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Research Article
Hydrophobicity of Tropical Peat Soil from an Oil Palm Plantation in North Sumatra

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Abstract

Objective: The hydrophobicity of tropical peat soil was assessed on different oil palm plantations in Labuan Batu District, North Sumatra, Indonesia. **Methodology:** The level of hydrophobicity was measured by the Water Drop Penetration Time (WDPT) method and using Fourier transform infrared (FTIR) spectroscopy for analysis of hydrophobic and hydrophilic functional groups in this soil. The critical level of water content that caused hydrophobicity in peat soil was obtained from the exponential function relationship between soil water content and the probability of hydrophobicity. **Results:** The critical water content determined at which the probability of occurrence of hydrophobicity stands at 60-80%. The mean critical water content of peat soil from the Panai Jaya Plantation (PAJ; 247.06-265.3% w/w) was higher than from the Meranti Paham Plantation (MEP; 151.41-169.39% w/w) indicating PAJ soils will be more susceptible to hydrophobicity than those of MEP. When dryness occurs, the hydrophobic components of peat soil at PAJ cause those soils to become hydrophobic more rapidly than those of MEP. The ratio of hydrophobic/hydrophilic components and water content of peat soil generates an exponential relationship, showing that decreased soil water content increases the ratio of production of hydrophobic/hydrophilic components, thus increasing the hydrophobicity of peat soil. **Conclusion:** The ratio of hydrophobic/hydrophilic components on hydrophobic peat soil of PAJ ranged 0.457-0.511 (Sapric soil) and 0.494-0.509 (Hemic soil) and hydrophobic peat soil of MEP ranged 0.490-0.508 (Sapric soil) and 0.491-0.505 (Hemic soil). A decrease in the soil water content will result in an increase in this ratio and in the hydrophobicity of peat soil.

Key words: Critical water content, FTIR, hydrophobicity, oil palm plantations, peat soil

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The total tropical peatland of Southeast Asia has been estimated[1] as large as 247,778 km^2 or about 24.8 Mha. Within Shouteast Asia, Indonesia has a best estimate of 149,056 km^2 (about 14.9 Mha) of peatland[2]. Tropical peat soil naturally has a high water retention capacity that is associated with the large numbers of macrospores and high level of porosity present in the soil. The capacity of peat soil to retain water can range from 300-1000% of its weight[3,4] and some researchers claim that the capacity is even greater. However, most of the water consists of gravitational water and is strongly bound by solid peat soil particles[5]. The expansion of oil palm plantations into former peatlands in Shouteast Asia (especially Malaysia and Indonesia) requires draining the land to create an area suitable for palm tree roots[6,7]. Excessive drainage of peat soil will typically cause irreversible drying resulting in soil hydrophobicity[8].

Several factors cause this hydrophobicity of peat soil[9], namely: (1) The humic acid content which is organic material that is covered by wax, a characteristically and naturally hydrophobic substance, (2) The presence of non-polar groups such as ethyl, methyl and aromatic compounds that are characteristically hydrophobic, while the numbers of hydrophilic organic compounds decrease in abundance and (3) The absorption of hydrophobic compounds such as oils, fats and the organic fraction onto the surface of hydrophobic fractions. When peat soil dries, the polar functional groups will associate and interact with each other through hydrogen bonds. This bonding causes non-polar groups to become oriented on the surface of organic colloidal compounds in a way that reduces their affinity for water dramatically. Hydrophobic tropical peat soil loses much of its capacity to absorb water because of the reduced presence of hydrophilic components such as carboxylic and phenolic-OH groups[10].

Most researchers generally assess hydrophobicity by the Water Drop Penetration Time (WDPT) method that is based on the time required for a droplet of water to infiltrate into the soil[11-13]. Hydrophobicity will occur in peat soil if the water table drops and the soil water content passes below a critical level for the occurrence of hydrophobicity although that value varies depending on the properties of the peat. Dekker *et al.*[12] stated that this critical water content related to hydrophobicity occurs as a transition zone; this zone occurs in the upper soil at a hydrophilic/hydrophobic interface between wet soil above the interface that is hydrophilic and below where the soil is hydrophobic. The relationship between water content and the probability of hydrophobicity can be applied to determine the critical water content at which the probability of occurrence of hydrophobicity stands[14] at 60-80%.

In addition to the WDPT method, the hydrophobicity of peat soil can be evaluated through an analysis of the presence of functional groups carrying either hydrophilic or hydrophobic properties[15]. Functional groups with hydrophilic properties include hydroxyl (OH) and carboxyl (C=O) groups, while hydrophobic groups include aliphatic (C-H and C=C) groups. Fourier transform infrared (FTIR) spectroscopy can be used to identify functional groups in the peat soil[16,17] and an analysis of the distribution of hydrophobic and hydrophilic compounds can help determine soil hydrophobicity[18-20]. Hydrophobicity is expressed as the ratio of the components of hydrophobic to hydrophilic groups in peat soil[18].

The objectives of this study were to (1) Assess the hydrophobicity of peat soil derived from an oil palm plantation agro-ecosystem and (2) Determine the critical water content of the peat soil environment as it relates to hydrophobicity. Although, a large number of studies have analyzed the hydrophobicity of peat soil, this study emphasizes the analysis of the ratio of hydrophobic to hydrophilic functional groups in the peat soil. The FTIR spectroscopy was performed to identify the functional groups of peat soil. The results of this study provide a basis for sustainable peat soil management in oil palm plantations.

MATERIALS AND METHODS

Soil sampling and analysis: This study analyzed peat soil samples taken from the two oil palm plantations in Labuhan Batu District, North Sumatra Province, Indonesia. These two plantations include the 6 years Panai Jaya Oil Palm Plantation (PAJ; 2°22'25"-2°22'50" N, 100°16'0"-100°17'10" E) and the 20 years Meranti Paham Oil Palm Plantation (MEP; 2°16'20"-2°16'55" N, 100°9'10"-100°9'35" E). The soil thickness ranged from 343.65-502.92 cm where peat land soil samples were collected and their maturity levels ranged from hemic to sapric[21]. At both locations, the ground water table ranged from 60-70 cm during soil sample collection. Samples were collected from the 0-50 cm soil layer. Peat soil samples with sapric and hemic maturity from PAJ were obtained at depths of 0 to 10/20 cm and 10/20 to 50 cm, respectively. Meanwhile, similar samples from MEP were obtained at depths of 0 to 30/40 cm and 30/40 to 50 cm, respectively. All soil analysis were performed at the Soil Laboratory of the Indonesian Oil Palm Research Institute. Soil analysis included analysis on ash content, bulk density, available water, water retention (pF 2.54 and 4.2), peat maturity (Von Post method), pH and organic-C. Soil acidity was measured as the pH of H_2O with a ratio of 1:5 of soil and water; this was measured using a glass electrode. Determination of ash content and organic-C was conducted using the Loss of Ignition method at a temperature of 500°C for 6 h. Total acidity, carboxylic content and phenolic-OH were determined by a method developed by Pansu and Gautheyrou[22]. Analysis of fiber content, water retention and bulk density was done using a method developed by Radjagukguk *et al.*[23].

Observation of hydrophobicity: Hydrophobicity of the peat soil was calculated using the WDPT method[11,12]; that is, it was determined by observing the water droplets on the surface of peat soil samples, which had been smoothed prior to analysis. When the contact angle is <90° and water penetration occurs in <5 sec, the peat soil is able to reabsorb water. However, if the contact angle is >90° and penetration time is >5 sec, the peat is considered to be hydrophobic.

The probability of hydrophobicity was determined by observing a number of peat soil samples; these were divided in two ways, using two levels of peat soil maturity (sapric and hemic) and two landuse ages for oil palm plantations (PAJ and MEP). A total of 440 peat soil samples were heated at a temperature of 50°C with a time interval of 0-150 min and recorded the effects on hydrophobicity. The treatments were conducted to obtain a series of data with peat soil water content ranging from dry to wet.

Hydrophobicity was observed to obtain the probability of its occurrence for each sample unit using a discrete binomial probability distribution, i.e., the occurrence or non-occurrence of peat soil hydrophobicity. After the hydrophobicity of all peat soil samples had been observed, a number of soil properties, including soil water content, total acidity, carboxylic content (COOH) and phenolic-OH were then analyzed.

Determination of critical water content: Critical water content of the peat soil, the point at which hydrophobicity occurred was determined by constructing the relationship between soil water content and the probability of the occurrence of soil hydrophobicity. The relationship model was applied to determine the critical soil water content, that is the point at which the probability of the occurrence of hydrophobicity was between 60 and 80%. This relationship is assumed to have an exponential pattern[14,24].

Analysis of FTIR spectroscopy: An ALPHA spectrometer (Bruker Optik GmbH, Ettlingberg, Germany) was used to perform FTIR spectroscopy analysis on the peat soil samples after they had been heat treated. Before reading the FTIR, the soil samples were prepared in advance by adding KBr powder. The used samples of air-dried peat soil had an approximate 1:100 ratio of peat soil sample to KBr weight. These soil samples were made into pellets using a tablet holder and then measured using the FTIR spectroscope at a wavelength ranging from 400-4,000 cm^{-1}. Interpretation of the results of FTIR analysis was performed based on Artz *et al.*[16], while, the spectral curve analysis was conducted using OPUS 6.5 software. The intensity of peak of each functional group was obtained by calculating the peak area of each curve found for the functional groups. The peak area was determined using the peak integration facility.

RESULTS AND DISCUSSION

Characteristics of peat soil: Table 1 presents the physical and chemical characteristics of peat soil from the two study sites. The locations of PAJ and MEP allowed comparison of site age of oil palm plantations soils (6 and 20 years, respectively). The peat soil from the PAJ site was sapric in the upper layer (0 to 10/20 cm) and hemic in the lower layer (10/20 to 50 cm), with a fiber content of 44 and 68%, respectively. The peat soil from the MEP site was sapric in the upper layer (0 to 30/40 cm) and hemic in the lower layer (30/40 to 50 cm), with a fiber content of 32 and 64%, respectively. The peat soil was very acidic.

The sapric soils of MEP exhibited the highest bulk density, reaching more than 0.2 g cm^{-3}, while the sapric soils of PAJ has a bulk density of 0.18 g cm^{-3}. The bulk density of hemic soils from both locations ranged from 0.16-0.17 g cm^{-3}. The more intensive cultivation activities in the older plantation are

Table 1: Characteristics of peat soil of the Panai Jaya and Meranti Paham sites

	Panai Jaya		Meranti Paham	
Soil characteristics	Sapric	Hemic	Sapric	Hemic
pH (H_2O)	3.68	3.50	3.73	3.60
Organic-C (%)	55.08	55.26	53.33	53.94
Total acidity (me g^{-1})	3.82	4.35	5.93	5.18
Carboxylic content (me g^{-1})	0.61	0.43	0.65	0.18
Phenolic-OH content (me g^{-1})	3.21	3.84	5.31	4.99
Ash content (%)	5.05	4.73	8.07	7.00
Fiber content (%)	44.00	68.00	32.00	64.00
Bulk density (g cm^{-3})	0.18	0.17	0.28	0.16
Porosity (%)	88.00	90.67	82.33	91.50
Water content at pF 2.54 (% w/w)	354.21	375.93	253.34	377.34
Water content at pF 4.2 (% w/w)	171.48	179.10	165.61	128.96

believed to have caused the higher soil bulk density observed at that site. Verry *et al.*[25] stated that the capacity of peat soil to retain water is a function of its bulk density, because the ability of soil to bind water increases with an increase in soil bulk density.

Hydrophobicity and critical water content of peat soil: An exponential relationship model was developed between the hydrophobicity of the peat and the soil water content in this study (Fig. 1). The relationship was significant ($p<0.05$) for all the studied peat types. The regression coefficients (R^2) of sapric and hemic peat soil of PAJ were 0.735 and 0.768, respectively, whereas those of MEP soils were 0.948 and 0.918, respectively (Table 2). Based on that relationship, one can see that a decrease in water content of peat soil results in an increase in the probability of the development of hydrophobicity in that soil. The relationship model obtained here is similar to the results of Salmah *et al.*[24] and Azri[14].

Based on the exponential function between the soil water content and hydrophobicity, the critical water content of the studied peat soils was obtained. The critical water content of the peat soils is a transition zone of soil water content between hydrophobic and hydrophilic conditions[12]. Table 2 presents the critical water content of peat soil obtained from each type of studied peat soil, which shows the critical water

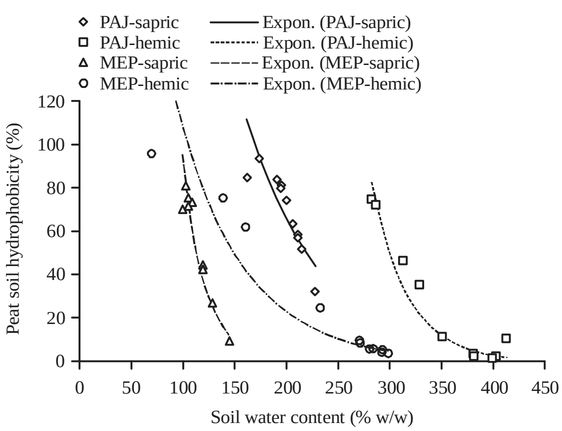

Fig. 1: Relationship between the probability of hydrophobicity and peat soil water content of the Panai Jaya (PAJ) and Meranti Paham (MEP)

content of hemic peat soil was higher than that of sapric soils at both sites, PAJ and MEP. This shows that hemic peat soil will experience hydrophobicity earlier than sapric soils. Additionally, hemic soil has a higher fiber content than sapric soil, giving it a higher water holding capacity. Riwandi[26] also found that the critical water content of hemic peat soil is greater than that of sapric soil.

The average of critical water content of peat soil in PAJ was greater than that in MEP, indicating that PAJ's peat soil required a higher water content to prevent the soil from becoming hydrophobic. With decreasing water content, the peat soil of PAJ will experience changes in the composition of its hydrophobic and hydrophilic components faster than the peat soil of MEP. When the number of hydrophobic components in soil increases to a critical value, the peat soil will become hydrophobic. The differences in the critical water content of peat soil from PAJ and MEP were also associated with differences in soil properties such as maturity, bulk density, ash content and water retention.

Relationship between hydrophobicity and peat soil properties: The observed hydrophobicity of peat soil in this study was attributed with several soil properties including soil water content, soil total acidity, carboxylic content and phenolic-OH content. A negative relationship was observed between the peat soil hydrophobicity and the peat soil properties. Table 3 provides the correlation coefficients. Decreases in soil water content, soil total acidity, carboxylic content or phenolic-OH content will result in increased hydrophobicity of peat soil. The highest correlation coefficient was obtained for the relationship between the hydrophobicity and soil water content while the lowest correlation coefficient was observed between the relationship with hydrophobicity and phenolic-OH groups.

Soil water content had a positive relationship with total soil acidity, carboxylic content and phenolic-OH content, in which an increase of the values of these soil properties causes an increase in soil water content. The highest correlation coefficient was obtained for the relationship between soil water content and carboxylate content and ranged from 0.714-0.801 ($p<0.05$) and from 0.665-0.72 ($p<0.05$) for peat

Table 2: Exponential functions, regression coefficients and critical water content of peat soil hydrophobicity from the research sites

Location	Peat soil type	Exponential model	Regression coefficient (R^2)	Critical water content (% w/w)
Panai Jaya	Sapric	$Y = 1094e^{-0.01X}$	0.735*	201.19-223.33
	Hemic	$Y = 28011e^{-0.02X}$	0.768*	292.92-307.30
	Average			247.06-265.31
Meranti Paham	Sapric	$Y = 9127e^{-0.04X}$	0.948*	118.42-125.62
	Hemic	$Y = 505.7e^{-0.01X}$	0.918*	184.39-213.16
	Average			151.41-169.39

*Significant at $p<0.05$ (n = 11), Y: Probability of peat soil hydrophobicity, X: Soil water content

Table 3: Correlation coefficient (r) of the relationship between the probability of peat soil hydrophobicity and Soil Water Content (SWC), Soil Total Acidity (STA), carboxylic content (COOH) and phenolic-OH (phen-OH) content of peat soils from the Panai Jaya (PAJ) and Meranti Paham (MEP) sites

	Sapric				Hemic			
Locations	SWC	STA	COOH	phen-OH	SWC	STA	COOH	phen-OH
Panai Jaya								
Soil water content		0.667	0.801	0.202		0.616	0.714	0.378
Probability of hydrophobicity	−0.897	−0.652	−0.735	−0.166	−0.916	−0.779	−0.700	−0.606
Meranti Paham								
Soil water content		0.766	0.725	0.655		0.692	0.665	0.172
Probability of hydrophobicity	−0.970	−0.746	−0.725	−0.668	−0.995	−0.695	−0.633	−0.185

Values (r) are significant at $p<0.05$, $n = 11$

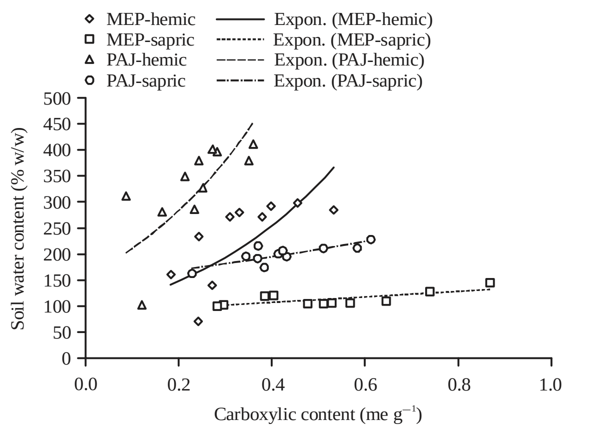

Fig. 2: Relation between soil water content and carboxylic content on studied peat soils. Coefficient of determinations are 0.631, 0.400, 0.516 and 0.388 for PAJ's sapric, PAJ's hemic, MEP's sapric and MEP's hemic soils, respectively ($n = 11$, $p<0.05$)

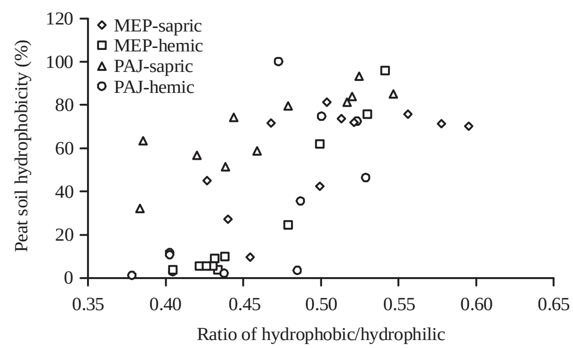

Fig. 3: Relationship between hydrophobicity of peat soil and the ratio of hydrophobic/hydrophilic soil components of peat soil from Panai Jaya (PAJ) and Meranti Paham (MEP)

soil from PAJ and MEP, respectively. Figure 2 shows the relationship between soil water content and carboxylate content. The relationship is an exponential function where an increase of carboxylate content resulted in a significantly increased soil water content for all soil types studied here ($p<0.05$). According to Sabiham[10], the presence of various carboxylic compounds plays a role in chemical binding of water by peat soil.

Evaluation on hydrophobicity using FTIR spectroscopy: Hydrophobicity in peat soil is often attributed with the presence of organic compounds. The FTIR analysis focused on the identification of the presence of functional groups carrying hydrophobic properties (C-H, C=C); this is called a hydrophobic component of the soil. Those carrying hydrophilic functional groups (O-H, C=O) are called hydrophilic components. The C-H, C=C, O-H and C=C O functional groups were found in the wavelengths ranging from 2,630-3,000 cm^{-1}, 1,525-1,685 cm^{-1}, 3,000-3,740 cm^{-1} and 1,681-1,829 cm^{-1}, respectively. The FTIR measurements were performed on all samples of peat soil which had been heated at a temperature of 50°C with a time interval of 0-150 min. Calculations of the peak area were performed on each functional group containing a hydrophobic or hydrophilic component.

The ratio of functional groups with hydrophobic components against those with hydrophilic components was determined using the value of the peak area. The ratio describes the condition of hydrophobicity of the peat soil being analyzed[18]. Increased heat treatment caused an increase in the ratio of hydrophobic to hydrophilic components ($R^2 = 0.587$-0.828, $p<0.05$) for all peat soils studied; that is, an increase in soil hydrophobicity is characterized by an increase in this ratio (Fig. 3).

The regression coefficient (R^2) of sapric soils at the PAJ and MEP sites and hemic soils at the PAJ and MEP sites (Fig. 3) were 0.721 and 0.448 (Sapric) and 0.662 and 0.921 (Hemic; all $p<0.05$), respectively. A decrease in soil water content will result in an increase in the ratio of hydrophobic/hydrophilic

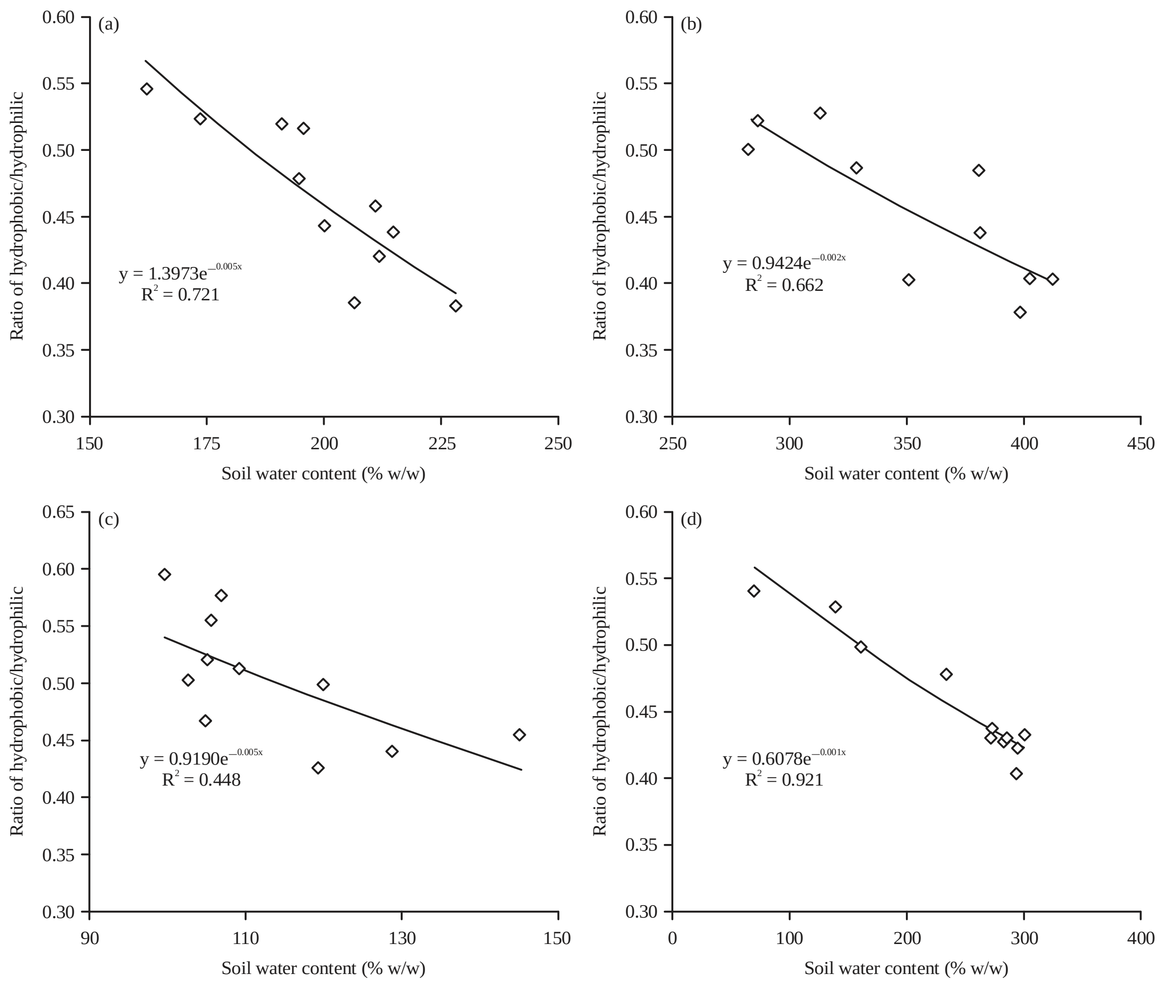

Fig. 4(a-d): Relationship between soil water content and the ratio of hydrophobic/hydrophilic components of peat soil from Panai Jaya (PAJ) and Meranti Paham (MEP), (a) PAJ-sapric, (b) PAJ-hemic, (c) MEP-sapric and (d) MEP-hemic

components; a higher ratio indicates that the content of hydrophobic components has increased in comparison with the hydrophilic components, making the peat soil more hydrophobic, a finding that confirms the findings of Ellerbrock *et al.*[27].

An increase in concentration of the hydrophobic components compared with the concentration of hydrophilic components in drained peat soil will occur as the result of increased bonding between the various polar functional groups so that the non-polar groups become oriented on the surface of the organic colloids[9]. Based on the obtained equation (Fig. 4), the ranges of the ratio of hydrophobic/hydrophilic components on peat soil that were observed when the probability of hydrophobicity was in the range of 60-80% were 0.457-0.511 and 0.490-0.508 (Sapric soils) and 0.494-0.509 and 0.491-0.505 (Hemic soils) for the sapric soils at the PAJ and MEP sites and hemic soils at the PAJ and MEP sites, respectively.

CONCLUSION

The hydrophobicity of peat soil is associated with a critical level of soil water content that is different for each peat soil type. The mean critical water content of peat soil obtained in this study at the PAJ site ranged from 247.06-265.31% (w/w) and was higher than the mean for the MEP site that ranged from151.41-169.39% (w/w). The peat soil of the PAJ site requires a higher water content if the soil is to remain hydrophilic. The critical water content of peat soil with a lower level of maturity is higher than for peat soil at a higher level of maturity; therefore, hemic soil will become hydrophobic with less drying than sapric soil.

The hydrophobicity of peat soil is closely and negatively related to soil total acidity, carboxylic content and phenolic-OH content. An evaluation on hydrophobicity was conducted using FTIR; this generated an exponential relationship between the ratio of hydrophobic/hydrophilic components with water content of peat soil. A decrease in the soil water content will result in an increase in this ratio and in the hydrophobicity of peat soil. The ratio of hydrophobic/hydrophilic components of peat soil that experience hydrophobicity ranged from 0.457-0.511.

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