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Nutrient Leaching Losses from Continuous Application of Washed Rice Water on Three Contrasting Soil Textures

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ABSTRACT

Washed rice water (WRW) is often used as liquid plant fertilizer. However, there is no study on nutrient leaching of soils due to frequent WRW application. Therefore, a column study was undertaken to evaluate the rate of nutrient leaching losses, nutrient retention, and recovery of elements in leachates of three different soil textures irrigated with WRW. The treatments were 3 soil textures and 2 water types. The treatments were evaluated for 8 weeks, and the soils and leachates were measured biweekly. Factorial and repeated measurements in a completely randomized design were therefore employed. Higher cumulative leaching of the elements was found in sandy clay loam soil with 666.29, 378.13, 138.51, 50.82, 44.61, and 27.30 mg L^{-1} of K, P, Mg, Ca, NH_4^+-N, and NO_3^--N, respectively. Higher percentages of elements recovery in leachate were found in the sandy clay loam soil with a range of increase by 37.8–283.1% than the other two soil textures. In contrast, after 8 weeks of WRW application, the clay and silt loam soils had a range of increase in nutrient retention by 0.43–1358.5% than the sandy clay loam, with P and NO_3^--N being the highest and the lowest elements retained, respectively, for all soil textures. This study showed that frequent WRW disposal on sandy textured soils risks higher environmental contamination, mainly due to the soil's lower water retention and nutrients, leading to nutrient leaching. Therefore, organic amendments should be added to sandy textured soils.

Keywords: Contamination, environment, leaching, nutrients, nutrient retention, soil texture

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INTRODUCTION

Milled rice is washed prior to cooking to remove the bran, dust, and dirt from the rice (Juliano, 1993). However, rice washing removed a significant amount of water-soluble nutrients from the rice into the washed rice water (WRW), and these leached nutrients could be used as a liquid plant nutrient source and soil amendment (Nabayi, Teh, et al., 2021). The WRW nutrient contents depend on the rice washing rates: the volume of water used, how long and how aggressively the rice is washed, as well as the time the WRW was kept before use. These factors have all been found to affect the concentration of the elements in WRW (Nabayi, Sung, Zuan & Paing, 2021; Nabayi, Sung, Zuan, Paing & Akhir, 2021). Several studies (Juliano, 1993; Wulandari et al., 2012) have reported the N, P, K, Ca, Mg, and S contents of WRW to range from 40 to 16,306 mg L^{-1}. Furthermore, He, Feng, Hu et al. (2016) reported that WRW has concentrations of NO_3^-,NO_2^-, NH_4^+, total N, and total P in the range of 4.19–10.14, 0–0.08, 2.57–39.72, 51.26–84.79, and 23.41–58.12 mg L^{-1}, respectively. Therefore, Siagian (2018) stated that the indiscriminate disposal of WRW is harmful to the environment (e.g., via N and P pollution).

Nutrient leaching varies with soil properties and rainfall amount. This problem is problematic for highly weathered tropical soils, e.g., Oxisols and Ultisols, characterized by low nutrient retention capacity and rapid organic residue decomposition (Ishak & Jusop, 2010). The leaching of nutrients is mainly controlled by the soil type and the soil's sand and clay contents (Tahir & Marschner, 2017). Malaysian soils range widely in texture, from having as low as 3% (sandy soils) to over 90% (clayey soils) of clay content. The average amount of sand in Malaysian soils is 41%, nearly the same as that of the clay content, 43% (Teh et al., 2017). Malaysian soils have bulk density values ranging from 0.8 to 1.9 Mg m^{-3} (Teh et al., 2017), depending on the soil management practices. Differences in the soil bulk directly affect soil porosity, determining soil water retention. Sandy soils usually have higher void ratios, leading to a higher leaching rate than clayey textured soils (Tahir & Marschner, 2017). Depending on the soil compaction, organic matter content, and soil texture, different soils have different saturation, field capacity, and permanent wilting points. For Malaysian soils, the volumetric soil water content at saturation, field capacity, and permanent wilting point can range between 36–89%, 10–67%, and 3–49%, respectively, giving the available volumetric soil water content between 1% and 13% (Teh et al., 2017). Therefore, in contrast to its clayey soils, sandy soils would experience larger nutrient leaching due to the former soils' higher porosity and hydraulic conductivity. Nutrient retention is typically low in sandy soils, and therefore, 20–80% of applied nutrients would be leached or runoff into ground and surface waters (Manevski et al., 2015; Yaghi & Hartikainen, 2013). Waste nutrients flow easily into the estuary because of the inherent properties of hydrological connectivity (Yin et al., 2020). If wastewater's soluble reactive P concentration exceeds 0.04 mg L^{-1}, eutrophication may develop (Zeng et al., 2016).

Similarly, because conventional K fertilizers are very soluble, a large amount of K might be lost through leaching (Alfaro et al., 2004).

WRW contains nutrients in appreciable quantities, including N and P, which found their way to the water bodies and environments; N and P are the two main sinks of all domestic and industrial waste. The improper disposal of the WRW could accumulate these elements in water bodies and the groundwater, resulting in eutrophication that threatens humans and marine life (He, Feng, Peng, et al., 2016). Many studies have reported using WRW as liquid fertilizer to increase plant growth, and they attributed the plant increased growth to the nutrients contained in the WRW (Bahar, 2016; Sairi et al., 2018; Wardiah et al., 2014). However, these WRW nutrients are in soluble forms, which makes them prone to leaching. Different soil textures exhibit different water and nutrient retention characteristics, with sandy soils having lower nutrient retention capabilities (Matichenkov et al., 2020). WRW is beneficial in what is probably the first and most in-depth study on WRW (Nabayi, Sung, Zuan, Paing & Akhir 2021), but what is still lacking is the information on nutrient losses when WRW have to be applied frequently (such as daily). Therefore, there is a need to assess the nutrient leaching rate of different soil textures for a short-term period to guide how different soil textures behave when subjected to a continuous WRW application. Hence, the objectives of the study were: (1) to determine the nutrients: NH_4^+–N, NO_3^-–N, P, K, Ca, and Mg leaching losses from different soil textures under continuous WRW application, and (2) to determine the soil nutrient retention and element percent recovery from the leachate of these soils due to the continuous WRW application.

MATERIALS AND METHODS

Soil Collection

Three soils with contrasting textures (i.e., sandy clay loam, silt loamy, and clay) were collected from various locations in Universiti Putra Malaysia (UPM), Faculty of Agriculture complex (2.984761° N, 101.7336° E). All soils were taken from a depth of 0-0.3 m. A preliminary survey was carried out to assess the soil textures before the soil collection. The soils (separately) were collected using a shovel and auger, mixed thoroughly, and air-dried in the laboratory (Department of land management, UPM). In addition, disturbed and undisturbed (using core samplers) soil samples were also collected to determine other physical and chemical properties.

Soil and WRW Preparation and Analysis

Washed rice water was prepared in the laboratory using commercially available medium-grained rice (Rambutan brand) (Padiberas Nasional Berhad, Malaysia). Fresh WRW was prepared in the volumetric water-to-rice ratio of 3:1, the recommended water-to-rice washing ratio by Nabayi, Sung, Zuan, and Paing (2021) and Nabayi, Sung, Zuan, Paing, and Akhir (2021). The mixture was obtained using a mixing machine (Bossman Kaden Matte BK-100S, Japan) at 80 rpm (0.357g) for 90 seconds. The mixture was then separated using sieves (<0.5 mm sizes). The WRW was only prepared during application time to preserve its freshness. Atomic absorption spectrophotometer (AAS) (Perkin Elmer, PinAAcle, 900T, Waltham, MI, USA) was used to determine K, Ca, and Mg elements, while P was determined by Auto Analyzer (AA) (Leachat QuikChem FIA+ 8000 series, Ontario, Canada). NH_4^+–N and NO_3^-–N were determined by the Kjeldahl procedure (Stevenson, 1996).

Soil pH was measured in a soil-water suspension with a soil: water ratio of 1:2.5 (McLean, 1983) using the 827pH lab meter (Metrohm AG, Zurich, Switzerland). The combustion method measured soil total C and N (Skjemstad & Baldock, 2007) using the Leco CR-412 Carbon Determinator (LECO Corp., St. Joseph, MI, USA). The contents of exchangeable soil bases (K, Ca, and Mg) and cation exchange capacity (CEC) were assessed by AAS and AA, respectively, after being extracted by the leaching method using neutral 1 M ammonium acetate (NH_4OAc) solution (Thomas, 1982). Soil available P was extracted using the Bray II method (Bray & Kurtz, 1945) and determined using AA (Leachat QuikChem FIA+ 8000 series, Ontario, Canada).

The pipette method determined soil particle size analysis (Gee & Bauder, 1986). The pressure plate method measured the soil water retention curve for matric potentials 0.0 to -1.5 MPa (Richards, 1947). Soil water content at saturation (SAT), field capacity, and the permanent wilting point is the amount of water held in the soil at 0.0, -0.33, and -1.5 MPa, respectively. Volumetric soil moisture contents were determined following Gardner (1986).

Preparation of Soil Columns

Each soil texture was air-dried and sieved through a 4-mm sieve, removing the stones and soil clods. Soil columns were constructed and fitted using PVC tubing and end caps on the bottom. Drainage holes of about 0.3 cm were made through the caps' end and attached to each column's end. Each column measured 78 mm in diameter, and 300 mm in length, giving a volume of 1433.7 cm^3. A plastic net was cut and placed at the bottom of each tube, followed by 100 g of coarse sand to prevent waterlogging. The concave part of the end cap that extended below the base of the PVC column was filled with sand (Figure 1). Each soil column was packed with air dry weight equivalent of about 2.15

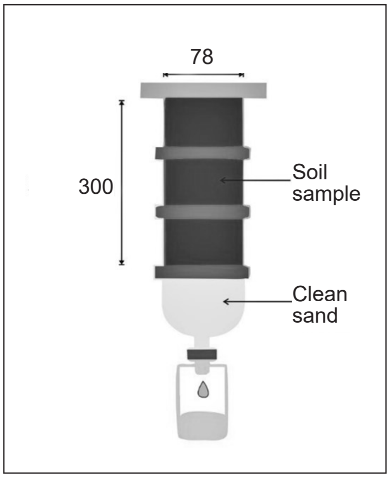


Figure 1. Lysimeter column set-up
Note. Dimension in mm

kg soil via packing down the columns with concurrent soil addition. All the columns, irrespective of their soil texture content, were finally packed to have a bulk density of 1.5 Mg m^{-3}.

Soil Column Incubation and Leaching

For 8 weeks, the columns were incubated at a constant temperature and relative humidity of 28 ^{o}C and 65%, respectively. A total of 18 columns were used, with 9 (3 soil textures replicated 3 times) receiving WRW treatments, while the remaining 9 (3 soil textures replicated 3 times) receiving tap water treatment. Before the application of either WRW or tap water, the dry soils, after packing, were wet to their initial saturation level (SAT) moisture content. The amount of water added was computed by multiplying the SAT moisture content of each soil texture by the volume of the PVC tube. The water was added slowly with glass to prevent water ponding and pores clogging and help diffuse water drops. After 12 hrs of the initial wetting, the application of the treatment (WRW or tap water) started. About 5 mm equivalent of either water type was applied once daily. Leachate was collected using a plastic bottle attached to the leaching tube to minimize evaporation from each column for about 24 hrs after the start of the leaching event. The leachate collected was measured daily before a subsequent watering event and transferred into a plastic vial. The leachates collected were pooled biweekly and measured for NH_4^+–N and NO_3^-–N using the Kjeldahl digestion and distillation procedure (Stevenson, 1996). About 100 mL of leachates samples were filtered (Whatman No. 2, 11µm size) and analyzed for P, K, Ca, and Mg after acidifying (using 0.1N HCl) biweekly using AAS (Perkin Elmer, PinAAcle, 900T, Waltham, MI, USA). The different soils under WRW treatment were also sampled biweekly for volumetric moisture content determination.

Data Analysis

The overall experimental design used was completely randomized in factorial arrangement, which comprised 3 soil textures and 2 water types with 3 replications (18 columns). Leachate samples were collected from each leaching column daily for 8 weeks, while the nutrient analysis was carried out biweekly. Nutrient retention of the elements in the soils was determined using Equation 1, and the mass balance analysis was used to estimate the percentage of element recovery in the leachate using Equation 2, as given by Laird et al. (2010):

$$\text{Nxi} = \text{Nwrx} - \text{NLi} \qquad [1]$$

$$R_{xi} = \frac{(X_{li} - X_c)*100}{X_{mwi}} \qquad [2]$$

where *Nxi* is the mass retained for *X* element for column i, *Nwrx* is the mass of *X* element present in the WRW, *NLi* is the mass of the element leached *L* from column *i*, R_{xi} is the percent nutrient recovery of *X* element for column *i,* X_{Li} is the mass of *X* element that leached from column *i*, X_c is the average mass of *X* element that leached from control columns for the different soil texture, and X_{mw} is the mass of *X* element in the WRW that was added to column *i*. The nutrient retention was only analyzed for WRW treatment based on the different soil textures. Statistical analysis was conducted using Minitab for Windows, *version* 20 (Pennsylvania State University, USA). Percent element recovery and soil nutrient retention were analyzed using one-way ANOVA, while nutrient leaching was analyzed factorially with the soil texture and sampling weeks as factors. Significant means were separated using Tukey's Studentized Range test at a threshold probability level of 5%.

RESULTS AND DISCUSSION

Effect of WRW Application on Nutrient Leaching

The highest leaching of all elements was consistently observed in sandy clay loam soil, which differed significantly ($p<0.01$) from the other two soil types that mostly have similar losses with each other irrespective of the sampling week. The leaching of the elements increased in the order of sandy clay loam> silt loam> clay for NH_4^+–N, NO_3^-–N, P, K, Ca, and Mg. In the last week of the experiment (8 weeks), the sandy clay loam soil had a range increase in NH_4^+–N, NO_3^-–N, P, K, Ca, and Mg leaching by 29.6–33.6, 21.3–25.9, 34.5–36.8%, 31.9–40.9%, 26.9–39.9%, and 30.3–46.5%, respectively, then the silt loam and clay soils (Figure 2). The leaching losses for other elements in clay and silt loam soils are constant over time. Significantly higher leaching of the elements in sandy clay loam soil could be attributed to its lower water and nutrient retention relative to the other two soils. Sandy soils usually have low nutrient retention capabilities (Matichenkov et al., 2020). The lower retention of nutrients in the sandy clay loam could also be seen in its comparatively lower water-holding capacity than the other two soil textures (Table 1). The leaching of the elements from these soils due to the continuous WRW application indicates the nutrient leaching potentials of WRW to the groundwater, particularly in sandy soils, because of its lower water retention that led to the higher leaching volume, as shown in Figure 3a. Sandy soils have a higher leaching rate than clayey textured soils due to the higher void ratios of the former (Tahir & Marschner, 2017).

The physical structure and water-holding capacity have been suggested as the main factors that affect the soil retention capacities of NO_3^- and P (Pratiwi et al., 2016). The addition of WRW over time has slightly raised the volumetric moisture contents of the soils used in this study (Figure 3b). Sandy clay loam soil had the least response to WRW amendment application, with only a 4.8% increase in volumetric moisture content at week

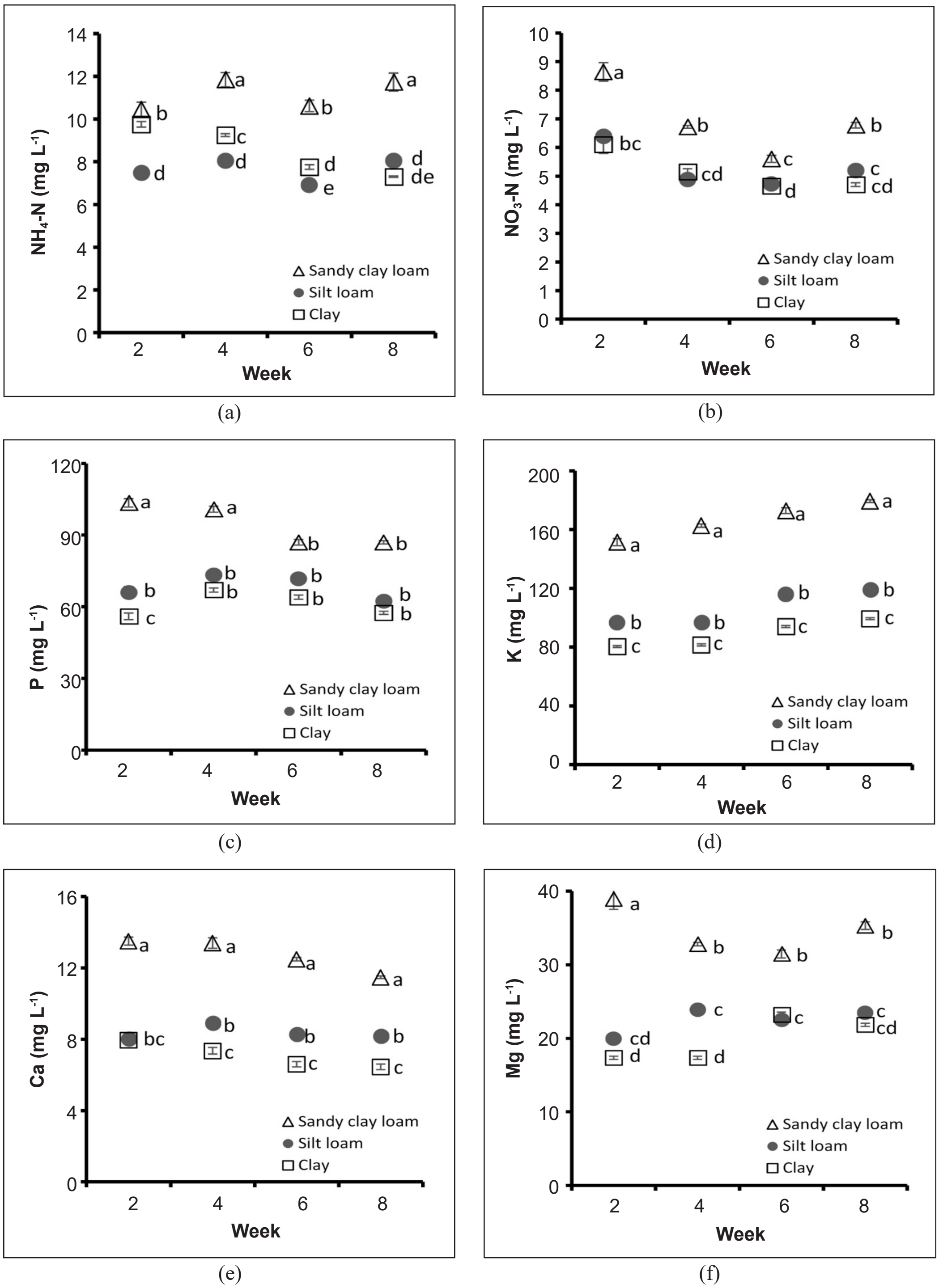
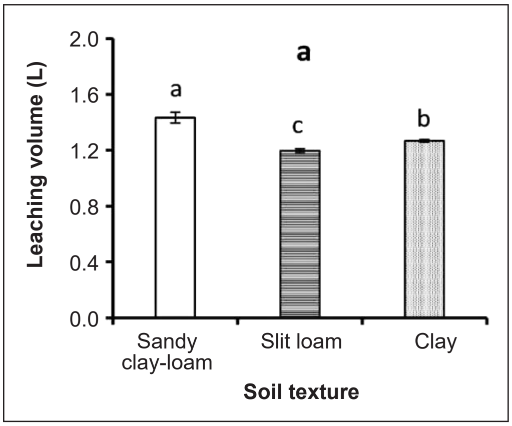
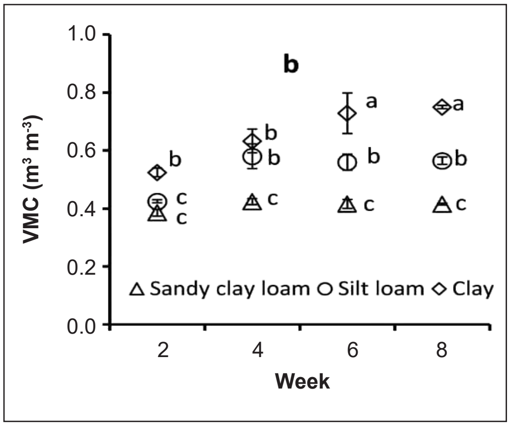


Figure 2. Means (± SE) of the interaction effect between sampling week and soil texture on the leaching of (a) NH_4^+–N, (b) NO_3^-–N, (c) P, (d) K, (e) Ca, and (f) Mg. Within the same chart, means with different letters are significantly different ($p<0.05$) based on the Tukey test



(a)



(b)

Figure 3. Means (± SE) of (a) leaching volume under continuous WRW application and (b) interaction effect between the soil texture and sampling week on volumetric moisture content. Within the same chart, means with different letters are significantly different ($p<0.05$) based on the Tukey test

Table 1
Physicochemical properties of the different soils used in the study

Parameters	Sandy clay loam	Silt loam	Clay
pH	5.32±0.21	6.3±0.11	6.8±0.26
EC (dS m^{-1})	0.72±0.05	1.03±0.10	0.62±0.04
Particle size distribution (%)			
Clay (<2 μm)	21.59±1.21	17.8±1.01	65.19±2.76
Silt (2-50 μm)	6.63±0.67	54.69±1.37	9.28±0.07
Sand (> 50 μm)	71.78±3.41	27.51±1.62	25.53±1.60
Texture class (USDA)	Sandy clay loam	Silt loam	Clay
Total C (%)	1.01±0.05	1.47±0.10	1.75±0.03
Total N (%)	0.08±0.01	0.12±0.01	0.15±0.01
NH_4^+–N (mg kg^{-1})	38.8±0.24	31.9±1.26	34.54±1.75
NO_3^-–N (mg kg^{-1})	3.70±0.12	5.96±0.42	4.85±0.32
P (mg kg^{-1})	12.4±0.41	23.6±1.02	19.2±0.81
K (cmol kg^{-1})	2.70±0.08	0.98±0.05	1.51±0.03
Ca (cmol kg^{-1})	7.89±0.52	5.41±0.11	7.79±0.22
Mg (cmol kg^{-1})	2.81±0.11	1.72±0.03	0.95±0.05
Bulk density (Mg m^{-3})	1.50±0.04	1.60±0.04	1.55±0.02
CEC (cmol kg^{-1})	7.24±0.13	6.33±0.14	11.24±0.30
Volumetric soil water content (m^3 m^{-3})			
Saturation	0.62±0.03	0.73±0.02	0.78±0.03
Field capacity	0.31±0.01	0.37±0.01	0.45±0.01
Permanent wilting point	0.13±0.01	0.21±0.01	0.26±0.01

8 relative to the second week of sampling. The addition of amendments found improved soil aggregate and pore structure and subsequent increase in water holding capacity of soils (Liu et al., 2020; Villagra-Mendoza & Horn, 2018). In this study, the improvement in volumetric moisture content could be due to WRW elements, particularly the C content that is transferred altogether during the watering. Continuous rice washing will increase the nutrients leaching from the rice into the WRW. The WRW contains a greater amount of carbon (3.63 g L^{-1}) (Table 2), which could help bind the soil particles together, thereby improving the water and nutrient-holding capacity of the soil. Nabayi, Sung, Zuan, Paing, and Akhir (2021) reported C among the greater elements leached from washing rice, which could help improve the soil's retention capacity. The significantly lower retention of the NO_3^-–N in the soils, especially the sandy clay loam, could be attributed to the lower retention and higher leaching of NO_3^-–N in the soil relative to the other soil textures. Leaching results by Cui et al. (2021) infer that NO_3^-–N is more susceptible to leaching than the P, corroborating our results. The decrease in the concentration of P leaching of the soils relative to what was added from the WRW could be due to the increase in soil P retention or precipitation of P by Ca and or Mg ions, as stated by other studies (Fang et al., 2020; Mitrogiannis et al., 2017). Similarly, Tahir and Marschner (2017) reported lower leaching of inorganic N in clay-amended soil than in sandy soil.

The cumulative leaching of the elements from the different textured soils at the end of the 8-week study was in the order K > P > Mg > NH_4^+–N > Ca > NO_3^-–N. The higher cumulative leaching of K and P could be due to their greater content in the WRW relative to other elements (Table 2). The least Ca leachate recorded in the soils relative to other elements could be attributed to its precipitation by P and other micronutrients such as Zn.

Table 2
Means (± SE) element analyses of washed rice water (WRW) and tap water

Parameters	WRW *	Tap Water
pH	6.53 ± 0.02	6.58 ± 0.02
EC (μS cm^{-1})	372.83 ± 34.53	125.36 ± 28.21
Total C (g L^{-1})	3.63±0.12	0.03 ± 0.002
S (g L^{-1})	0.60±0.04	100 ± 9.64
Total N (mg L^{-1})	80.50 ± 5.20	30.20 ± 4.12
NH_4^+–N (mg L^{-1})	18.88 ± 1.68	1.44 ± 0.04
NO_3^-–N (mg L^{-1})	16.02 ± 1.41	1.45 ± 0.03
P (mg L^{-1})	57.74±3.76	0.05 ± 0.02
K (mg L^{-1})	123.84±14.21	5.74 ± 0.15
Ca (mg L^{-1})	18.68±2.10	10.95 ± 0.06
Mg (mg L^{-1})	19.37±1.76	0.97 ± 0.06

Note. * the WRW was obtained at 3:1 volumetric water-to-rice ratio washed at 80 rpm

Kleinman et al. (2002) and Nabayi, Sung, Zuan, Paing, and Akhir (2021) found a positive relationship between Ca and P which indicates that the availability of one would affect the other. The higher cumulative leaching of K, irrespective of the soil texture, could be due to its monovalent nature, which makes it more easily leachable than other elements. Monovalent elements such as K, NH_4^+–N, and NO_3^-–N, among others, have higher solubility relative to their divalent counterparts (i.e., Ca and Mg) (Petrucci et al., 2011) and, therefore, leached easily (Nabayi, Sung, Zuan, Paing & Akhir, 2021). For soil texture, the sandy clay loam had higher cumulative leaching of the elements with 666.29, 378.13, 138.51, 50.82, 44.61, and 27.30 mg L^{-1} of K, P, Mg, Ca, NH_4^+–N, and NO_3^-–N, respectively, while the least were mostly obtained in the textured clay soil (Figure 4). After 8 weeks of WRW application, the clay and silt loam soils were shown to retain the WRW nutrients more than the sandy clay loam soil. The higher retention in clay and silt loam soils could be due to their greater proportions of smaller particle sizes with higher surface area to attract the elements rather than being allowed to leach, as was the case in the sandy clay loam soil. Clay soil is dominated by micropores which can retain higher water and nutrients than sandy soil (Bollyn et al., 2017). Tahir and Marschner (2017) reported that amending sandy soil with clay soil decreased N and P nutrient leaching and increased their retention in the sandy amended soil.

The summary of ANOVA for the leachate analyzed parameters under different soil textures, water types, and weeks is presented in Table 3. The interaction between soil texture, water type, and week on NH_4^+–N and NO_3^-–N, P and K, and Ca and Mg, respectively, showed that significantly higher elements were observed in the WRW-treated soils while the least was obtained in the tap water treated soils (Figures 5 to 7). Under all the tap water treatments, the leaching of the nutrients was in the order Ca > K > Mg > P > NH_4^+–N > NO_3^-–N. The tap water treatments, irrespective of the soil texture, leached lower NH_4^+–N (152.6-206.6%), NO_3^-–N (37.1–170%), P (1509.8–1815.9%), K (896.4–1080.0%), and Mg (329.1–431.1%) than the WRW treated soils. On the other hand, the tap water-treated soils had higher leaching of Ca (25.5–47.7%) than the WRW-treated soils.

Table 3

Summary of analysis of variance (ANOVA) showing Pr > F for leachate analyzed parameters under different soil texture (ST), water type (WT), and week (W)

Parameters	ST	WT	W	STxWT	STxW	WTxW	STxWTxW
NH_4^+–N	**	**	**	**	**	ns	*
NO_3^-–N	**	**	**	**	**	ns	*
P	**	**	**	**	**	**	**
K	**	**	**	**	ns	**	ns
Ca	**	**	ns	ns	**	**	**
Mg	**	**	ns	***	**	*	**

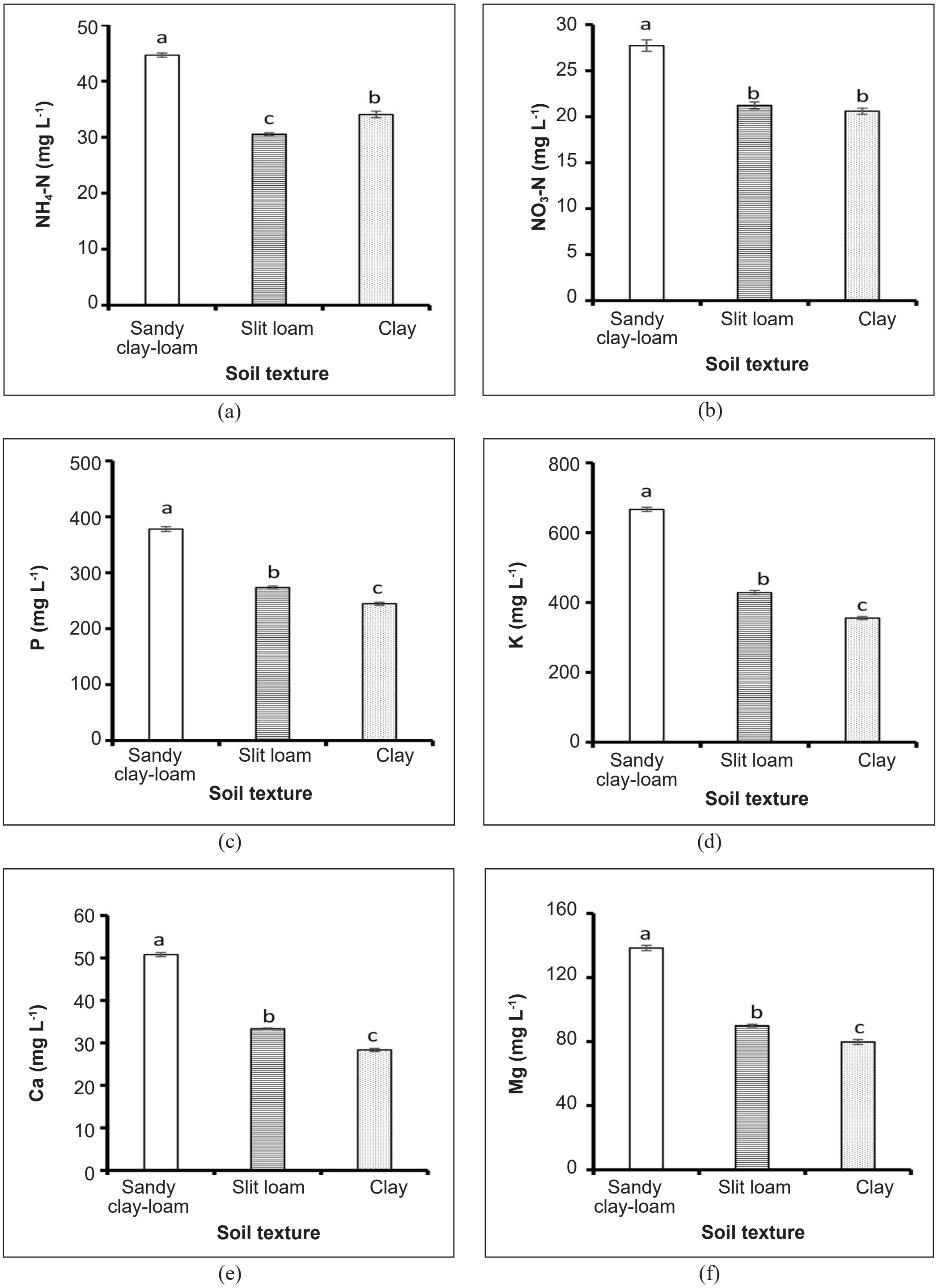
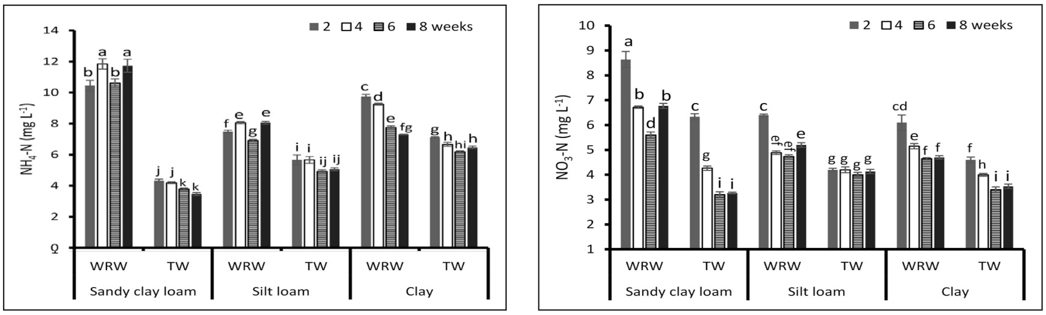
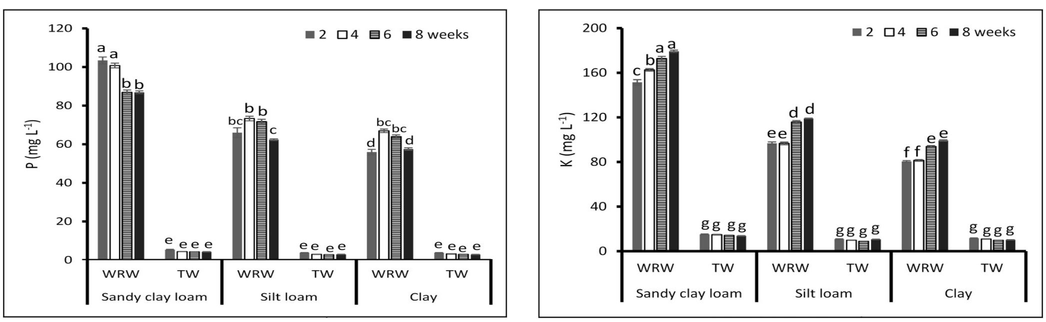


Figure 4. Cumulative leaching (±SE) after 8 weeks for (a) NH_4^+–N, (b) NO_3^-–N, (c) P, (d) K, (e) Ca, and (f) Mg under different soil textures. Within the same chart, means with different letters are significantly different ($p<0.05$) based on the Tukey test



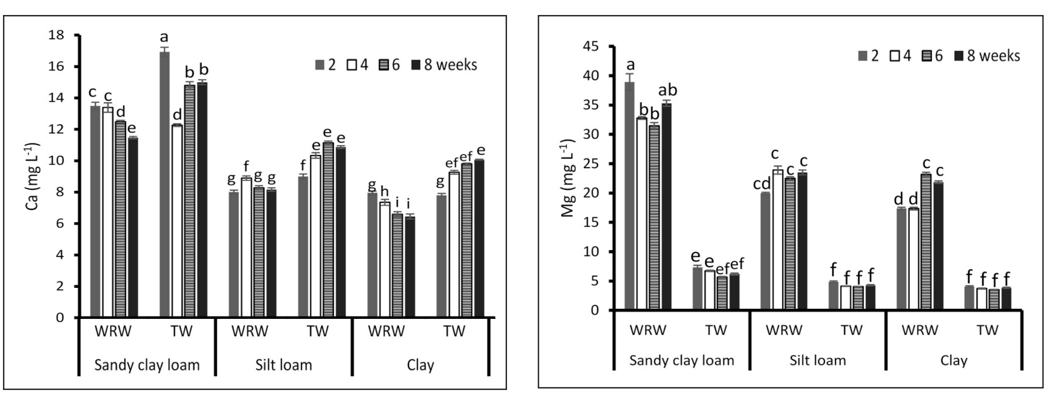
(a) (b)

Figure 5. Means (± SE) of an interaction effect between ST, WT, and W on (a) NH_4^+–N and (b) NO_3^-–N leaching. Within the same chart, means with different letters are significantly different ($p<0.05$) based on the Tukey test (means separations based on all treatment combinations). WRW washed rice water, TW tap water, ST soil texture, WT water type, W sampling week



(a) (b)

Figure 6. Means (± SE) of an interaction effect between ST, WT, and W on (a) P and (b) K leaching. Within the same chart, means with different letters are significantly different ($p<0.05$) based on the Tukey test (means separations based on all treatment combinations). WRW washed rice water, TW tap water, ST soil texture, WT water type, W sampling week



(a) (b)

Figure 7. Means (± SE) of an interaction effect between ST, WT, and W on (a) Ca and (b) Mg leaching. Within the same chart, means with different letters are significantly different ($p<0.05$) based on the Tukey test (means separations based on all treatment combinations). WRW washed rice water, TW tap water, ST soil texture, WT water type, W sampling week

Soil Nutrient Retention and Percentages of Elements Recovery in Leachate

The mass of the elements added with the WRW, nutrient retention in the soil after WRW application for 8 weeks, and percentage mass of element recovery in leachate is shown in Table 4. In contrast to the cumulative nutrients leached from different soil textures, there was higher retention of the nutrients due to the WRW application observed in clay soil, followed by silt loam, while the sandy clay loam soil had the least. The clay and silt loam textured soils had a range increase of 3.9–18.2% NH_4^+–N, 0.43–8.4% NO_3^-–N, 25.4–1358.5% P, 18.1–187.5% K, 5.3–30.1% Ca, and 25.2–705% Mg than the sandy clay loam textured soil. The K was the highest element leached and retained regardless of soil texture. Despite its solubility, the higher retention of the K could be associated with its greater amount (relative to other elements) in the WRW (Table 2). Despite K being easily leached due to its higher solubility (Nabayi, Sung, Zuan, Paing & Akhir, 2021; Petrucci et al., 2011), it also can replace elements in the soil surface via adsorption. The higher retention of other elements in the clay compared to the silt loam and sandy clay loam soils could be attributed to the soil's higher nutrient and water retention capacity, indicated in its higher CEC (Table 1).

The availability of nutrients in soils and streams is mainly affected by the soil colloids, and the smaller the colloids, the higher the retention sites of the soils (Bollyn et al., 2017). The soil colloids may bind large portions of readily available plant nutrients and organic matter (Carstens et al., 2018). Clay soil is dominated by micropores that retain higher water and nutrients than sandy soil. Tahir and Marschner (2017) reported that amending sandy soil with clay soil decreased N and P nutrient leaching and increased their retention in the sandy amended soil. However, the least retained element was Mg, irrespective of the soil texture, which was negative in sandy clay loam (Table 4). The negative retention in sandy clay loam indicated the leaching of Mg greater than the amount added through WRW application, and this surplus came from the inherent soil Mg content. The lower retention of Mg in all soil textures could be associated with the lower Mg content of the WRW. The significantly ($p<0.01$) higher percentage recovery of the elements in the leachate was recorded in the sandy clay loam, which differed from the other soil textures.

The increase in the recovery of the elements was higher in the sandy clay loam leachate by 212.5–283.1% NH_4^+–N, 106.5–128.8% NO_3^-–N, 37.8–55.5% P, 58.6–97.1% K, and 58.6–76.5% Mg. Irrespective of the soil texture, the Ca recovered in the leachate was higher than the Ca content of the WRW, which led to a negative percent recovery (Table 4). The percentage recovery result agrees with the cumulative leachate results (Figure 2), which still highlights the sandy textured soils' inefficiency in retaining nutrients compared to other soil textures. The results ranging from the nutrient leaching of the elements to the percentage of elements recovered in the leachates by the different soil textures, suggested

Table 4

Mass of the elements added with the WRW (mg per column), Nutrient retention in the soil after WRW application for 8 weeks, and percentage mass of element recovery in leachate due to WRW application. The percentage of elements added with the WRW was computed based on mass balance calculations (mass: mass). The percent recovery for each element was calculated by subtracting the average mass of each element recovered in the leachate for columns that did not receive WRW from the mass recovery for columns that did receive WRW, dividing by the mass of the element in the WRW added to the column, and then multiplying by 100

Mass of elements added to the columns with the WRW (mg element per column)						
Soil texture	NH_4^+–N	NO_3^-–N	P	K	Ca	Mg
All soils	30.6	28.22	97	208.06	31.38	32.54
Nutrient retention per column (mg element per column)						
Soil texture	NH_4^+–N	NO_3^-–N	P	K	Ca	Mg
Sandy clay loam	19.42 ± 0.59b	21.28 ± 0.39b	2.46 ± 0.21c	41.46 ± 4.10c	18.66 ± 1.63b	-2.08 ± 0.11c
Silt loam	22.96 ± 0.72a	22.92 ± 0.51a	28.62 ± 2.20b	100.92 ± 6.4b	23.06 ± 2.14ab	10.06 ± 0.57b
Clay	22.08 ± 0.84a	23.08 ± 0.43a	35.88 ± 1.87a	119.22 ± 3.98a	24.28 ± 0.81a	12.60 ± 0.35a
Percentage of elements added with the WRW recovered in the leachate (mg added: mg recovered)						
Soil texture	NH_4^+–N	NO_3^-–N	P	K	Ca	Mg
Sandy clay loam	23.56 ± 4.22a	9.44 ± 2.03a	92.71 ± 4.83a	74.02 ± 11.06a	-6.27 ± 0.76a	86.79 ± 12.94a
Silt loam	7.54 ± 1.31b	4.14 ± 0.32b	67.27 ± 3.82b	46.66 ± 5.84b	-6.37 ± 0.61a	54.70 ± 4.20b
Clay	6.15 ± 0.91b	4.57 ± 0.74b	59.61 ± 3.29c	37.55 ± 4.98c	-6.89 ± 0.69a	49.17 ± 3.12b

Note. Numbers followed by a different letter(s) within the same column differ significantly from one another at a 5% level of significance based on the Tukey test

an improvement in the soil's water and nutrient retention so that these elements can be retained and used by plants.

Though greater improvement is needed in the sandy clay loam, it would also be equally influential in the silt loam and clay soils. In addition, despite the higher recovery of K in the silt loam and clay, the K could create an imbalance in plant nutrient uptake. Adding lower-density organic materials such as biochar and compost could improve the soil's retention of water and nutrients from the WRW. Furthermore, adding the organic amendment would also improve the CEC of the soils, thereby raising their fertility levels. Recent research has demonstrated that using biochar improves soils' ability to retain NO_3^-–N and phosphate-P, hence lowering leaching (Chandra et al., 2020; Matichenkov et al., 2020; Riddle et al., 2018; Wu et al., 2019), which could also reduce the leaching of K, Ca, and Mg due to the improved CEC that will result from the use of the amendment. In addition, applying natural minerals such as zeolite reduced K leaching (Macolino & Zanin, 2014). Soil optimization of mycorrhizal biomass can also decrease element losses of K, NO_3^-, NH_4^+, and other elements (Cavagnaro et al., 2015). The increase in the soil microbial population can also promote nutrient retention and improve a plant's ability to sequester nutrients, thereby reducing their leaching (Drinkwater et al., 2017). The 38-day leaching study on two contrasting soils by Cui et al. (2021) suggested the addition of mineral-loaded biochar to potentially lower the soil P and NO_3^-–N leaching risk. Similarly, using clay soil to amend sandy soil was also found to increase the retention of N and P by more than 2-fold in the amended soil (Tahir & Marschner, 2017).

The findings of this study show that WRW addition to the contrasting soil textures improves the nutrient contents of the soils. The results agree with Laird et al. (2010), who reported that improved retention of these nutrients in the soil profile should increase the possibility for plants to uptake these nutrients, thus minimizing the risk of environmental pollution and contamination that the accumulation of the leached nutrients would have caused. This study's overall impact will enhance the efficiency of nutrient and water use, reducing the chemical fertilizer need. A long-term field experiment aimed at testing this hypothesis is underway.

The present study is limited to using only a fresh form of WRW for 8 weeks. Washed rice water fermented at different periods exhibits chemical and biological behaviors (Nabayi, Teh et al., 2021) and physically, which could affect the leaching pattern of the different soil textures. On the other hand, though the results reported in this study are tentative, as *a priori* subjecting the soils to WRW application for a longer period will show the soils' water and nutrient retention at full capacity.

CONCLUSION

This study's 8-week leaching experiment demonstrated that continuous application of WRW could potentially lead to surface and groundwater contamination, particularly due to the relatively higher P and K contents of the WRW. Different soil textures responded differently to the WRW application, where the sandy clay loam soil had more leaching losses in terms of nutrient concentrations (37.8–238.1%), and leaching volume (13.1–19.8%), but the other two soil textures (silt loam and clay) had comparable results with each other. The least nutrient and water retention were observed in the sandy clay loam soil, with 26–44% lower than the other two soil textures. This study highlighted the need for amendment strategies to retain these elements in the soils for plant use. Therefore, it is suggested that the WRW should be used as a plant nutrient source rather than discarded for agricultural purposes. It is also recommended that organic material should be added to the soil prior to the WRW application to improve the water and nutrient retention of the soils, particularly for soils high in sand content, and that WRW should be added in small amounts but frequently to minimize the risk of nutrient leaching losses.

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