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REGULAR ARTICLE

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How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching

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Abstract
Aim Recycling of cocoa pod husks has potential to contribute to mineral nutrition of cocoa. Yet little is known of the nutrient content and nutrient release patterns from the husks. The potassium (K) rich husks are usually left in heaps in cocoa plantations in Africa. We aimed to understand and quantify release patterns of K and other nutrients from husks under varying rainfall regimes and assessed the effects of partial decomposition and inundation on nutrient leaching rates.
Methods We incubated chunks of cocoa pod husks to assess decomposition rates and we measured nutrient leaching rates from two sets of husk chunks: one set was placed in tubes that were submitted to simulated scheduled rainfall events while the second set was continuously inundated in beakers.
Results Decomposition of husks followed a second-order exponential curve (k: 0.09 day^{-1}; ageing constant: 0.43). Nutrient losses recorded within 25 days were larger and more variable for K (33%) than for other macronutrients released in this order: Mg > Ca ≈ P > N (less than 15%). Potassium leaching was mainly driven by rainfall frequency ($P < 0.05$) and reinforced by intense rainfall, especially at lower frequency. Under water-saturated conditions, 11% of K was leached out within 48 h from fresh husks compared with 92% from partially decayed husks.
Conclusion Some initial decomposition of cocoa pod husks is required to expose K to intense leaching. As decomposition progresses, abundant K losses are to be expected under frequent and/or intense rainfall events.

Keywords Nutrient cycling · Potassium · Cocoa pod husks · Leaching tubes · Farmer practices

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Introduction

Cocoa (*Theobroma cacao* L.) is a major source of income for about 5 million small-scale farmers (Poelmans and Swinnen 2016). Approximately 74% of the global production originates from four countries in West and Central Africa: Côte d'Ivoire, Ghana, Cameroon and Nigeria (ICCO 2020), where the cocoa plantations are among the least productive in the world (Oomes et al. 2016). A recent survey in the two countries that produce the most cocoa - Côte d'Ivoire and Ghana - set the average cocoa bean yields at 352 and 423 kg ha^{-1} respectively (Bymolt et al. 2018). This is less than one-tenth of the potential yield of cocoa in West Africa (Zuidema et al. 2005). The most often reported causes of this poor productivity are high incidence of pests and diseases, sub-optimal farming practices such as pruning and shade management, ageing of plantations, and the lack of adequate plant nutrient supply (Wessel and Quist-Wessel 2015). The vast majority of cocoa plantations in West Africa is planted on cleared forest land whose nutrient capital accumulated over a long period (Ruf et al. 2014). The fertility of the forest soil is progressively depleted by continuous nutrient offtakes in the cocoa beans with inadequate recycling or inputs of nutrients.

At cocoa harvest the ripe pods are plucked and taken to a work station located on the plantation or nearby where the pods are split to extract the beans. The husks of the cocoa pods are most often simply left to rot in heaps at the work station. The cocoa pod husks contain substantial amounts of nutrients, especially potassium (van Vliet and Giller 2017). With an amount of nutrients estimated at 10.6–31.4 kg N ha^{-1} and 27.2–77.2 kg K ha^{-1} for 1000 kg of cocoa beans harvested (Hartemink 2005), poor management of the husks can cause fairly large losses from the plantations. The fresh cocoa husks weigh 10 times more than the dry beans they contain (Khanahmadi et al. 2016; Mansur et al. 2014). Based on this ratio and with an estimated 80% moisture content of the husks (Campos-Vega et al. 2018), the West African production of 3.5 million tons of dry beans (ICCO 2020) corresponds to 35 million tons fresh matter (FM) and seven million tons dry matter (DM) of cocoa husk generated in 2019, most of which is not actively managed. Active management of the cocoa pod husks thus provides a great opportunity to improve nutrient cycling in cocoa plantations.

Recommended Good Agricultural Practices (GAP) for cocoa plantations include active husk management (e.g. composting, mulching). When the pods are infected with black pod disease due to *Phytophthora* spp., they should be incorporated in soil or burnt to avoid inoculant dissemination through aerosols and insects. For healthy pods, it is recommended that farmers should use the husks to mulch the plantation (Asare and David 2011). Yet we lack a thorough understanding of how rapidly nutrients are lost from the husks or how they should best be managed as mulch. The initial high moisture content of the husks and humid climate in which cocoa is grown are conducive to rapid decomposition, and leaching losses from the soil can be further exacerbated by abundant rain.

Knowledge of the nutrient value and nutrient release patterns from cocoa pod husks is lacking, yet essential to improve plantation management. Although previous studies have revealed that rainfall is the main driver of nutrient leaching from various crop residues (Calonego et al. 2005; Rosolem et al. 2005; Salètes et al. 2004), little is known about cocoa pod husks which have a thick and highly differentiated pericarp (Lu et al. 2018). Indeed, most experimental designs did not differentiate the effect of the amount of rainfall from that of its frequency. Besides, when cocoa is grown in lowlands, heaps of cocoa pod husks may be exposed to temporary inundation. The speed and magnitude of nutrient leaching under such conditions remain poorly understood. Our research objective was to describe the kinetics of nutrient leaching from the husks and evaluate the effects of rainfall amounts and frequency, biomass decay, and inundation on nutrient leaching patterns. We hypothesised that leaching rates of K depend on water saturation, rainfall frequency and amounts, but not on biomass decomposition. To test this hypothesis, three laboratory experiments were conducted. The first experiment quantified the decomposition rate of cocoa pod husks at ambient temperature, high relative humidity, and in absence of biotic manipulation; the second experiment assessed the effect of the size of husk chunks and the amount and frequency of rainfall on nutrient loss rates from the chunks inserted in leaching tubes; and the third experiment tested the rate of nutrient leaching from husks in conditions of permanent water saturation that simulated inundation.

Materials and methods

Thirty freshly-harvested cocoa pods were collected from a smallholder cocoa farm in Cote d'Ivoire. After splitting the pods and removing the beans and pulp, the husks were packed and shipped to the Netherlands where they were stored at 4 °C. All the husks were delivered as half-pod, broken longitudinally. Before using any husk, we discarded 2 cm from both proximal (close to the peduncle) and distal ends, as well as 1 cm from the longitudinal edge to reduce any potential gradient in nutrient partitioning as observed in pears (Saquet et al. 2019) and to avoid bruised areas. We carried out a preliminary analysis of the husk nutrient content and the values were well within indicative ranges (Table 1).

Table 1 Composition of cocoa pod husks

Component	Measured values (average±standard deviation, %)	Ranges reported in literature (%)	References
C		40.9–50.23	1, 3, 8
N	1.21±0.38	0.17–2.23	1, 3, 8
P	0.14±0.04	0.15–0.32	2, 3, 4, 8
K	2.89±0.84	2.52–3.8	2, 3, 4, 8
Mg	0.26±0.06	0.11–0.28	2, 3, 4, 8
Ca	0.26±0.10	0.18–0.46	2, 3, 4, 8
S		0.14–0.97	1, 3, 8
Cellulose		12.9–35	2, 4, 5, 6, 7
Hemicellulose		8.7–12.8	2, 4, 7
Lignin		14–38.8	2, 4, 6, 7

(1) Adjin-Tetteh et al. (2018) (2) Campos-Vega et al. (2018) (3) Fidelis and Rajashekhar Rao (2017) (4) Lu et al. (2018) (5) Mansur et al. (2014) (6) Thomsen et al. (2014) (7) Titiloye et al. (2013) (8) Tsai and Huang (2018)

Experimental setup

We conducted three laboratory experiments. To analyse the relation between decomposition and leaching kinetics, an incubation experiment (Experiment 1) was established to measure the decomposition rate of husks. We ran two separate leaching experiments which differed in the degree of water saturation and duration of saturated conditions (Experiments 2 and 3).

- Experiment 1: decomposition of cocoa pod husks

In the first experiment the decomposition rate was analysed. Six replicate husks were sliced into 10 chunks of 25 g, giving a total set of 60 chunks that were used to quantify biomass loss over 63 days. At the onset of the experiment, the weight of each chunk was measured while the initial moisture contents of the husks were assessed from additional pieces. All the 60 chunks were incubated in the dark at 20 °C and a relative humidity (RH) of 100%, in aerobic conditions. To realise these conditions, the chunks were placed in individual aluminium crucibles, floating in a tray filled with water, the whole apparatus being enclosed in a plastic foil, with an ample headspace. At 0, 2, 4, 6, 8, 12, 16, 28, 49 and 63 days, one chunk per replicate was randomly selected and both fresh and dry weight (after 48 h in a 105 °C oven) were recorded.

- Experiment 2: nutrient leaching from leaching tubes

The treatments applied in this experiment were the size of the chunks, the frequency of the simulated rainfall, and the rainfall amount per rain event. We selected 16 husks of 400–600 g each, which were sliced into chunks of 2 g, 5 g or 25 g (hereafter referred to as small, medium, and large, respectively). Fifty grams fresh matter (FM) of chunks of the same size from each husk were used to fill individual PVC cylinders of 10 cm diameter to a height of 20 cm. Chunks from a given husk served to fill entirely one or more tubes. Two leaching treatments with demineralized water were used to simulate either a heavy (50 mm per event) or a light rain shower (12.5 mm per event). The water was sprinkled over each tube at 2, 4, or 8 day intervals. A treatment was a unique combination of either level of the three above-mentioned factors (e.g. '2 d, 50 mm, small' represented a tube containing small chunks that received every other day the equivalent of 50 mm of water, see Appendix Table 3). A blank treatment (leaching tube with no cocoa pod husk) was also included to detect any background nutrient contamination. The experiment ran for 31 days and was arranged in a 3 × 3 × 2 completely randomized design with three replicates. Room temperature was maintained at 20 °C throughout the experiment, while a paper-cup placed on the top of the leaching tube raised the RH inside the tubes to about 100%.

The leaching tubes (Fig. 1) were blocked at their base with a flat rubber-stopper perforated in the centre to create a small outlet. A filter-paper (20 μm mesh) was inserted in the tube, and mounted on the top of the rubber-stopper. The top of the tube was loosely covered with a perforated paper-cup used as dripper that delivered 1–1.6 mL/min. All leachates were collected until 48 h after water had been sprinkled; the volume was measured for each tube. A leachate sample was taken for each tube and analysed for K content. In addition, selected samples (Appendix Table 3) were analysed for other nutrients (N, P, Ca, Mg). At the end of the experiment (day 31), residual DM weight of chunks was determined.

- Experiment 3: potassium leaching under water-saturated conditions

In this experiment two batches of husks were subjected to permanent water-saturation: the first batch had only fresh husks while the second one consisted of

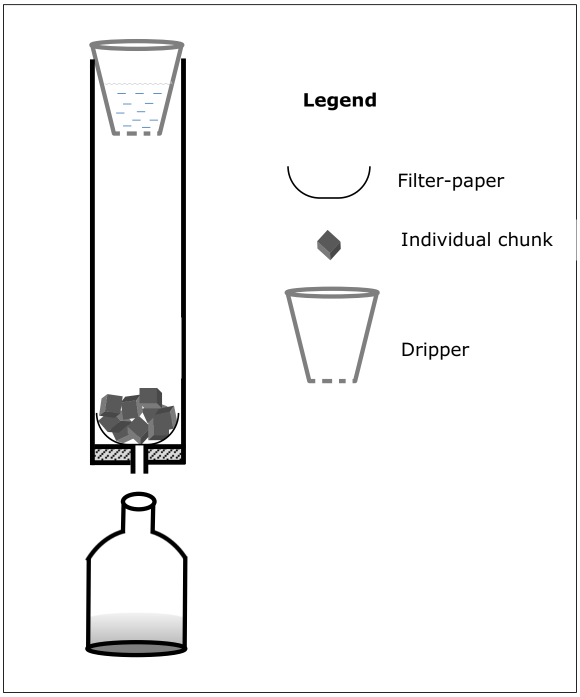

Fig. 1 Sketch of an individual leaching tube in Experiment 2

husks that already decayed for three-weeks to reflect the initial phase of husk decomposition. Three husks served as replicates, and were sliced into chunks of 25 g. Individual chunks (one per husk) were maintained at 15 cm depth in a beaker containing 2 l of distilled water. Over the first 48 h, a sample of the solution (10 ml) was taken at 20 min, 40 min, 1, 1.5, 2, 3, 4, 6, 10, 20, 36, and 48 h and each sample was analysed for its K content. The same procedure was repeated 3 weeks later with the second batch, using chunks from the same pods that had been kept in the incubator at 20 °C at a relative humidity of 100%.

Nutrient contents of leachates and of the initial husks were estimated. Potassium (K), Ca, and Mg were determined using Atomic Absorption Spectroscopy (AAS), whereas N-NO_3^-, N-NH_4^+ and P-HPO_4^{2-} were measured spectrophotometrically with a segmented-flow analyser as described by Houba et al. (2008). Due to the relatively-limited presence of ionic forms of N, P and Ca in the cell, we refer to these as "structurally-bound" elements in contrast with K and to a lesser extent Mg.

Data analysis

We expressed the residual amount of nutrients in husks and the residual weight (DM) as percentage of the values at the start of the experiments. The data were analysed for each experiment, with weight losses in experiments 2 and 3 estimated from curves developed using data from experiment 1 (explained below). Model performance was evaluated using the Akaike Information Criterion (AIC), the Schwarz Bayesian Criterion (BIC), the residual mean square error (RMSE), and the likelihood ratio test.

- Experiment 1

To describe the decomposition of the chunks, we used a second-order exponential model (Eq. 1, Yang and Janssen 2000). It expressed the percentage residual dry weight (C) as a function of time t (days), and was characterized by a constant decomposition rate k (day^{-1}) and a rate-modifier termed the 'ageing coefficient' (a) which basically allows for decrease of parameter k over time [1, 6].

$$C_i = e^{-kt^a} \qquad \text{for the } i\text{th husk}; i\in \tag{1}$$

A decomposition curve was fitted to observations with a non-linear mixed-effects model with pod as the random factor to account for non-linearity of most biological processes and the expected pod-to-pod variability in initial nutrient concentration. In doing so, we determined the model's parameters and estimated the loss in weight of husks over time.

- Experiment 2

We first compared losses of the different nutrients, by plotting the average residual amounts observed in the husks. We found that K losses followed curvilinear patterns for most leaching tubes, whereas trends were unclear for the other nutrients. Since we did not observe losses larger than 20% for the structurally-bound elements (N, P, Ca, Mg), we only compared their respective losses on day 25. For these elements we ran an analysis of variance (ANOVA) based on a linear mixed-effect model, considering only four contrasted treatments: '2 d, 12 mm, large', '2 d, 50 mm, small', '8 d, 12 mm, large', and '8 d, 50 mm, small' (see Appendix Table 3 for detail of treatments).

Potassium (K) was lost in larger and more variable amounts than the other nutrients. All the treatments were thus taken into account in the following analyses. We used a non-linear mixed-effect regression to describe K loss kinetics over a period of 50 days and to analyse the variations among treatments. This model (see details below) described residual K as a logistic function of time, but it also involved a multiple linear regression of the estimated parameters on the predictors (rainfall amount, frequency, size of chunks). Because the effect of chunk size was minimal in the full model that explained variation of one of the parameters, it was excluded from the set of explanatory variables for that parameter.

We compared the residual amount of the structurally-bound nutrients on the 25th day of experiment 2, based on a linear model (Eq. 2). The explanatory variables were the type of nutrient (X_1) and the treatment (X_2).

$$Y_{k,i|j} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 \quad (2)$$

where $Y_{k,i\|j}$	was the residual amount of the *k*th nutrient, measured on the *j*th tube on which the *i*th treatment was imposed, with $j \in [1, 12]$, $k \in [1, 4]$, and $i \in [1, 4]$;
X_1	was the macronutrient analysed;
X_2	was the treatment imposed on the chunks in the *j*th tube;
β_0	was the global intercept of the model;
β_1, β_2, and β_3	were the estimated coefficients associated to the individual effects of the macronutrient, the treatment and their interaction, respectively.

In order to describe patterns and evaluate variance of K loss through leaching, a non-linear regression (including a logistic function) was fitted to data from experiment 2. The logistic function (Eq. 3) was required to fit the general model which included two imbricated sub-models (Eq. 4 and Eq. 5) that were multiple linear regressions. The parameters *Xmid* (time to 50% K loss, days) and *RL* (leaching rate, day^{-1}) were regressed on rainfall, rain frequency, and size, while the parameter *Asym* (unitless) was kept constant throughout with a unique estimated value of 1.16 ± 0.02 ($P < 10^{-4}$).

$$Y_{abc|j} = \frac{Asym}{1 + e^{RL_{ab|j}\left(X - Xmid_{abc|j}\right)}} \quad (3)$$

with

$$Xmid_{abc|j} = \beta_0 + \beta_1 X_a + \beta_2 X_b + \beta_3 X_c + \beta_4 X_a X_b + \beta_5 X_b X_c + \beta_6 X_a X_c + \beta_7 X_a X_b X_c \quad (4)$$

and

$$RL_{ab|j} = \beta_8 + \beta_9 X_a + \beta_{10} X_b + \beta_{11} X_a X_b \quad (5)$$

as sub-models,

where *Y*	was the percentage residual K measured on the *j*th tube at *X* days, $j \in [1, 54]$;
Asym	was the coefficient describing the asymptotic value of initial K content (unitless);
Xmid	was the coefficient describing the inflexion point or time at 50% K loss (days);
RL	was the coefficient describing the leaching rate (day^{-1});
X_a	was the frequency at which rainfall events were scheduled, with $a \in [1, 2]$;
X_b	was the amount for individual rainfall events, with $b \in [1, 2]$;
X_c	was the size of the chunks, with $c \in [1, 3]$;
β_0 and β_8	were the global intercepts of the sub-models;
β_1-β_7,and β_9-β_{11}	were coefficients associated to the individual and combined effects of either predictor.

- Experiment 3

In inundated husks, K loss through leaching was expected as result of the strong concentration gradient between the immersed husks and the surrounding water, in line with Fick's first law of solute diffusion. To test if different rates of cocoa pod husk decay resulted in similar trends of K loss, we compared K leaching kinetics from fresh chunks with a set of chunks that was allowed to decompose for a 3-week period in an incubator at 20 °C. Loss of K under water-saturated conditions was described using Eq. 1, where *C* now represented the residual K (%) in the chunk at time *t* (hours). Similar to decomposition, the second-order decay curve was fitted to the data, using a non-linear mixed effects model. The estimated coefficients were compared using Welch's modified t-test (Welch 1947).

All the models were fitted in R (R Core Team 2013) via restricted maximum likelihood (REML) using the '*nlme*' package (Pinheiro et al. 2019) whereas t-tests were run with the '*BSDA*' package (Arnholt and Evans 2017). The mixed-effects models included a random-intercept (husks for Experiments 1 and 3, and tubes for Experiment 2) with unconstrained variance-covariance matrices obtained via Log-Cholesky parametrization (Pinheiro and Bates 1996).

Results

Decomposition of cocoa pod husks

Cocoa pod husk decay was described satisfactorily by a second-order exponential function ($R^2 = 0.77$, Fig. 2). The fitted second-order exponential model showed a sharp decrease with 24% and 32% DM weight loss after 14 and 30 days respectively, gradually followed by a phase of slower weight loss and reduced decomposition rates. Extrapolating this model to a year suggested that more than 33% of the initial DM weight of the husks would remain in absence of exogenous factors such as human manipulation, macrofauna activity or fluctuating environmental conditions. The second order model was more accurate (RMSE of 0.05%) than the first-order model (RMSE = 0.11%) which had a smaller coefficient of determination ($R^2 = 0.71$, Appendix Table 4).

Overview of nutrient leaching under scheduled rain simulations

Of all the nutrients tested, K losses were strongest and most variable across the treatments (e.g. 33 ± 21% on day 25). More structurally-bound nutrients N, P, Ca, Mg recorded average losses of less than 15% at the end of the experiment (day 31, Fig. 3). Nutrient losses on day 25 significantly differed among the more structurally-bound nutrients ($P < 0.05$), with Mg being the most leachable among these (10 ± 9%). On the contrary, N was hardly released throughout the experiment, with less than 1% lost from any of the treatments, suggesting that the inorganic N content of the husk cells was either very small or that any N released was strongly immobilized. Treatments did not affect nutrient losses ($P > 0.05$, Appendix Table 5).

Effects of the size of chunks, amounts and frequency of rainfall on potassium leaching

Leaching curves

For most combinations of rainfall amount (12.5 and 50 mm) and frequency (2, 4 or 8 day intervals) the size of the chunks did not consistently influence K leaching patterns over the simulated period (0–50 days, Fig. 4), with exception of 12.5 mm rainfall at an 8-day interval. For this latter treatment, leaching curves were very dissimilar across chunk sizes, with the smallest chunks losing 33% more K than the largest chunks on day 50 (Fig. 4c).

The effect of the interaction between frequency of rainfall and rainfall amount on K leaching was significant ($P < 0.05$, Table 2). The rainfall frequency did not affect K loss patterns when 50 mm rainfall events were provided. Treatments with 50 mm and 2, 4 and 8-day rainfall frequency intervals did not differ more than 18% in the total amount of K lost on day 50 (Fig. 4b and c). The estimated effect of rainfall frequency was larger at 12.5 mm rainfall. Treatments with 12.5 mm and 8-day intervals lost 12–45% K on day 50 while the treatments with 12.5 mm and 2 day intervals lost 80–82% K (Fig. 4a and c).

The amount of rainfall per rainfall event intensified K losses, more so for less frequent rainfall events (Fig. 4). The differences between the treatments with 12.5 mm and 50 mm per rainfall event at 2, 4 and 8-day intervals were 4–5%, 10–23% and 22–56% respectively.

We also compared rainfall regimes, 12.5 mm every 2 days with 50 mm every 8 days, with the same cumulative amount of rainfall (200 mm at day 31). The total K lost did not differ between rainfall regimes, with largest differences about 13% on day 47 (Fig. 4). Based on the model, it was expected that these differences would become smaller if the experiment were run for a longer period of time, to less than 5% by day 83 (not shown).

Model parameters

The rainfall frequency had the largest effect on the estimated values of time to 50% K loss (*Xmid*) and K leaching rate (*RL*, Fig. 5). Potassium leaching from cocoa pod husks increased with rainfall frequency. Reducing rainfall frequency from 2 to 8-day intervals, resulted in increased *Xmid* value of 19 days ($P < 0.001$), decreasing leaching rates by 54% ($P < 0.001$).

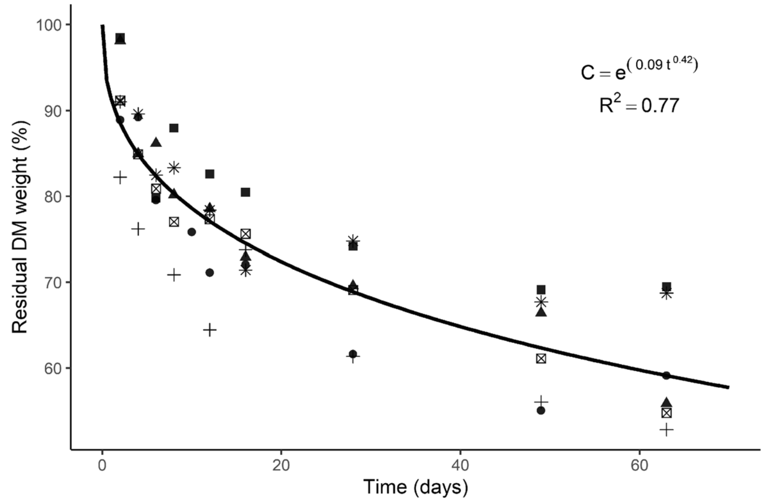

Fig. 2 Fitted decomposition model to observations from chunks of cocoa pod husks left at 20 °C, 100% RH. Each replicate is represented by a different symbol

Overall, quadrupling the amount of water did not have a significant effect on the parameters *Xmid* and *RL* (Table 2). However, at 8-day rainfall intervals, *Xmid* decreased by 15 days ($P < 0.05$), and *RL* increased from 0.03 to 0.05 day^{-1} ($P < 0.05$) for the 50 mm when compared to the 12.5 mm treatments. The effect of the size of chunks was not significant, except for *Xmid* at a rainfall frequency of 8 days with 12.5 mm, with the largest chunks retaining more K than the smallest ($P < 0.05$, not shown).

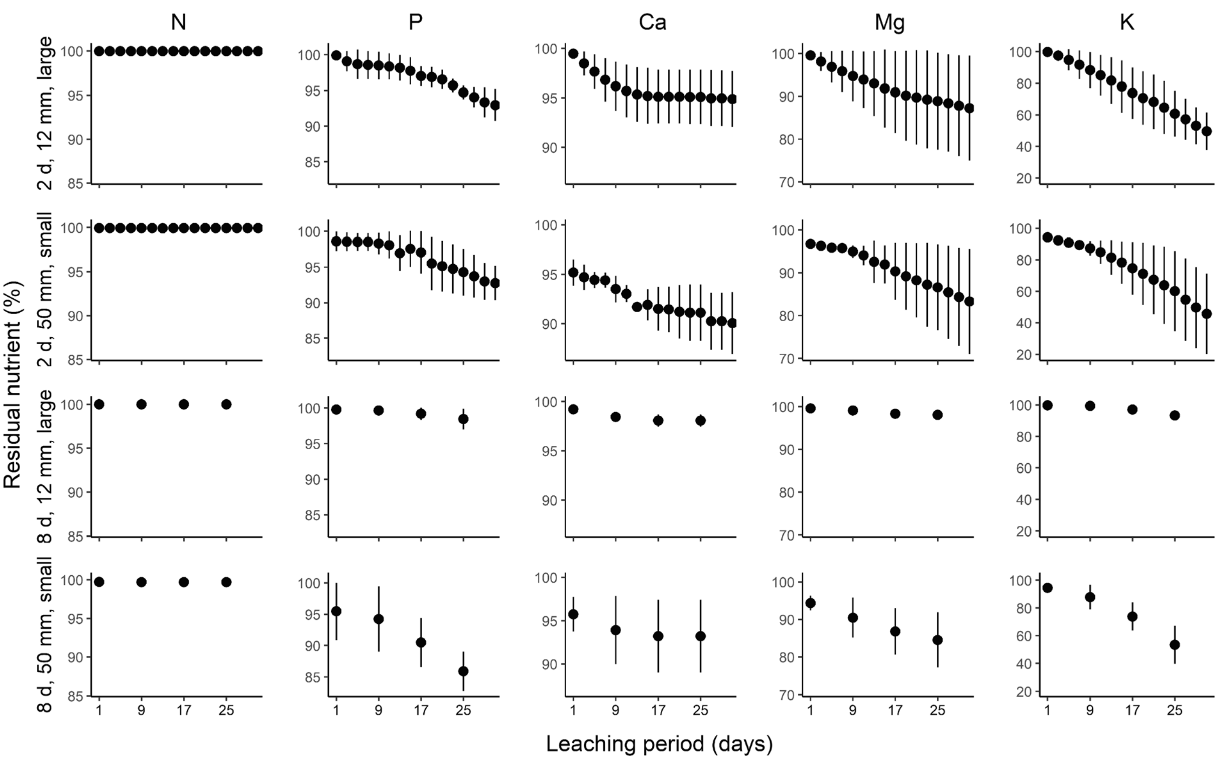

Fig. 3 Average (± standard deviation) nutrient losses from cocoa pod husks ($n = 3$) for selected treatments in a scheduled leaching experiment (Experiment 2). For each row, the minor y-axis was labelled after the treatment with, in this order: rain frequency (2-day versus 8-day intervals), rainfall amount (12.5 versus 50 mm per event), and size of the chunks (small versus large)

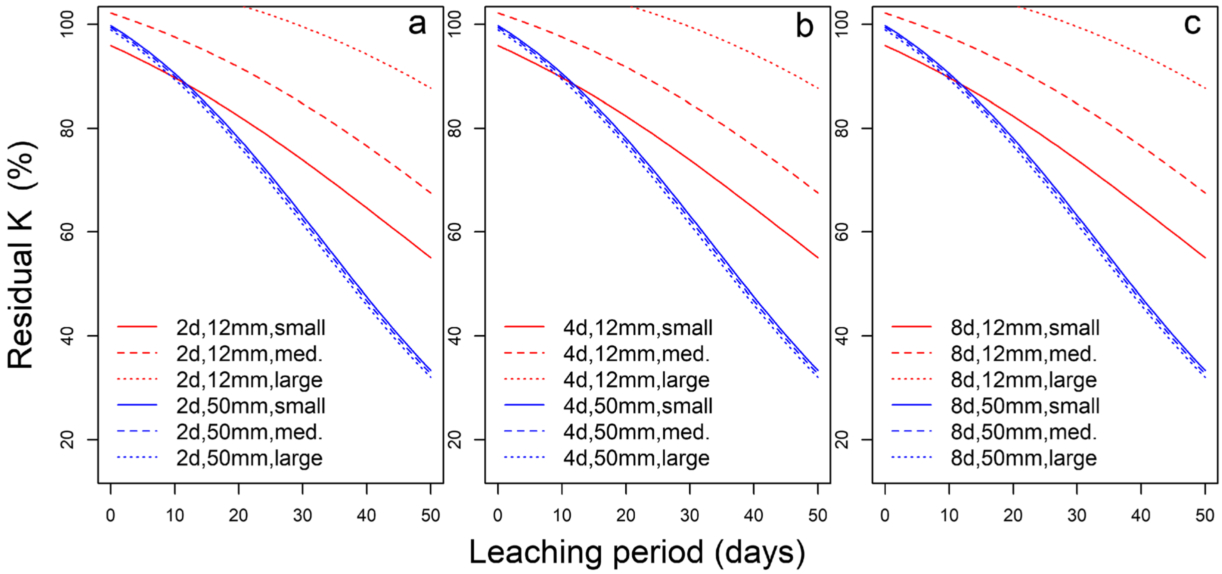

Fig. 4 Simulated effects of the chunk size of cocoa pod husks (line type) and rainfall (line colour) on K leaching patterns at different scheduled rain frequencies (subplots) over a period of 50 days. Treatments are indicated in the legend in this order: rainfall frequency (day intervals), rainfall amount (mm), and size of the chunks (small, medium or large)

Effect of decomposition on K leaching from cocoa pod husks under water-saturated conditions

Fresh husks under water retained most of their K with less than 11% of K lost after 48 h (Fig. 6), partially accounting for nutrient release due to bruising during chunk slicing. The observed K loss followed an exponential pattern, with a small leaching constant (k = 0.03 day^{-1}). A protective jellified layer of hydrated pectates was formed around the chunks immersed in water, temporarily preventing husks from further water absorption. In comparison, K leaching from husks was much faster, with 81% and 92% losses recorded within 24 and 48 h respectively when inundated after a period of 3 weeks of decay (Fig. 6), corresponding to a weight loss of only 28% in aerobic conditions (Fig. 2). The estimated values for both the k and a coefficients were significantly larger ($P < 0.001$, not shown) for these partly decayed husks when compared with fresh husks.

Table 2 Significance (probability of Wald F-tests) of the effects of rainfall frequency, rainfall amount, and size of the chunks on K leaching patterns from cocoa pod husks in a scheduled leaching (experiment 2)

Main and Interaction terms of regression	Estimated parameters		
	Asymptotic leachability	Time to half K (*Xmid*)	Leaching rate (*RL*)
Intercept	<0.001	< 0.001	< 0.001
Rain frequency (‘Frequency’)		< 0.001	< 0.001
Rainfall		NS	NS
Size		NS	
Frequency x Rainfall		<0.05	<0.05
Frequency x Size		<0.01	
Rainfall x Size		NS	
Frequency x Rainfall x Size		<0.01	

NS non-significant. Empty cells indicate terms for which selected coefficients were not available as a consequence of constraints imposed on the model structure

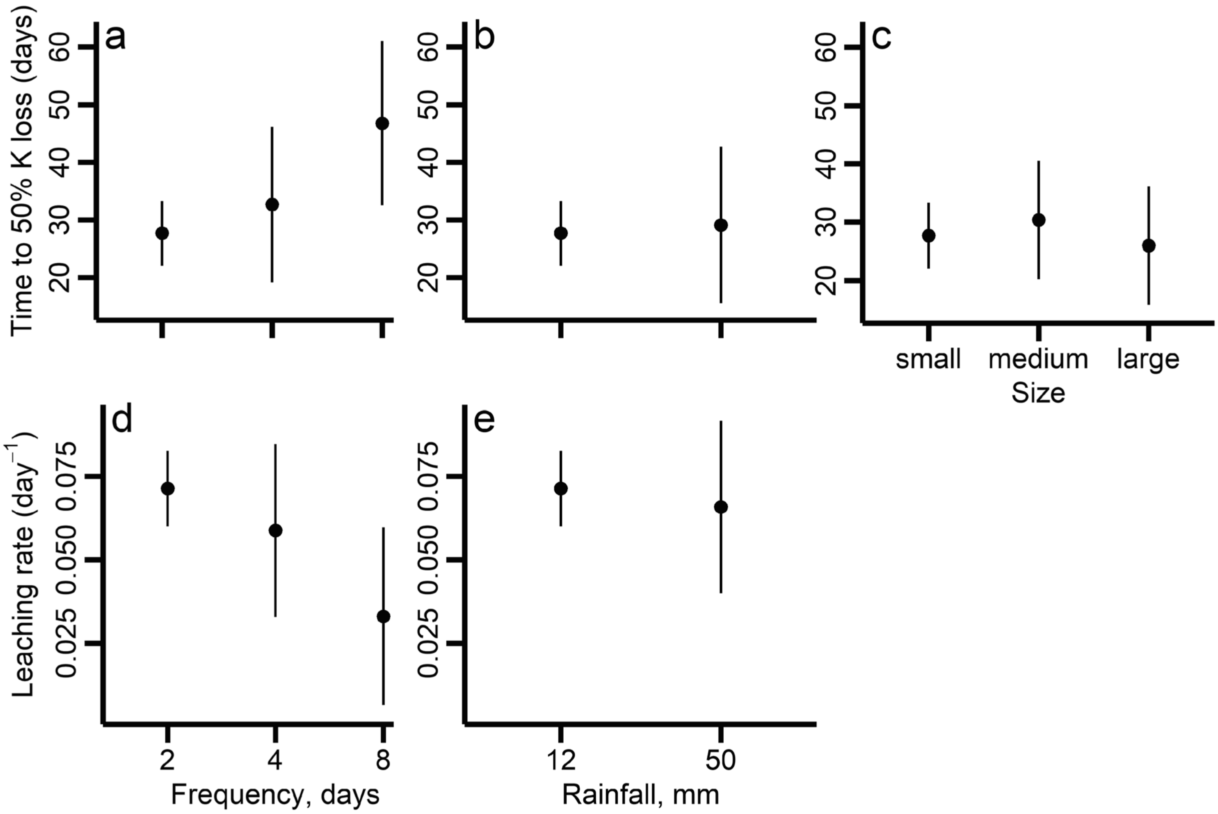

Fig. 5 Estimated main effects (±95% confidence intervals) of rainfall frequency (**a**, **d**), rainfall amount (**b**, **e**), and size of chunks (**c**) on time to 50% K loss (**a**, **b**, **c**) and K loss rate (**d**, **e**) from cocoa pod husks in a scheduled leaching experiment (experiment2). All interaction effects are displayed in Appendix Table 6

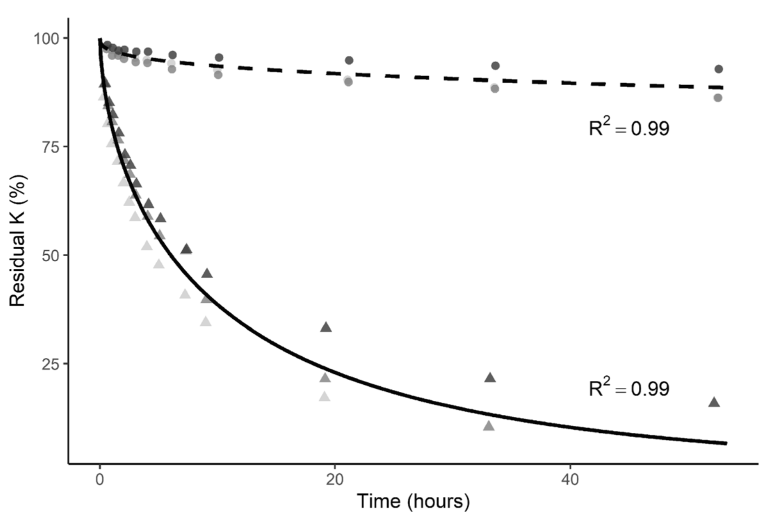

Fig. 6 Changes in the residual K under saturated conditions for fresh and partially decomposed cocoa pod husks after a 3-week incubation at 20 °C and 100% humidity. The changes in the percentage of residual K as a function of time were described with a second-order exponential model. Circles and triangles (replicates in grey-scale) represent fresh and partially decayed (3-week) husks, respectively. Fitted models are shown with dashed and solid lines for fresh and partially decayed husks, respectively. Coefficients are estimated in Appendix Table 7

Discussion

To gain insights into the temporal availability of nutrients in cocoa pod husks, we analysed the losses of K, Mg, Ca, N and P in leaching experiments. The husks contain large amounts of K with concentrations of about 3%. Potassium is a yield-limiting nutrient in many cocoa plantations, especially in more demanding environments with limited shade conditions (Ahenkorah et al. 1987). We observed that K leached rapidly from the husks, with leaching rates varying as a function of rainfall amount and frequency (Fig. 4). Under frequent and abundant rainfall events (2-day interval, 50 mm per event), we recorded less than 11% K losses after 10 days, and up to 45% K losses after 31 days. Our fitted regression model predicted that 78% K will be lost after 50 days. By contrast, more structurally-bound nutrients in the husks (such as Ca, P and N) did not leach in large amounts during the same period (less than 15% after 31 days for all treatments, Fig. 3). Under inundated conditions, K leaching from decomposed husks occurred rapidly when compared to fresh husks (92% versus 11% K respectively lost within 2 days, Fig. 6). Therefore, inundation occurring during the first days after pod breaking would likely not deplete a husk pile of K. This is likely because the cocoa pod has a waxy, water repellent epicarp which needs to be broken down before K can leach rapidly. Although the artificial conditions imposed in our experiments limit extrapolation of the leaching rates to on-farm contexts, they show the relative importance of the factors tested when assessing kinetics of nutrient leaching. Our results highlight the need for a proper on-farm management of fresh husks to reduce K losses from cocoa farms, even more if there are risks of inundation.

To describe K leaching patterns under successive rainfall events, we used a logistic function (S-shape) since the exponential function (with initial drastic decrease) poorly fitted our data. We only observed an exponential K release from cocoa pod husks under water-saturated conditions, reflecting a rapid initial loss of K. Extremely rapid release of K has been reported for other crop residues (Talgre et al. 2014). We did not find literature reporting on K leaching from cocoa pod husks. Nutrient leaching from various organic materials such as cereal straw (Li et al. 2014; Lupwayi et al. 2006; Rosolem et al. 2005), legume residues (Lupwayi et al. 2006); oilseeds, roots and tubers, and farm manure (Kolahchi and Jalali 2012; Ranjbar and Jalali 2012), weeds, household compost, fruit and vegetable wastes (Ranjbar and Jalali 2012), wood chips and pruned materials (Ordóñez-Fernández et al. 2014) have been studied in the past. The associated loss kinetics varied strongly, depending on the crop residues and the experimental conditions. Potassium loss curves from cereal straw, legume residues and prunings under intermittent rainfall events were described by power or exponential functions (Lupwayi et al. 2006). Similar patterns were proposed for empty fruit bunches, the major residues from oil palm milling (Caliman et al. 2001; Lim and Zaharah 2000). However, these functions do not account for the limited initial K loss that was observed in the very first days of the second experiment we ran.

We hypothesised that waterlogging provoked fast K losses from fresh and decayed husks. Water saturation provoked substantial K release for partially-decomposed husks, but not for fresh husks (Fig. 6) suggesting that some decomposition is required to allow release of K. This is in contrast to Vanlauwe et al. (1995) and Lupwayi et al. (2006) who found that K leaching is independent of decomposition. The findings align with observations from Calonego et al. (2005) that K losses from leaves increase with senescence. Similarly, Li et al. (2014) recorded K losses of 80% in fully senesced rice straw in the first two hours and 90% after 3 days of inundation.

Potassium leaching is not restricted to pod husks in a cocoa plantation, but also occurs from canopies in forest environments (Moslehi et al. 2019). Rain droplets collected at the forest floor contain 10–40 times more K than rain droplets above the canopy (McDowell et al. 2020). Foliar K leaching (rain-wash minus direct rainfall) in 15–30 year old cocoa plantations was estimated at 23.1–39.7 kg ha^{-1} year^{-1}, two to three times more than in sole rainfall (13.6 kg ha^{-1} year^{-1}, Dawoe et al. 2017). Although the quantity of K leached from canopies is larger than from cocoa pod husks, it remains in the system in contrast to poorly managed husks.

As hypothesised, the amount and frequency of rainfall altogether determined K loss patterns in our scheduled rainfall simulations (Table 2). The effect of rainfall frequency was more prominent than that of rainfall amount, and their interaction was significant. In general, rainfall has a large effect on K leaching from crop residues (Cavalli et al. 2018; Schreiber 1999). In a single rain event, K losses from millet straw gradually increased with rainfall amount and reached a plateau as from 40 mm (Rosolem et al. 2005). Our results show that rainfall amount interacted with rainfall frequency, with significant differences ($P < 0.05$) between large and small rainfall amounts at low but not high rainfall frequencies. At times of recurrent rainfall, delayed management of cocoa pod husks would result in rapid K release from the residues. Likewise, when rainfall amounts are high, regardless of the frequency, cocoa husks need to be actively managed to avoid large K losses.

We did not find significant differences in husk weight at the end of the scheduled leaching experiment ($P > 0.05$, not shown), suggesting that microbial decomposition was not affected by the amount or frequency of rainfall, contrasting with the findings of Joly et al. (2019). This similarity in decomposition rates was likely due to the constantly moist environment in the leaching tubes which Joly et al. (2019) did not observe. Since water content of the husks is high (80%, Lu et al. 2018), the conditions in heaps of cocoa pod husks are likely to be similar to our tubes with a high humidity in a moist environment, and we expect therefore that decomposition of heaped husks is not strongly affected by rainfall frequency and amounts.

Beside K, the husks also contain other nutrients which are relevant to cocoa nutrition. We found that more structurally-bound nutrients that are less abundant as free ions in the vacuole and cytosol were lost at much slower rates than K ($P < 0.05$). Macronutrients were lost in this relative order K $>>$ Mg $>$ Ca $\approx$ P $>$ N, aligning with the findings of Ranjbar and Jalali (2012). However, these authors found faster loss rates for Mg and Ca than we observed, which may be related to tissue composition and the state of the residues used (dryness, stage of decomposition). For cocoa pod husks, limited losses were observed for Mg, and even less for Ca. The relative immobility of Mg and Ca in the husks can be related to their abundance in cell wall pectins and sparingly soluble salts (Gerendás and Führs 2013). However, Mg appeared more mobile than Ca probably because it is also stored in ionic form in the vacuoles. Together, Mg and K also play an important role in osmotic regulation and the cation-anion charge balance (Marschner 2012), therefore their abundance in the vacuoles makes them more leachable than the other nutrients. In addition, K^+ has the lowest valence and thus moves more freely through disintegrating plant tissue.

To what extent does husk management contribute to K recycling and cocoa nutrition? For current regional mean cocoa bean yields of 400 kg ha^{-1} in west Africa, about 17–31 kg K ha^{-1} can be expected in cocoa pod husks (Hartemink 2005). These are modest amounts in relation to crop requirements (up to 300 kg K ha^{-1}, Von Uexküll and Cohen 1980) and husk recycling alone is insufficient to meet the K needs of cocoa, highlighting the importance of K fertilizer additions. Yet, over the life time of a plantation, poor husk management can remove large amounts of K. Indeed, when heaps of cocoa pod husks are piled repeatedly at the same location, the local soil K reserves will progressively be concentrated and lost, benefiting only a few neighbouring trees. Unfavourable drainage will worsen the K losses from the production system. Ideally, the husks should be redistributed over the whole plantation, although yield benefits are expected to be small while the labour required would be substantial. Instead, rotating the pod breaking station and sequential mulching of small field patches would reduce labour requirements while contributing to improved K recycling and reduce K fertilizer requirements in these resource-constrained smallholdings. In addition to the spatial aspects of cocoa pod husk management, asynchrony between nutrient release from residues and uptake by trees also needs consideration. Despite the lack of reports on the temporal dynamics of K demand in cocoa, uptake can be thought of as a continual process, characterized by steady uptake when soil moisture is satisfactory and the tree is growing actively, increased rates during pod enlargement, and declines under water stress. K supply from cocoa pod husks is primarily governed by the seasonality of production through the major and minor crops. The major crop coincides with the dry season in most production zones in West Africa, and therefore desiccation followed by rapid rewetting of the cocoa pod husks will likely provoke a fast release of K. The minor crop harvest coincides with the rainy season, and our analysis would be relevant to describe kinetics of nutrient release. As K is released from the cocoa pod husks, its availability for absorption by the root system will depend on several soil characteristics, including hydrology, sorption capacity, texture and mineralogy (Alfaro et al. 2004; Freitas et al. 2018; Najafi-Ghiri et al. 2017; Rosolem and Steiner 2017). Of these properties, the cation exchange capacity will play a strong role in buffering nutrient fluxes.

Conclusion

Cocoa pod husks are rich in potassium and their potential contribution to tree nutrition is significant. Since risks of K losses through leaching are high, optimizing nutrient cycling in cocoa requires improved management compared with current practices of heaping and abandonment. We found that early-stage decomposition of the husks, water-saturation, and rainfall regime (amount and frequency) significantly altered K leaching patterns and the resulting nutrient losses. Knowledge about the kinetics of nutrient leaching from decaying husks can guide timely management of the husks, provided that accurate meteorological predictions are accessible to farmers.

We have briefly explored innovative methods of handling and disposing the husks to improve nutrient cycling, but more insight is needed both in terms of the outcomes on nutrient budgets, technical requirements, and farm resource utilization. For instance, we suggest that on-farm estimation of nutrient leaching from the husks under diverse climatic conditions and management practices is needed to better inform field management. Further, there is a paucity of knowledge about the fate of K as it leaches from the husks into the topsoil. Effective leaching study designs are required to capture the effect of the root system, soil characteristics, and pod management on K spatial distribution in soil and its temporal availability to cocoa trees.

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Appendix

Table 3 Cumulative amount of water (mm) sprinkled over tubes for each treatment in Experiment 2

Treatments	Days															
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31
2d, 12 mm, small	**12.5***	**25**	**37.5**	**50**	**62.5***	**75**	**87.5**	**100**	**112.5***	**125**	**137.5**	**150**	**162.5***	**175**	**187.5**	**200**
4d, 12 mm, small	**12.5***	12.5	**25**	25	**37.5***	37.5	**50**	50	**62.5***	62.5	**75**	75	**87.5***	87.5	**100**	100
8d, 12 mm, small	**12.5***	12.5	12.5	12.5	**25***	25	25	25	**37.5***	37.5	37.5	37.5	**50***	50	50	50
2d, 50 mm, small	**50***	**100***	**150***	**200***	**250***	**300***	**350***	**400***	**450***	**500***	**550***	**600***	**650***	**700***	**750***	**800***
4d, 50 mm, small	**50***	50	**100**	100	**150***	150	**200**	200	**250***	250	**300**	300	**350***	350	**400**	400
8d, 50 mm, small	**50***	50	50	50	**100***	100	100	100	**150***	150	150	150	**200***	200	200	200
2d, 12 mm, medium	**12.5***	**25**	**37.5**	**50**	**62.5***	**75**	**87.5**	**100**	**112.5***	**125**	**137.5**	**150**	**162.5***	**175**	**187.5**	**200**
4d, 12 mm, medium	**12.5***	12.5	**25**	25	**37.5***	37.5	**50**	50	**62.5***	62.5	**75**	75	**87.5***	87.5	**100**	100
8d, 12 mm, medium	**12.5***	12.5	12.5	12.5	**25***	25	25	25	**37.5***	37.5	37.5	37.5	**50***	50	50	50
2d, 50 mm, medium	**50***	**100**	**150**	**200**	**250***	**300**	**350**	**400**	**450***	**500**	**550**	**600**	**650***	**700**	**750**	**800**
4d, 50 mm, medium	**50***	50	**100**	100	**150***	150	**200**	200	**250***	250	**300**	300	**350***	350	**400**	400
8d, 50 mm, medium	**50***	50	50	50	**100***	100	100	100	**150***	150	150	150	**200***	200	200	200
2d, 12 mm, large	**12.5***	**25***	**37.5***	**50***	**62.5***	**75***	**87.5***	**100***	**112.5***	**125***	**137.5***	**150***	**162.5***	**175***	**187.5***	**200***
4d, 12 mm, large	**12.5***	12.5	**25**	25	**37.5***	37.5	**50**	50	**62.5***	62.5	**75**	75	**87.5***	87.5	**100**	100
8d, 12 mm, large	**12.5***	12.5	12.5	12.5	**25***	25	25	25	**37.5***	37.5	37.5	37.5	**50***	50	50	50
2d, 50 mm, large	**50***	**100**	**150**	**200**	**250***	**300**	**350**	**400**	**450***	**500**	**550**	**600**	**650***	**700**	**750**	**800**
4d, 50 mm, large	**50***	50	**100**	100	**150***	150	**200**	200	**250***	250	**300**	300	**350***	350	**400**	400
8d, 50 mm, large	**50***	50	50	50	**100***	100	100	100	**150***	150	150	150	**200***	200	200	200

Treatment code: For size, small, medium and large refer to chunks of 2, 5, and 25 g respectively. For rainfall amount, 12 mm and 50 mm refer to 12.5 mm/leaching event and 50 mm/leaching event, respectively. For rainfall frequency, 2d, 4d, and 8 8d refer to regular (every other day), intermittent (every 4 days), and irregular rainfall events (every 8 days), respectively. Cells with figures in bold correspond to effective days of leaching for a given Treatment. An asterisk (*) represents a day at which the leachate of a given treatment is analysed for other nutrients (N, P, Ca, Mg)

Table 4 Comparison of 1st and 2nd order exponential models used to describe cocoa pod husk decomposition with estimates (± 95% confidence intervals)

Predictor/Model evaluation criterion	1st order exponential model (Olson)	2nd order exponential model (Yang and Janssen)
Decomposition rate (k), day^{-1}	0.01±0.00	0.09±0.01
Ageing constant (a), unitless	NA	0.42±0.04
AIC	−69	−131
BIC	−60	−119
RMSE	0.11	0.05
R^2	0.71	0.77

NA not applicable

Table 5 Effects of treatments (combination of rainfall frequency, rainfall amount, and size of chunks) and type of structurally-bound nutrients on the total losses (±95% confidence intervals) estimated on day 25 of the scheduled leaching experiment (experiment 2). Note that the probability indicates the *P* value for differences between treatments based on the Wald F-test

Treatments	Nutrient losses (% of initial value in the husks)				Probability across treatments
	N	P	Ca	Mg	
2d,12 mm, large	0.02±5.22	5.27±5.22	4.91±5.22	11.12±5.22	0.99
2d,50 mm, small	0.06±5.22	5.72±5.22	8.89±5.22	13.36±5.22	
8d,12 mm, large	0.02±5.22	1.56±5.22	1.92±5.22	1.92±5.22	
8d,50 mm, small	0.3±5.22	14.09±5.22	6.78±5.22	15.47±5.22	
Probability across nutrients	0.03				0.17

Table 6 Effect of rainfall amount, rainfall frequency, and size of chunks on K leaching model's parameters (see Eq.3 in main text). The intercept of the model were set for '2d, 12mm, small' treatment

Parameter	Rainfall	Frequency	Size	Treatment label	Estimate(±95% confidence intervals)
Asym	All	All	All	All	1.16±0.04
Xmid	12.5 mm	2 days	Small	2d, 12 mm, small	27.68±5.6
Xmid	12.5 mm	2 days	Medium	2d, 12 mm, medium	30.35±10.14
Xmid	12.5 mm	2 days	Large	2d, 12 mm, large	25.95±10.13
Xmid	50 mm	2 days	Small	2d, 50 mm, small	29.11±13.58
Xmid	50 mm	2 days	Medium	2d, 50 mm, medium	28.46±24.68
Xmid	50 mm	2 days	Large	2d, 50 mm, large	28.04±24.79
Xmid	12.5 mm	4 days	Small	4d, 12 mm, small	32.67±13.52
Xmid	12.5 mm	4 days	Medium	4d, 12 mm, medium	31.01±24.68
Xmid	12.5 mm	4 days	Large	4d, 12 mm, large	36.71±24.54
Xmid	50 mm	4 days	Small	4d, 50 mm, small	24.25±32.82
Xmid	50 mm	4 days	Medium	4d, 50 mm, medium	27.51±60.21
Xmid	50 mm	4 days	Large	4d, 50 mm, large	25.57±60.09
Xmid	12.5 mm	8 days	Small	8d, 12 mm, small	46.77±14.27
Xmid	12.5 mm	8 days	Medium	8d, 12 mm, medium	59.86±31.22
Xmid	12.5 mm	8 days	Large	8d, 12 mm, large	83.87±50.57
Xmid	50 mm	8 days	Small	8d, 50 mm, small	33.18±34.63
Xmid	50 mm	8 days	Medium	8d, 50 mm, medium	32.7±72.53
Xmid	50 mm	8 days	Large	8d, 50 mm, large	32.13±110.3
RL	12 mm	2 days	All	2d, 12 mm	0.07±0.01
RL	50 mm	2 days	All	2d, 50 mm	0.07±0.03
RL	12 mm	4 days	All	4d, 12 mm	0.06±0.03
RL	50 mm	4 days	All	4d, 50 mm	0.07±0.06
RL	12 mm	8 days	All	8d, 12 mm	0.03±0.03
RL	50 mm	8 days	All	8d, 50 mm	0.05±0.06

Table 7 Comparison of model coefficients and parameters (estimates ±95% confidence intervals) for fresh and partially decomposed cocoa pod husks exposed to simulated inundation (experiment 3)

Estimate/Criterion	Fresh husks	Partially decayed husks
Leaching rate (k), day^{-1}	0.03±0.01	0.22±0.04
Ageing constant (a), unitless	0.35±0.05	0.63±0.05
AIC	−252.14	−177.22
BIC	−243.53	−167.56
RMSE, %	0.22	1.32
R^2	0.995	0.992

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