

Effects of lime and fertiliser applications on the physical properties of tropical peat soils in Peninsular Malaysia

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SUMMARY

The aim of the study was to determine the changes in aggregate size distribution and water retention of hemic (moderately decomposed) and sapric (strongly decomposed) peat materials from agricultural liming and fertiliser application. Sapric (0–30 cm) and hemic (40–60 cm) peats were collected from a secondary peat swamp forest with a peat depth of > 2.5 m and were used as a potting medium for maize plants. The maize was cultivated in a net-house for 17 weeks with four treatments applied to both peat materials. The treatments were: control (C), compound fertiliser NPK(MgS) (12:12:17:2) (T1), dolomite adjusted to pH 5.5 (T2), and NPK fertiliser combined with dolomite (T3). The aggregate size distribution and water-holding capacity (pressure plate method) were determined before and after the plant growth period. It was found that hemic and sapric peat materials showed different responses to the application of lime and fertiliser. For hemic peats, both T2 and T3 resulted in significant reductions of aggregate size and water-holding capacity, whereas no changes occurred in T1. For sapric peats, T3 caused a reduction in large soil aggregates and water-holding capacity, but no changes were observed in T1 and T2. This indicates that applications of lime and fertiliser may promote the peat decomposition process, causing large-sized organic matter particles to break down and resulting in a loss of soil water-holding capacity.

KEY WORDS: aggregate size distribution, hemic peat, sapric peat, water-holding capacity

INTRODUCTION

The characteristics of Histosols have long been recognised as being distinctively different from those of mineral soils due to their high organic matter content of more than 50 % in the uppermost 80 cm of the soil profile (Andriess 1988). In the current progressive conversion of tropical peat swamp forest to agricultural production (Yew *et al.* 2010), lime and fertilisers have been extensively applied to alleviate the extreme acidity and imbalanced nutrient complements of these soils, in order to meet the requirements of vegetable growing and commercial cropping. Generally, when lime is applied to the soil, cations such as Ca²⁺ and Mg²⁺ will displace H⁺, Fe²⁺, Al³⁺, Mn⁴⁺ and Cu²⁺ ions from the soil adsorption sites causing an increase in soil pH. Apart from that, the introduction of lime into peat soils supplies significant amounts of Ca and Mg (Kaila & Rytö 1968). Other common indirect benefits of liming include the increased availability of other nutrients such as P, Mo and B (Ameyu 2019). The application

of lime also creates more favourable conditions by increasing the availability of nutrients which would otherwise be strongly limited by low soil pH (Rastija *et al.* 2014). An increase in soil pH as a result of liming increases microbial activity (Rousk *et al.* 2010), thus improving nitrogen mineralisation (Robinson *et al.* 1992). Aside from ameliorating soil pH and improving nutrient availability to crops, the application of lime can also affect the physical properties of the soil; for example, it can improve soil structure (Nekesa *et al.* 2005). Thus, in peat soil engineering, lime is often applied as a chemical stabiliser to increase the strength and reduce the shrink-swell characteristics of the soil such that it becomes completely suitable for construction in the longer term (Khalid *et al.* 2014). For tropical peat soils, Zambri & Ghazaly (2018) showed that the addition of lime improves the strength properties because Ca²⁺ increases the bonding between soil particles.

Few studies have been done to investigate the effects of lime and fertiliser applications on physical



properties of tropical peats that would in turn influence the performance of agricultural crops and the long term sustainability of the peat soil itself. Most of these studies have focused on nutrient availability, productivity, gas emission and other important elements in the peat (e.g., Caporn *et al.* 2007, Biasi *et al.* 2008, Nur & Adzmi 2014). However, according to Lal & Shukla (2004), the efficiency of water and nutrients usage by crops is dependent on soil physical properties. As a result, good soil physical quality enhances the chemical and biological properties of the soil (Sassenrath *et al.* 2018). Another important yet challenging characteristic of peat is the varying degree of decomposition of its organic components with depth below the surface. Recent studies have reported that disparity in the stages of decomposition results in different types of peat having different physical and chemical attributes (Reeza *et al.* 2014, Reeza 2019). Vertical variations in the degree of decomposition arise because the soil layers are differently exposed to oxidation and further mineralisation at different levels of the ground-water table. Ilnicki & Zeitz (2003) report that the mineralisation and pedogenetic transformations of soil organic matter caused by drainage of peat induce the formation of crumbly aggregates, then polyhedral and prismatic ones, shrinkage cracks, and finally a fine-grained dust-like topsoil moorsh horizon. Consequently, the majority of topsoils in drained agricultural peatlands are strongly decomposed without any recognisable plant remains, in contrast to deeper soil layers where the structure of the parent vegetable matter may remain intact. Apart from that, the process of mineralisation can also be induced by a rise in pH due to liming as well as by nutrient loading attributed to fertiliser application. Altogether, these processes lead to an increase in bulk density and a decrease in total porosity (Rovdan *et al.* 2002) which creates the observed variation in physical characteristics across the peat soil profile.

Therefore, it is necessary to investigate the causes of change in the structure of peat materials upon the application of lime. This can be attributed either to the chemical reaction of lime with the organic matter, or to the effect of lime on biological activity and thus on decomposition processes in the soil. The objective of this study was to assess the effects of lime and fertiliser applications on the aggregate size distribution and water holding capacity of hemic and sapric peat materials. We hypothesised that the application of lime and fertiliser causes a breakdown of aggregates through soil biological activity which consequently reduces the water holding capacity of the peat materials under study.

METHODS

Study site and fieldwork

Hemic and sapric peat materials were collected from secondary peat swamp forest situated on a flat coastal plain, about 8 km inland from the west coast of Peninsular Malaysia in Kampung Kundang, Batu Laut, Tanjung Sepat, Selangor, (2° 42' 83" N, 101° 33' 26" E). The woody peat deposit, comprising continuous layers of organic materials, is more than 2.5 metres thick and categorised as deep peat. The peatland is classified as ombrogenous (rain-fed) and oligotrophic (nutrient-poor). While most parts of the peatland are protected as forest reserve, a small portion of the area has been opened up for agricultural use since the year 2012. The climate of the area is classified as equatorial rainforest, fully humid (Kottek *et al.* 2006) without distinct dry and wet seasons, since Malaysia receives rain all year round with 2600 mm per year. The average maximum temperature is around 32.7 °C, the average minimum temperature is 24.2 °C, and the mean annual temperature is 27.6 °C (Malaysian Meteorological Department 2019).

Surface (0–30 cm) and subsurface (40–100 cm) soil layers were identified as sapric and hemic peat materials, respectively, based on degree of decomposition (H1–H10) according to the von Post scale (von Post 1922). These peat materials were sampled using an Eijkelkamp peat sampler that extracted 50 cm long cores with diameter 5.2 cm. Additionally, twelve soil pits (each about 1 m²) were dug manually down to 1 m depth with a shovel to uncover the sapric and hemic peat layers for excavation. The peat materials were collected and placed in burlap sacks. In addition to regular (disturbed) samples, bulk samples (undisturbed) were collected for bulk density determination using stainless steel rings (diameter 5.2 cm, height 6.0 cm).

Preparation and analysis of samples

In the laboratory the peat materials were spread evenly on the floor to air-dry for one week, so that they could be used as potting media. Several analyses were conducted on fresh field-moist samples. Degree of decomposition was determined using the Sodium Pyrophosphate Extract Colour (SPEC) method and the percentage of unrubbed fibre content was determined following the method of Lynn *et al.* (1974). Soil organic matter (SOM) content was determined by the loss-on-ignition method after placing samples in a muffle furnace at 300–550 °C for five hours (ASTM 1988). Particle density was measured following the pycnometer method, using absolute (99.6 %) ethanol in place of water to



guarantee complete saturation of the sample (Heiskanen 1992). Total carbon was measured using a TruMac CNS Auto-analyser (Version 1.1x LECO Corporation, St Joseph, MI). Soil pH was determined potentiometrically in soil suspensions consisting of 1:10 volumetric ratio of peat sample to distilled water (Reeza *et al.* 2021). The bulk densities and moisture contents of the undisturbed (bulk) samples were determined by the dry-weighing method (Chambers *et al.* 2011). Total porosity (TP) was calculated according to the formula of Nimmo (2004):

$$TP = \frac{\text{Particle density} - \text{Bulk density}}{\text{Particle density}} \times 100 \quad [1]$$

Treatments

After the peat materials had been air dried, they were tested for field capacity using the pressure plate method (Richards 1947) then adjusted to 60 % field capacity to be used as potting medium for the maize plants. The peat materials were then packed into five-litre pots at a rate of 4 kg per pot. Twelve pots were filled with hemic peat and another twelve with sapric peat. Four treatments (Table 1) were applied in triplicate to each of the two types of peat material, in a Randomized Complete Block Design (RCBD).

The liming material used in this study was powdered dolomite, and its function was to raise the soil pH from about 3.7 (hemic peat) and 3.8 (sapric peat) to 5.5. According to the results of a lime requirement test using the method of Dunn (1943), the hemic peat needed 91.5 g of dolomite per pot (equivalent to 10.4 t ha⁻¹) while the sapric peat required 73.8 g of dolomite per pot (equivalent to 9.72 t ha⁻¹). The added dolomite was mixed homogeneously with the peat material which was then left to incubate for one week before sowing seeds, to give time for the liming material to react with the soil and reach equilibrium. After a week of incubation, both peat materials were tested for pH to ensure that the desired pH (5.5) was met.

Four *Zea mays* var. *saccharata* seeds (improved

Mas Madu variety) were sown in each pot and thinned after germination to a single plant per pot. The plants were then grown for 17 weeks to study the effect of progressive peat decomposition on structural changes with time. This was done in a net-house with daily manual watering of about 1 litre of water per pot. Two weeks after planting (after the emergence of four true leaves), 16 g of NPK(MgS) granular fertiliser of 12:12:17:2 was broadcasted onto T1 and T3 only. The amount of fertiliser added was based on the Malaysian Agricultural Department (Jabatan 2008) recommendation of 500 kg ha⁻¹ of 12:12:17:2 NPK compound fertiliser, equivalent to 8 g of fertiliser per pot. However, during preliminary planting, it became apparent that the recommended amount was insufficient as the plants were showing several symptoms of nutrient deficiency. Therefore, the dosage was increased to 16 g of fertiliser per pot. After 17 weeks, the plants were harvested and soil samples were collected for determination of chemical and physical properties.

The determination of aggregate size distribution followed the method described by Teh & Talib (2006) using a set of nested sieves with mesh sizes of 8.0, 4.76, 2.83, 2.0, 1.0, 0.5 and 0.3 mm. The weight of peat materials (aggregates) collected from each sieve was expressed as a percentage of the total weight of peat retained by all of the sieves. Aggregate size distribution can also be expressed using a single empirical unit known as mean weight diameter (MWD), which refers to the sum of the mean diameter (\bar{x}_i) of each aggregate size fraction, as well as the proportion of the total sample weight (w_i) occurring in the corresponding size fraction, as documented by van Bavel (1950):

$$MWD = \sum_{i=1}^n \bar{x}_i w_i \quad [2]$$

Another way to present aggregate size distribution is to calculate the percentage of aggregates larger than 2 mm by summing up the total amounts of particles remaining in the sieves of sizes 2.0–8.0 mm.

Table 1. Treatments applied to the hemic and sapric peat materials.

Treatment	Description
Control	No application of lime or fertilisers
T1	Application of fertiliser N:P:K:Mg (12:12:17:2)
T2	Application of dolomite to raise pH to 5.5
T3	Application of dolomite to raise pH to 5.5 and fertiliser N:P:K:Mg (12:12:17:2)

Soil water retention was determined using the pressure plate method of Richards (1947). The amount of available water was calculated by subtracting the volume of water retained between 33 and 1500 kPa and expressing it as a percentage of the weight of the peat materials.

Both analyses (aggregate size distribution and water retention) were performed prior to planting and after 17 weeks to assess any changes in physical soil properties that occurred during the period of plant growth.

Statistical analysis

Differences between the beginning and end of the growing period in aggregate size distribution, MWD, the amounts of aggregates larger than 2 mm and water holding capacity of both peat materials in the various treatments were analysed using the T-test. Analysis of variance (ANOVA) was used to test treatment effects, while the comparison of means between treatments was performed using Tukey's test.

RESULTS

Initial physical and chemical characteristics of peat materials

Selected physical and chemical properties of the hemic and sapric peat materials prior to planting are shown in Table 2. The degree of peat decomposition according to the von Post (1922) scale was H6 -

moderately decomposed (hemic) and H8 - very highly decomposed (sapric). The percentage content of unrubbed fibre was correspondingly higher in hemic (40.0 %) than in sapric material (26.7 %). The colour of the pyrophosphate solution of the sapric material, as indicated by the value and chroma according to the Munsell Colour System, was 3/4 (dark yellowish brown) and much darker than the solution of hemic material (7/4; very pale brown). We found that bulk density had an inverse relationship with fibre content, i.e., the more fibre the soil contained per unit volume, the lower its weight per unit volume became. Hence, the hemic peat material, which contained more fibre, had a lower bulk density (0.15 g cm^{-3}) than the sapric peat material (0.18 g cm^{-3}). Organic matter content was slightly lower in the sapric (92.5 %) than in the hemic (98.5 %) peat. Nevertheless, organic matter content exceeded 65 % in both types of peat material and, therefore, both exhibited typical characteristics for peat soil. In the case of porosity, the greater the bulk density of the peat material, the lower its porosity became. In other words, the sapric peat material had higher bulk density and lower porosity (85.0 %) than the hemic peat (88.0 %). Moisture content was also lower in the sapric (68.6 %) than in the hemic peat (72.1 %). A similar pattern was found in organic carbon content, which was lower (52.1 %) in the more decomposed sapric than in the less decomposed hemic material (55.2 %). In contrast, pH was slightly higher in the sapric (pH 3.9) than in the hemic peat (pH 3.8).

Table 2. Selected physical and chemical properties of the hemic and sapric peat materials prior to planting. The values provided are means of three replicate determinations (n=3). In each case, standard deviation (SD) is shown in parentheses. H6 = well decomposed; H8 = very strongly decomposed.

Properties	Type of peat material	
	Hemic	Sapric
Degree of peat decomposition (von Post scale)	H6	H8
Unrubbed fibre content (%)	40.0±2.72	26.7±2.72
Value and chroma of pyrophosphate solution	10YR 7/4	10YR 3/4
Moisture (%)	72.1±3.57	68.6±4.49
Organic matter content (%)	98.5±2.89	92.5±2.11
Bulk density (g cm^{-3})	0.15±0.02	0.18±0.03
Porosity (%)	88.0±0.55	85.0±0.65
pH	3.8±0.1	3.9±0.1
Organic carbon (%)	55.2± 2.33	52.1± 2.11

Changes in aggregate size distribution

All of the results discussed from this point onwards are deemed significant if $p < 0.05$. Prior to planting, MWD differed significantly between the hemic (4.75 mm) and sapric (4.08 mm) peat materials, implying that the sapric material had a lower size range of aggregates. After 17 weeks of plant growth, there was a significant reduction of MWD in the hemic peat material in both T2 (lime only) and T3 (lime and fertiliser), as shown in Figure 1. On the other hand, MWD for the hemic material did not exhibit any significant change in T1 (fertiliser only)

or in the control. This indicates that the addition of lime, but not the addition of fertiliser alone, resulted in structural change in the hemic material. However, when both lime and fertiliser were added to the hemic peat, the process of structural change intensified - the aggregates were larger in T1 and the control than in T2 and T3 (Figure 1). It is also evident that physical change was most apparent in T3, where the aggregates were smallest. This is supported by the observation that the percentage of particles larger than 2 mm was smallest in T3 (Figure 2). The effect of lime and fertiliser addition is further emphasised

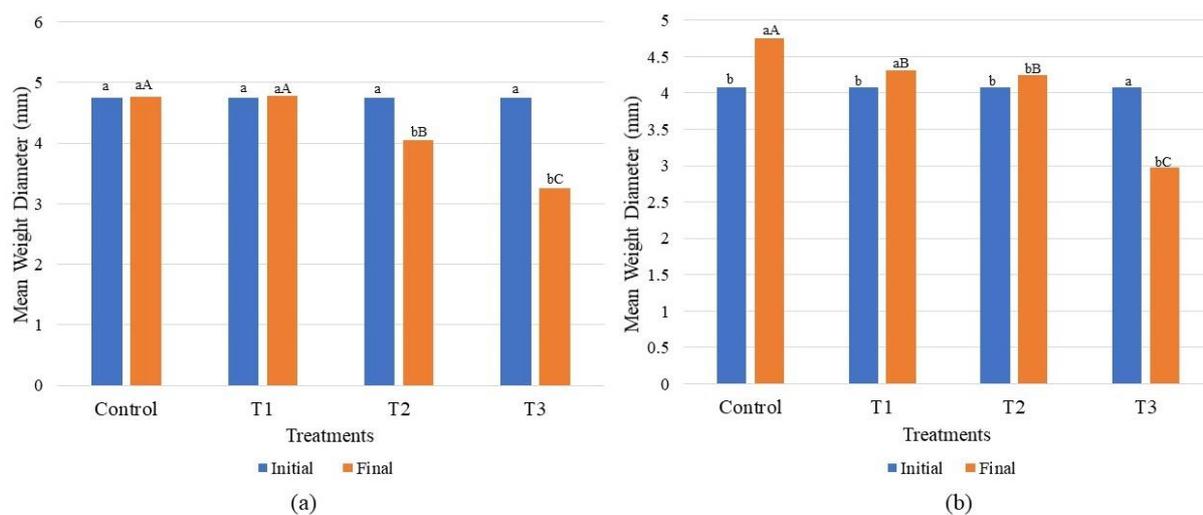


Figure 1. Comparison of Mean Weight Diameter (MWD) between the initial and final weeks of the 17-week growing period for different treatments in (a) hemic and (b) sapric peat materials. Capital letters indicate mean separation among treatments, while lowercase letters refer to mean separation within treatments using Tukey at $p=0.05$.

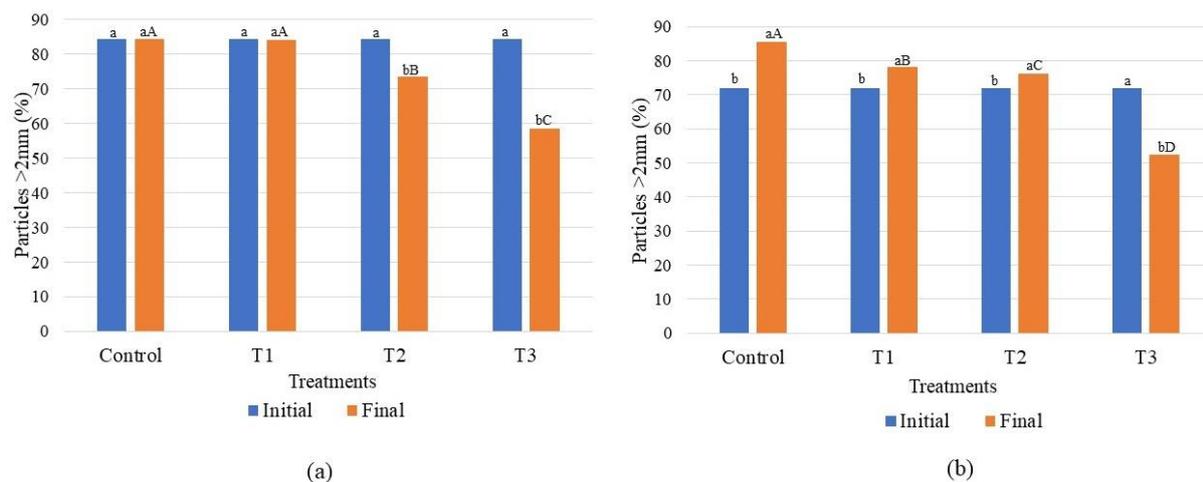


Figure 2. Comparison of the percentages of (a) hemic and (b) sapric particles >2 mm in all treatments between the initial and final weeks of the 17-week growing period. Capital letters indicate the mean separation among treatments, while lowercase letters refer to mean separation within treatments using Tukey at $p=0.05$.

by the distribution of particle sizes, as the breakdown of larger aggregates was evident in T2 and T3 and the percentages of smaller particles were highest in T3 (Figure 3).

In contrast, MWD increased significantly in the sapric control and T1 (fertiliser only) treatment compared to the initial condition (Figure 1). However, T2 did not display any significant change in MWD while T3 exhibited a significant decline in MWD when compared to the initial sapric peat. This demonstrates that only the application of both lime and fertiliser will affect the particle size and thus alter the physical structure of the organic matter in sapric peats, where T3 caused a decline in large aggregates to the lowest percentage of >2.00 mm particles observed across all treatments (Figure 2). Also, the soil aggregates were more evenly distributed in T3 than in the other treatments (Figure 3).

On the other hand, the sapric control resulted in a significant increase in the amount of largest and second-largest particle sizes (8.00–4.75 mm and 4.75–2.80 mm). This was also found in T1 and T2, where the proportion of particles >2.00 mm increased during the weeks of plant growth, although the increase was more pronounced in the control treatment (Figure 2). This observation was completely opposite to the result in hemic material, implying that the hemic and sapric peat materials showed different responses to the treatments applied.

Changes in available water and pH

For hemic peats, a significant reduction in available water was observed after 17 weeks, when all treatments showed a reduction in available water

(Figure 4) compared to the initial sample. However, the amount of available water for hemic in T1 after 17 weeks was not significantly different from that in the control, indicating that the application of fertiliser (alone) did not cause a significant change in water-holding capacity. The non-significant difference might be due to the peat pH being similar in these two treatments (pH 3.9 in control and 3.8 in T1), and also close to the initial pH value of the hemic material (pH 3.8). However, a significant decline in available water was found when the peat was amended with lime (T2), as well as with a combination of lime and fertiliser (T3) which resulted in the least amount of available water. This effect might be attributed to the significant increases in pH observed in T2 (pH 5.6) and T3 (pH 5.1).

Available water in the sapric material was initially only half (52.4 %) of that in the hemic peat (105 %) (Figure 4). The amount of available water in the control (51.8 %) and T1 (52.8 %) did not change significantly during the period of plant growth compared to the initial condition prior to planting (52.4 %) and this finding contrasted with the results for the hemic material. However, treatments that showed insignificant changes in water content during the growth period also showed no significant changes in pH, as for the hemic peat material. In contrast, for both peat materials, the remaining two treatments (T2 and T3) produced a decline in available water, with T3 containing less (30.5 %) than T2 (38.4 %). The application of lime and fertiliser in the latter two treatments caused pH to increase substantially compared to the initial condition (pH 3.9), with T2 rising to pH 5.8 while T3 increased to pH 5.7.

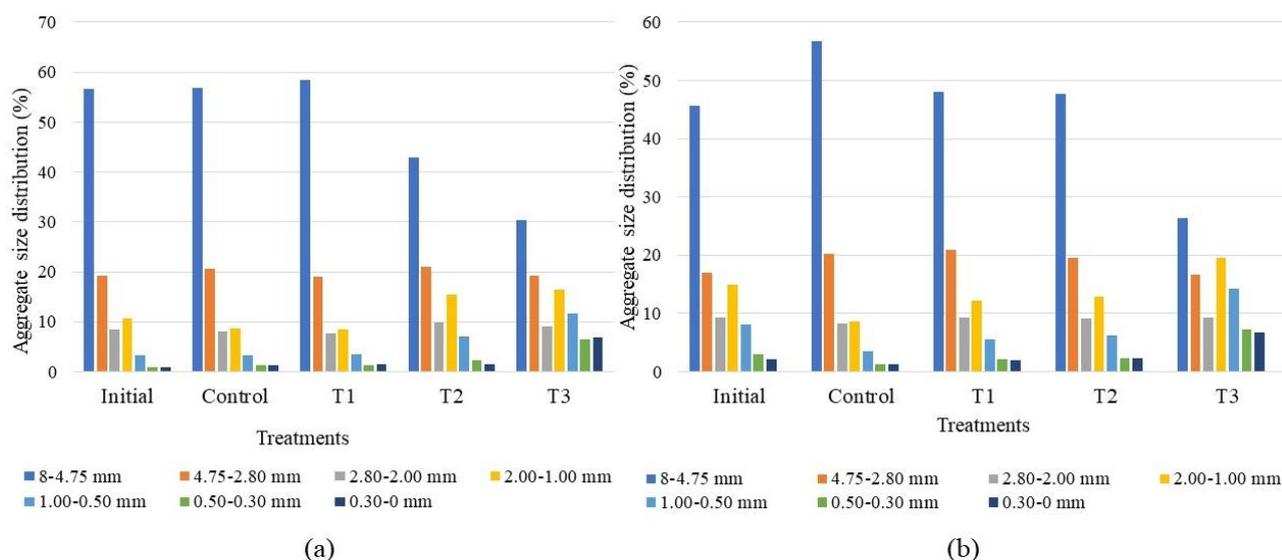


Figure 3. Distribution of aggregate size (%) in (a) hemic and (b) sapric peat materials in the initial and final weeks of the growing period.

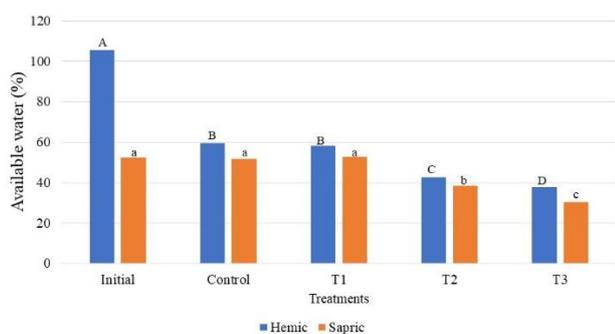


Figure 4. Comparison of available water content (%) between the start and end (week 17) of the growing period for all treatments in hemic and sapric peat materials. Capital letters refer to mean separations among treatments for hemic material, while lowercase letters refer to mean separations among treatments for sapric material, using Tukey at $p=0.05$.

DISCUSSION

Changes in aggregate size distribution

The initial condition of the peat materials before planting showed that MWD for the hemic peat material was significantly higher than for the sapric material. Similar findings that less decomposed hemic peat has higher porosity and, therefore, a higher proportion of large aggregates than sapric peat was reported by Sampurno *et al.* (2018). According to Teh & Talib (2006), larger values of MWD denote a higher proportion of larger aggregates in the soil sample and these aggregates often indicate favourable soil structure for agriculture. Although hemic peat materials contain larger aggregates than sapric materials, their suitability for agricultural activities is not promising because they are often waterlogged for most of the year, with much lower bulk density and correspondingly lower bearing capacity (Andriessse 1988, Arabia *et al.* 2020). Hemic materials will also tend to become sapric when they undergo further decomposition upon drainage (Andriessse 1988).

Seventeen weeks after planting maize, we found that the application of lime (T2) as well as the addition of both lime and fertiliser (T3) to hemic and sapric peats resulted in a decrease of MWD, while no effect on MWD was observed when fertiliser alone (T1) was applied to hemic materials. Based on study of peatland near Holmes Moss in the Southern Pennines (UK), Caporn *et al.* (2007) observed similarly that the addition of both lime and fertiliser increased the establishment of a grass mix over seeded plots without these treatments, and that the

application of lime alone was most beneficial and promoted growth in the absence of added nutrients. In contrast, fertiliser addition was beneficial only when lime was also added. They found that the optimum growth was observed when both fertiliser and lime were added together at the maximum rates in the experiment. Another study by Murayama & Abu Bakar (1996) reported a similar significant promotive effect of increased soil pH resulting from liming on decomposition in Malaysian tropical peat soils, yet no effect was observed when NPK fertiliser alone was applied. They also found that the CO_2 flux from the soil surface was positively correlated with soil acidity and ash content, which could reflect the CO_2 evolution from microbial respiration that may be actively degrading the organic materials. They further mentioned that the higher the soil pH and/or ash content, the greater the CO_2 flux. However, no such correlation was observed when fertiliser alone was applied. Such findings suggest that the addition of nutrients from fertilisers may not be sufficient alone to cause the changes observed in the physicochemical properties of hemic peats, and that the change of pH is the predominant causative factor in increasing microbial activity to further transform the organic matter comprising these peat materials, resulting in the breakdown of particles as shown by the decrease of MWD in this study. However, the addition of lime only (T2) to sapric material did not affect MWD, while the addition of fertiliser alone (T1) increased MWD, in contrast to the observations on hemic materials mentioned previously. This demonstrates that different peat materials can behave differently upon the application of lime and fertiliser, even when the materials share the same location, botanical origin, vegetation, climate and topography (Reeza *et al.* 2014, Reeza 2019).

Changes in available water and pH

As mentioned previously (see Results), the well decomposed sapric peat initially (prior to planting) had lower available water content than the moderately decomposed hemic material. According to Boelter (1964), water storage characteristics vary significantly between different peat types and these variations may have hydrological implications. This observation is consistent with the findings of Andriessse (1988) and Lucas (1982) that the weight of water held by the least decomposed fibric peat can be as much as 20 times its own weight, whereas sapric material contains less than twice its own weight of water. Thus, the difference in degree of decomposition appears to influence water availability in these two different types of peat material. This is directly related to porosity differences, with hemic

peats having more varied pore sizes which enables them to absorb and retain more water than sapric peats (Sampurno *et al.* 2018).

It was also clearly observed that the addition of lime and fertiliser resulted in a further significant reduction in available water content regardless of peat type, indicating that further decomposition attributed to the rise in pH due to liming had caused breakdown into smaller aggregates which, in turn, affected the water holding capacity. Such structural changes affect bulk density, moisture content and porosity which, in turn, will affect the availability of water to plants rooted in the peat material (Rezanezhad *et al.* 2016). The structural changes may also have undesirable effects on erodibility and water penetration, which is a serious issue in the context of environmental productivity and sustainability because such changes indicate further degradation of the peat soil (Guillaume *et al.* 2016, Decena *et al.* 2021). Similar findings have also been reported by Jauhiainen *et al.* (2012), Lampela *et al.* (2014) and Decena *et al.* (2021).

Processes and mechanisms underlying changes in the structure of peat materials

Taking into consideration the nature of peat, which originates from organic matter loaded with macro- and micro-organisms, the results of this study showed that, apart from the chemical reaction of lime with organic matter, the changes in physical structure of the hemic and sapric materials might be greatly influenced by biochemical processes undergone by the inhabitants of these soils. This is due to the fact that, regardless of peatland type, the composition of microbial communities inhabiting peat is sensitive to changes in pH and in the concentrations of mineral elements such as calcium (Andersen *et al.* 2013).

In the limed treatments (T2 and T3), which imposed a change from an extremely acidic pH of 3.8 to a pH of 5.6, we suppose that the peat materials experienced a sudden flush in activity of microbes awakened from dormancy, which is consistent with many reports (Shah *et al.* 1990, Condron *et al.* 1993, Smolander & Mälkönen 1994). This supposition is supported by the findings of Gardiner (1975) who, after liming peat soils, observed a substantial increase in numbers of bacteria that were previously inhibited by the acidic conditions, but no effect on the fungal population as fungi are able to tolerate a wide range of pH. It seems likely that this sudden increase in pH might stimulate an almost immediate increase in the metabolic activity of soil microbes, particularly zymogenous (opportunistic) bacteria, with rapid assimilation of carbon derived from the carbonaceous materials that are abundant in peat being utilised as

an energy source for the bacterial population. As a result, the evolution of carbon dioxide from microbial respiration will increase exponentially in response to the increase in pH (Murayama & Abu Bakar 1996). We further suggest that such an increase in microbial activity requires these microbes to further break down the organic matter comprising the peat, which may consequently enhance the decomposition process, resulting in finer organic matter particles and explaining the increased proportion of smaller sized soil particles displayed in Figures 2 and 3. Gardiner (1975) also found that microbial activity in peat is enhanced by even the slightest addition of lime, and that although some oxygen may be used initially for non-biological reactions, the carbon comprising the peat becomes more available when the peat pH is raised. He also found that fertilising peat with nitrogen alone significantly depressed the rate of oxygen uptake, indicating a lowering of microbial activity and, consequently, of the decomposition process. Therefore, we postulate that the microbial population increased only in response to the addition of lime.

In T3, although the pH (5.1) was lower than in T2 (pH 5.6), due to solubilisation of the fertilisers (which releases H⁺ ions), the abundance of nutrients attributed to the addition of fertilisers further accelerates the decomposition process, explaining the significantly lower values for proportion of large sized particles and available water in T3. It should be noted that one of the important factors determining the rate of decomposition is the C/N quotient of the organic matter comprising the peat. The application of lime and fertiliser together provides a conducive environment for microbial activity as well as sufficient nitrogen to further break down, digest and assimilate the carbonaceous material in the peat. Findings by MacLean *et al.* (1967) on the effect of lime on the growth of potato crops planted in *Sphagnum* peat soil suggest that the application of lime causes a decrease in carbon as well as C/N which, in turn, speeds up the decomposition of organic matter. The carbon compounds in the peat materials are subjected to enzymatic oxidation, producing carbon dioxide alongside water and energy, which explains the reduction in carbon content. On the other hand, nitrogenous materials also succumb to microbial decay, releasing not only CO₂ and water but also ammonium and nitrates which, in turn, results in a decrease of C/N (Brady & Weil 2002).

As peat decomposition advances due to liming and fertiliser application, this will further reduce the proportion of large pores by breaking down plant debris into smaller fragments, thereby reducing the

inter-particle pore spaces (Moore *et al.* 2005, Bragazza *et al.* 2008) and increasing the quantity of dry material per unit volume. As the dry matter content increases, the space available for air and/or water will decrease, resulting in a decrease in water availability as shown in T2 and T3. Studies done by USDA (2008) found that smaller micropores hold water more tightly than larger pores, causing more of the water held in the soil at the permanent wilting point to be unavailable for plants. This may cause organic matter colloids to disperse and become finer, destroying the aggregation.

The results obtained in this study indicate that the physical properties of hemic and sapric peat materials respond differently when lime and fertilisers are applied. Continuous application of lime and fertiliser may cause the breakdown of large-sized organic matter particles which, in turn, enhances the susceptibility of the soil to wind and water erosion, which will lead to further degradation of the soil. The peat materials will also tend to lose their ability to retain water due to progressive decomposition. Therefore, peat materials that are treated with lime and fertiliser may require more water from time to time as a result of the reduction in pore space. This means that the water holding capacity of the soil should periodically be assessed to determine the amount of watering required by crops that are planted on a long-term basis. Therefore, lime and fertiliser should be used judiciously to avoid rapid deterioration of the physical quality of the peat material, and thus overall loss of organic material through rapid oxidation and decomposition processes.

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AUTHOR CONTRIBUTIONS

AAR: Conceptualisation, sampling design, methodology and investigation, processing of soil samples, data analysis and writing original drafts; AH: funding acquisition and reviewing and editing subsequent versions of the manuscript.

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