 49th, and 59th day from the sowing day to get the leachate for chemical analysis. We intended to delay conducting leaching events in order to capture maximum leaching of Ca and Mg due to their delay in leaching (Lehmann et al. 2003) and to distribute the four leaching events over the strong-growth period of rice plants. For each of the leaching event, around 1 l of leachate was collected for about 24 h by controlling the controllers attached to the sampling pipe. The collected leachate was sent to a laboratory at the

IUH for chemical analysis. The procedure by Carter and Gregorich (2008) was applied to determine the concentration of Ca, Mg, Na, K, Al, Mn, and Fe in the leachate using an inductively coupled plasma spectroscopy–optical emission spectrometer (ICP-OES, Spectro Analytical Instrument GmbH, 47,533 Kleve Germany).

The concentrations of NH_4-N, NO_3-N, and PO_4^{3-} (P) in the leachate were determined using manual spectrometric method (ISO 7150-1:1984), 2,6-dimethylphenol spectrometric method (ISO 7890-1:1986), and ammonium molybdate spectrometric method (ISO 6878:2004), respectively.

Before the experiment, three sub-samples of each soil and biochar were taken to analyze for effective cation exchange capacity (ECEC) and exchangeable nutrients the same as the leachate. The analyses were conducted by weighing 0.5 g of each sample into a centrifuge tube, adding 30.0 mL of 0.1 mol L^{-1} $BaCl_2$, and analyzing with ICP-OES (Carter and Gregorich 2008). ECEC was calculated as a sum of exchangeable concentrations of Ca, Mg, Na, and K. In addition, the pre-experimental materials (two soils and biochar) were analyzed for total organic carbon using Walkley–Black method, for concentrations of NH_4-N and NO_3-N using 2 mol L^{-1} KCl and for P concentration using 2.5 mol L^{-1} H_2SO_4 (Carter and Gregorich 2008). The pH of these sub-samples was also determined from a 1:2.5 (soil:water) solution using a pH meter. All these data are shown in Table 1 and Table S1, Electronic Supplementary Material - ESM).

2.4 Statistical analysis

The data of the leachate concentrations were statistically analyzed using the analysis of variance (ANOVA), following a three-factor completely randomized design, using JMP 10 (SAS Institute Inc., North Carolina, USA). The overall ANOVA model is $\gamma_{ijek} = \mu + \beta_i + \propto_j + \propto \beta_{ij} + \tau_e + \beta\tau_{ie} + \propto \tau_{je} + \alpha\beta\tau_{ije} + \varepsilon_{ijek}$, where γ_{ijke} is the response of individual treatment; μ is overall mean; β_i is a fixed effect of the ith soil; α_j is the fixed effect of the jth biochar rate; $\beta\alpha_{ij}$ is the interaction effect of soil and biochar factors; τ_e is fixed effect of eth leaching event; $\beta\tau_{ie}$ is the interaction effect of soil and leaching event; $\propto\tau_{je}$ is the interaction effect of biochar and leaching event; $\alpha\beta\tau_{ije}$ is the interaction effect of soil, biochar, and leaching event; and $\in_{ijek}$ is the random error with mean zero and having normal distribution (Akhtar and Memon 2009). When the ANOVA result indicated a significant effect at $P \leq 0.05$, a Tukey honestly significant different test was used to classify treatment means. Linear and nonlinear regression fittings were performed to examine dependent patterns of the concentrations of leached nutrients on biochar application rates. The regression analysis and figures were performed using Sigmaplot 12 (Systat Software Inc.).

Table 1 Selected properties of the studied materials (mg kg^{-1} dried matter)

Materials	Statistics	TOC (%)	pH*	ECEC (**)	Exchangeable form							Available form		
					Ca	Mg	Na	K	Al	Mn	Fe	NH$_4$-N	NO$_3$-N	P
Clayey soil	Mean	1.8	6.8	25.0	2284	1220	290	889	12.6	19.3	4.0	32.9	100.7	2.7
	SE	0.03	0.18	0.3	16	9	24	34	0.3	0.7	0.3	3.7	14.6	0.03
Sandy soil	Mean	0.8	7.0	5.6	1007	31	29	77	2.1	1.1	1.2	24.2	80.5	4.6
	SE	0.13	0.13	0.1	6	1	11	6	0.9	0.1	0.2	1.4	2.5	0.13
Biochar	Mean	37.2	8.7	33.7	1032	146	1271	8495	2.0	18.7	6.8	12.3	54.0	105
	SE	1.04	0.02	0.4	11	2	12	46	0.2	0.1	0.2	2.5	10.4	4.3

For the clayey soil, clay and sand contents were 61 and 6%, respectively. For the sandy soil, clay and sand contents were 5.5 and 91%, respectively. *TOC* total organic carbon, *SE* standard error; *ECEC* effective cation exchange capacity; *pH unit; (**) cmol$_c$ kg^{-1} ; $n = 3$

3 Results

3.1 Leaching of base cations

Overall, the three-way interaction of biochar, soils, and leaching event was not significant on the concentrations of the examined elements in the leachate. Nevertheless, the two-way interaction was found on all examined elements, except Al and NO$_3$-N. The Ca concentration in the leachate was significantly affected by the interaction of soil with leaching event and of biochar with soil (Fig. 1a, b). For sandy soil, Ca concentrations in the leachate were similar among four leaching events, varying from 336 to 418 mg L^{-1} (Fig. 1 and Table S2 - ESM). For the clayey soil, Ca concentrations decreased significantly with leaching events (days after sowing) at a rate of − 5.1 mg L^{-1} per day. Twenty-nine days after sowing, the Ca concentration in the leachate from clayey soil was 217 mg L^{-1}, lowered to 55 mg L^{-1} after 59 days. Ca concentrations in the leachate from the clayey soil added with different biochar rates were not significantly different (Fig. 1b), varying from 109 to 180 mg L^{-1}. In contrast, the leached Ca concentration was significantly higher from the sandy soil added without biochar (477 mg L^{-1}) and was lower from the same soil added with 5% biochar (293 mg L^{-1}). Change in the leached Ca concentration from sandy soil with biochar application rate was an exponential decay pattern. The leached Mg concentration was significantly affected by the interaction of soils with leaching events and by the main effect of biochar application rate (Fig. 1c, d). On the clayey soil, the concentration of Mg in the leachate was decreased significantly from leaching event 1 (29 days after sowing, 119 mg L^{-1}) to leaching event 4 (59 days after sowing, 33 mg L^{-1}), while on the sandy soil, the leached Mg concentration was similar among the four events. Biochar addition at 5% significantly increased the leached Mg concentration from both soils, compared to the other rates of 0, 0.5, 1, and 2% (Fig. 1d).
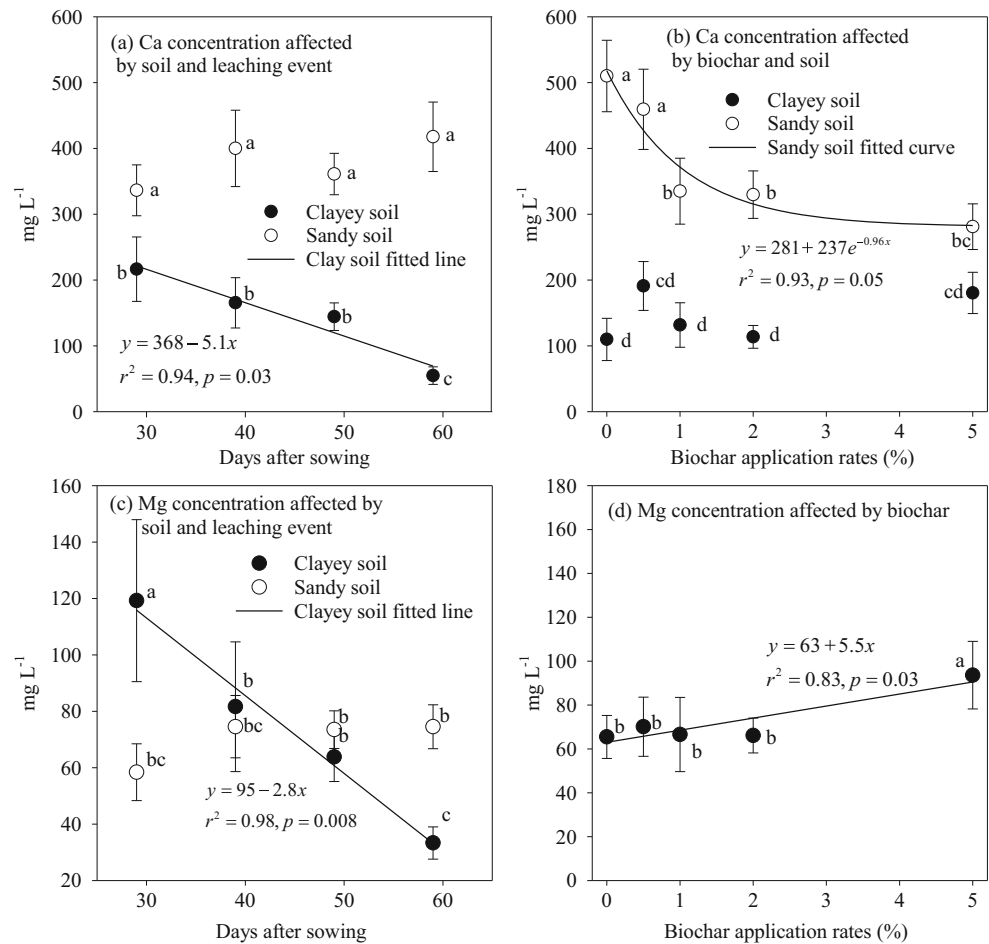
The leached Na concentration was significantly decreased with leaching events, changing from 108 mg L^{-1} at the first event (29 days after sewing) to 84 mg L^{-1} at the last event (59 days after sowing) (Fig. 2a and Table S2 - ESM). The leached Na concentration was significantly affected by the interaction of soil and biochar. At lower biochar rates (less than 2%), the leached Na concentrations were not clearly differentiated between the two soils, whereas at 5% rate, sandy soil leached a greater Na concentration (153 mg L^{-1}) than clayey soil (111 mg L^{-1}). The leached K concentration was significantly affected by the interaction of soil with leaching event and of soil with biochar (Fig. 2c, d). For the clayey soil, the leached K concentrations in four events were similar, varying from 101 to 29 mg L^{-1}, but for sandy soil, the leached K concentration was decreased significantly from the first event (385 mg L^{-1}) to the last event (141 mg L^{-1}). The decreased rate was 8.1 mg L^{-1} for every increasing day after sowing. The K concentration in the leachate was also influenced by the combination of soil and biochar (Fig. 2d). On the clayey soil, biochar addition at different rates did not affect K leaching, whereas on the sandy soil, biochar addition linearly increased the concentration of K in the leachate. The increased rate of the leached K concentration from sandy soil was 105 mg L^{-1} day^{-1}, while that from clayey soil was 13 mg L^{-1} day^{-1}.

3.2 Leaching of Al, Mn, and Fe

The Al concentration in the leachate was not clearly affected by any interaction but was significantly influenced by the main effects of the two experimental factors (Fig. 3). An increase in biochar rate reduced Al concentration in the leachate, from 1.4 to 1.0 mg L^{-1}, following an exponential decay, with a rapid decrease in leached Al concentration when the biochar rate increased from 0 to 2% (Fig. 3a). The leached Al concentration also decreased with leaching event, being highest at the first event (1.4 mg L^{-1}) and lowest at the third event (1.0 mg L^{-1}) (Fig. 3b). The clayey soil had a significantly higher leached Al concentration (0.13 mg L^{-1}) than sandy soil (0.09 mg L^{-1}) had (Fig. 3c).

Fig. 1 Calcium (Ca) and magnesium (Mg) concentration in the leachate. Errors bars are standard errors. Within a panel, data attached with the same letter are not significantly different from each other. Only significant relationship was fitted and shown with a fitted equation, r^2 (coefficient of determination) and p (probability)
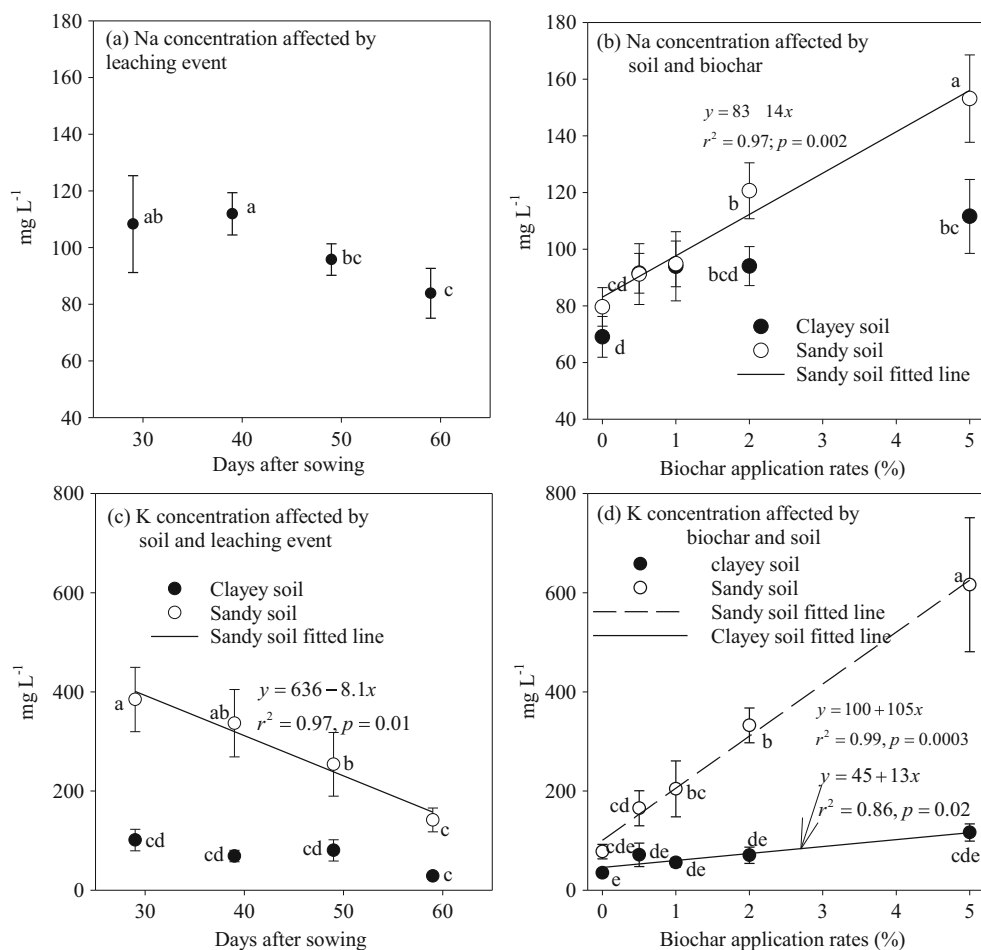

(a) Ca concentration affected by soil and leaching event

● Clayey soil
○ Sandy soil
— Clay soil fitted line

$y = 368 - 5.1x$
$r^2 = 0.94, p = 0.03$

(b) Ca concentration affected by biochar and soil

● Clayey soil
○ Sandy soil
— Sandy soil fitted curve

$y = 281 + 237 e^{-0.96x}$
$r^2 = 0.93, p = 0.05$

(c) Mg concentration affected by soil and leaching event

● Clayey soil
○ Sandy soil
— Clayey soil fitted line

$y = 95 - 2.8x$
$r^2 = 0.98, p = 0.008$

(d) Mg concentration affected by biochar

$y = 63 + 5.5x$
$r^2 = 0.83, p = 0.03$

Different from Al, Mn and Fe concentrations in the leachate were significantly affected by the interaction of soil with leaching event, and of leaching event with biochar (Fig. 4). The leached Mn concentration was decreased exponentially with leaching event but more rapidly on the clayey soil than on the sandy soil. On the clayey soil, Mn concentration in the leachate was decreased from 8.9 (the first leaching event) to 0.4 mg L^{-1} (the last leaching event). Meanwhile, on the sandy soil, Mn concentration was decreased from 4.3 to 1.2 mg L^{-1}, for the first to the last event, respectively (Fig. 4a). An increase in biochar rate reduced the leached Mn concentration exponentially that happened only in the first leaching event after 29 days from sowing. Similar patterns of the Mn concentration in the leachate were not found in the last three events. When biochar rate increased from 0 to 5%, the leached Mn concentration at the first event was decreased from 10.9 mg L^{-1} to 3.9 mg L^{-1}, respectively. Meanwhile, at the other events, the leachate Mn concentration varied from 0.6 to 2.8 mg L^{-1}, irrespective of biochar rate (Fig. 4b). On the clayey soil, the Fe concentration in the leachate was exponentially decreased from the first to the last leaching events, whereas on the sandy soil, Fe concentrations were not obviously different among the four leaching events (Fig. 4c). The leached Fe concentration was significantly

decreased exponentially with biochar application rate for the first event, whereas the Fe concentration was similar among the five biochar rates for the last three events (Fig. 4d).

3.3 Leaching of NH$_4$-N, NO$_3$-N, and P

Overall, the NO$_3$-N concentration in the leachate varied from 27 to 77 with a mean of 51 mg L^{-1} (Fig. 5c and Table S3 - ESM) and was not significantly affected by any interaction or single effects of the experimental factors. The NH$_4$-N concentration in the leachate was significantly affected by the main effect of biochar and by a combination of soil and leaching event (Fig. 5a, b). With an increase in biochar rate, the leached NH$_4$-N concentration significantly decreased exponentially from 17.3 in the non-biochar treatment to 12.0 mg L^{-1} in the 5% biochar treatment (Fig. 5a). The leached NH$_4$-N concentration was similar between the two soils for the first two events, whereas its concentration was significantly higher in the clayey soil (17.7) than in the sandy soil (11.4 mg L^{-1}) for the last two events (Fig. 5b). The P concentration in the leachate was significantly affected by a combination of soil with biochar and of soil with leaching events. On the sandy soil, biochar addition significantly increased the P concentration in

Fig. 2 Sodium (Na) and potassium (K) concentration in the leachate. Errors bars are standard errors. Within a panel, data attached with the same letter are not significantly different from each other. Only significant relationship was fitted and shown with a fitted equation, r^2 (coefficient of determination) and p (probability)


(a) Na concentration affected by leaching event

(b) Na concentration affected by soil and biochar

$y = 83 + 14x$
$r^2 = 0.97; p = 0.002$

● Clayey soil
○ Sandy soil
— Sandy soil fitted line

(c) K concentration affected by soil and leaching event

● Clayey soil
○ Sandy soil
— Sandy soil fitted line

$y = 636 - 8.1x$
$r^2 = 0.97, p = 0.01$

(d) K concentration affected by biochar and soil

● clayey soil
○ Sandy soil
-- Sandy soil fitted line
— Clayey soil fitted line

$y = 100 + 105x$
$r^2 = 0.99, p = 0.0003$

$y = 45 + 13x$
$r^2 = 0.86, p = 0.02$

the leachate linearly, from 1.9 in the zero biochar treatment to 11.9 (mg L^{-1}) in the 5% biochar treatments, whereas on the clayey soil, biochar addition at five rates resulted in similar leached P concentration (Fig. 5d). For the clayey soil, the leached P concentration was similar between the first two combined leaching events and the last two combined events, whereas for the sandy soil, the P concentration in the leachate was significantly lower in the last two combined events (3.7 mg L^{-1}) than in the first two combined events (5.9 mg L^{-1}) (Fig. 5e).

4 Discussion

Of the ten leached elements selected to test in the current study, four (Ca, Na, K, and P) were significantly affected by the combination of the two experimental factors (biochar and soil): one (NO_3-N) is not affected by both factors and the rest were affected by single factors. An interesting finding from the current study is that the effect of biochar added to the sandy soil on element leaching (Ca, Na, K, and P) was stronger (either reducing or increasing) than that added to the clayey soil. This is in line with our initial hypothesis that biochar

affected nutrient leaching more profoundly on the sandy soil than on the clayey soil.

4.1 The single effect of biochar and tested soils

In the current study, the clayey soil has higher clay content (61%) and lower sand content (6%) than sandy soil has (5.5% clay and 91% sand) (Table 1). The clayey soil also had higher total organic carbon (TOC), ECEC, exchangeable concentrations of Ca, Na, and K than the sandy soil (Table 1 and Table S1 - ESM). Due to having high clay content, TOC, and CEC, the clayey soil could have higher nutrient holding capacity than the sandy soil (Tahir and Marschner 2017), which may restrict nutrient loss from leaching. This could result in lower leaching of Ca, Na, K, and P in the clayey soil than in the sandy soil (compared two soils applied without biochar in the current study). This is an important reason to explain K leaching from the clayey soil, less obvious than from the sandy clay loam soil (Rosolem et al. 2010). Similarly, Vinten et al. (1994) found that the clayey soil had a significantly lower total leaching in the second and third year than sandy soil.

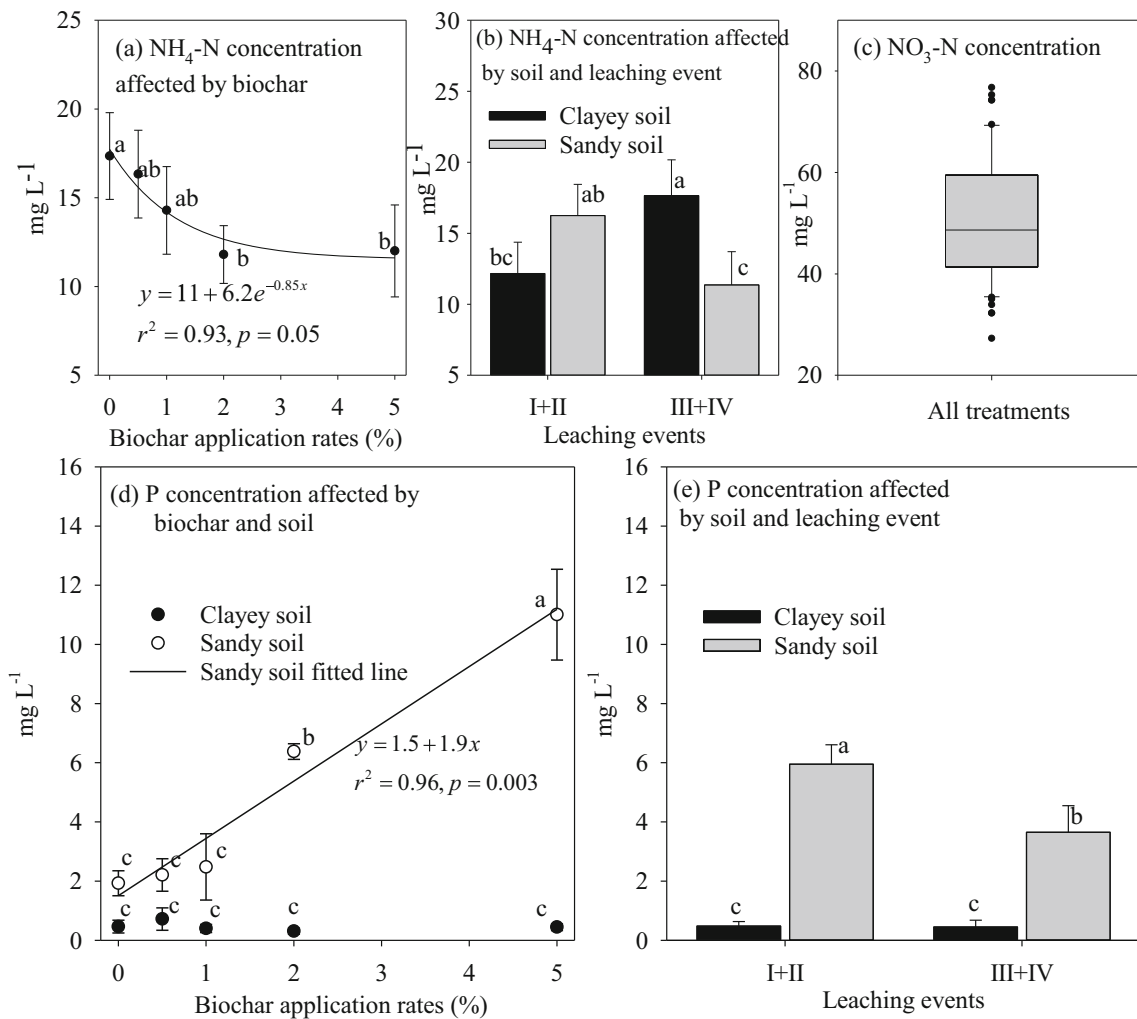**Fig. 3** Aluminum (Al) concentration in the leachate. Errors bars are standard errors. Within a panel, data attached with the same letter are not significantly different from each other. Only significant relationship was fitted and shown with a fitted equation, r^2 (coefficient of determination) and p (probability)

(a) Al concentration affected by biochar

$$y = 0.1 + 0.04e^{-1.8x}$$
$$r^2 = 0.98, p = 0.02$$

(b) Al concentration affected by leaching event

(c) Al concentration affected by soil
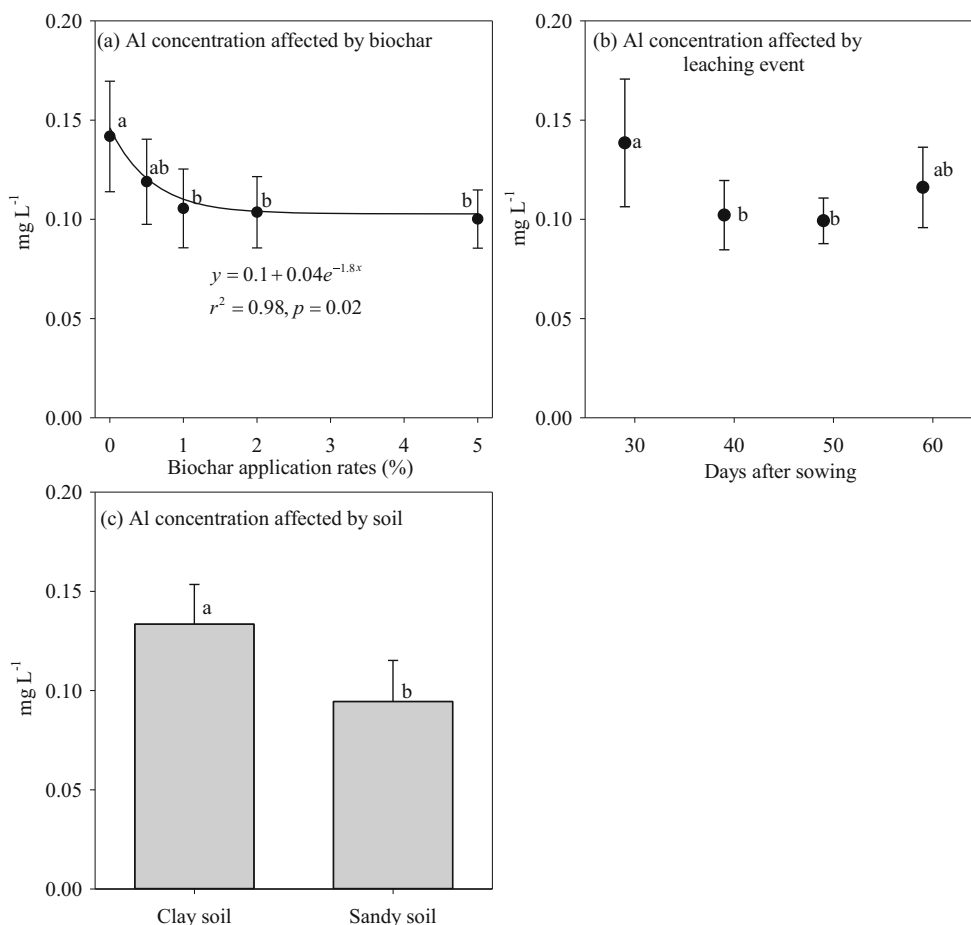
For the biochar, several mechanisms could explain the findings (biochar reducing leaching of Al, Mn, Fe, and NH$_4$-N) from the current study. Biochar was reported to have a great surface area, which increased CEC of biochar-amended soil (Liang et al. 2006). Because biochar was also demonstrated to have great nutrient adsorption (Ding et al. 2016), its addition may increase nutrient adsorption of the biochar-added soil, leading to significantly lower leaching of NH$_4$-N on a paddy field (Wang et al. 2017). Biochar was reported to adsorb Al on its surface (Qian and Chen 2014) that may contribute to reduced Al leaching as observed in the current study. Liming effect induced by biochar addition (Borchard et al. 2019; Gao and Deluca 2016) could be another mechanism in affecting nutrient leaching. Biochar had a higher pH value (8.7) than the two examined soils did (6.8 for clayey and 7.0 for sandy soil, Table 1) in the current study. After the experiment, the pH of the clayey soil added with 5% biochar was increased by 0.38 units, and of sandy soil was 0.33 units compared to the soil added without biochar (data not shown). The increased pH by biochar addition was reported by El-Naggar et al. (2018) and Silva et al. (2017). Because of the increased pH, the available concentrations of some metals in soil such as Al, Fe, and Mn were reported to

decrease (Patra et al. 1994; Dong et al. 1999; Li and Johnson 2016; Pandit et al. 2018). These may explain the reduced leaching of these ions from the biochar-added soil, comparing the non-biochar-added soil in the current study.

Although the reason responsible for the increased concentration of Mg in the leachate because of biochar addition was not clearly understood, there could be some possibilities. Addition of 1.0 mol L^{-1} KCl solution was used to extract exchangeable Mg cation in soil (Bortolon and Gianello 2010), indicating that a sufficiently high concentration of K in soil might displace Mg ion from exchange sites, increasing Mg concentration in the soil solution. A similar mechanism could happen in the current study that an increase in K concentration in the leachate and possibly in the soil solution, because of biochar addition, might increase exchangeable—Mg concentration in the soil solution and subsequent in the leachate. In addition, Mg was demonstrated to bind to exchange sites less strongly than Ca due to the smaller ionic radius and larger hydrated radius (Shaul 2002; Gransee and Führs 2013). This is in line with the assumption that sufficiently high K concentration in soil solution might firstly push exchangeably bound Mg to soil solution, increasing Mg concentration in the leachate as found in Fig. 1d.

Fig. 4 Manganese (Mn) and iron (Fe) concentration in the leachate. Errors bars are standard errors. Within a panel, data attached with the same letter are not significantly different from each other. Only significant relationship was fitted and shown with a fitted equation, r^2 (coefficient of determination) and p (probability)
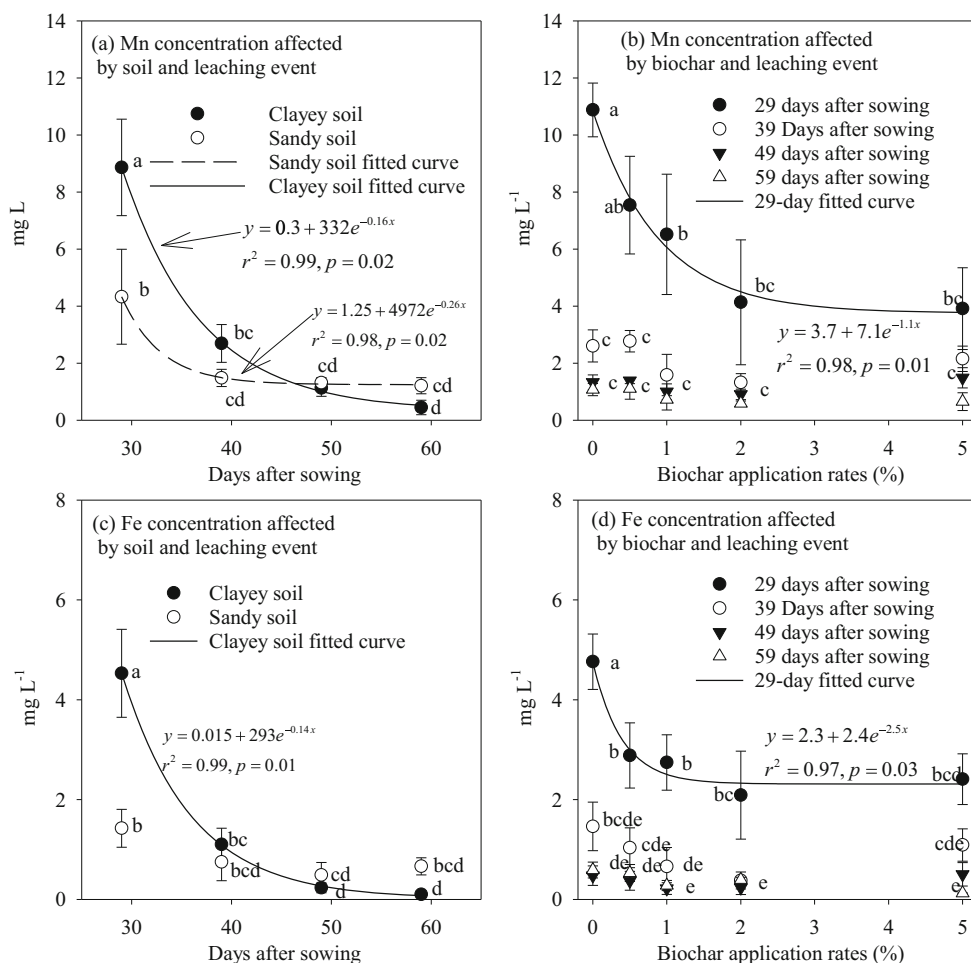
4.2 Interaction effects of biochar with soil

However, biochar addition was found to reduce Ca leaching significantly from the sandy soil but insignificantly from the clayey soil (Fig. 1b). The related reason could be that because the effective magnitude of biochar on cation leaching could be similar to that of clay mineral (Dempster et al. 2012); the addition of biochar to the clayey soil did not significantly influence Ca leaching from the biochar-added soil. Meanwhile, with a high-leaching feature, sandy soil amended with biochar could reduce Ca leaching significantly due to high Ca adsorption of the amendment, compared to the sandy soil.

An increase in leaching of Na, K, and P, because of biochar addition, stronger on sandy soil than clayey soil was also found in the current study (Figs. 2b, d, and 5d). The exchangeable K concentration of biochar (8495 mg kg^{-1}) was 110 and 9.6 times higher than that of sandy (77) and clayey soil (889 mg kg^{-1}), respectively. Similarly, the exchangeable Na concentration of biochar (1271) was 44 and 4.4× higher than that of sandy (29) and clayey (290 mg kg^{-1}) soil, respectively (Table 1). As a result, the concentration of these nutrients in

the leachate was linearly proportional with biochar rates on sandy soil. Likewise, Major et al. (2012) and Lehmann et al. (2003) found that biochar addition increased K leaching from the topsoil layer. Novak et al. (2009) reported that the leached K and Na concentrations were increased with biochar rates on sandy soil. On the other hand, the clayey soil, having a higher ECEC (Table 1) and a higher buffering capacity (Jansen van Rensburg et al. 2009) compared to the sandy soil, could minimize the change in dissolved-nutrient concentrations of K and Na, and subsequently, reduce their concentration in the leachate, caused by biochar addition.

The leaching of P increased linearly with biochar application rates on sandy soil in the current study is similar to other studies. Bu et al. (2017) found that biochar addition increased P leaching by up to 108% from the sandy soil. Silva et al. (2017) found that P leaching was increased linearly with biochar application rate on an Oxisol having 78% of clay content. Three possibilities could explain the increased P leaching. An available P concentration (105 mg kg^{-1}) of biochar was 23× higher than that of sandy (4.6 mg kg^{-1}). Therefore, the first possibility could be that the increased P concentration in the

Fig. 5 NH₄-N, NO₃-N, and P concentration in the leachate. Errors bars are standard errors. Within a panel, data attached with the same letter are not significantly different from each other. Only significant relationship was fitted and shown with a fitted equation, r^2 (coefficient of determination) and p (probability). The leachate from the first two events was pooled together (I + II) and that from the last two events were pooled together (III + IV)

leachate could be derived from biochar. With an increase in biochar addition rate, an increase in pH of the biochar-added soil (see above discussion) could be the second possibility. The increased pH may dissolve a portion of immobilized P in soil (Devau et al. 2009), making P more soluble, and thus susceptible to leaching. The third possibility could be related to soil Al and Fe solubility, which could be reduced, indicated through lowered Al and Fe leaching (Figs. 3 and 4), as biochar application rate increased. Because P ion could precipitate with Fe and Al (Hinsinger 2001), the reduced Al and Fe solubility in soil may make P more soluble in the soil solution and more P leaching. Nevertheless, the effect of biochar on P leaching was not obvious on clayey soil. This could be due to higher exchangeable concentrations of Al, Fe, and Mn in the clayey soil than in the sandy soil (Table 1), resulting in P precipitation with these metals.

4.3 Interaction effects of soil with leaching event

The interactive effects of soil and leaching event were also observed on Ca, Mg, K, Mn, Fe, NH₄-N, and P concentrations in the leachate. On the clayey soil, the leached concentrations of these nutrients (Ca, Mg, Mn, and Fe) were decreased rapidly over leaching events, whereas on sandy soil, the leached concentration of Ca and Mg remained similar, or reduced at a slower rate (Mn and Fe) over the leaching events. Similarly, Singh et al. (2010) reported a significant interactive effect of soil and leaching event on NH₄-N leaching that the Vertisol had higher NH₄-N leaching in the first leaching event than in the second event, whereas the Alfisol did not. One possible reason to explain the dynamics could be related to a high clay content of the clayey soil that may rapidly immobilize the soluble nutrients due to high nutrient holding capacity,

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