

Properties of Indonesian Peat in Relation to the Chemistry of Carbon Emission

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Abstract: The discussion is focused on several properties of peat, such as the composition of peat materials, critical water content in relation to irreversible drying, concentration of -COOH , and the chemistry of C emission as a result of the reduction and oxidation processes of peat materials. The experiments were divided into two steps: (i) laboratory experiments and (ii) field experiments. For the laboratory experiments, peat samples of fibric, hemic and sapric decomposition degrees were taken from Jambi, Sumatra and Central Kalimantan. On the field, the experiments were focused in Central Kalimantan. Based on the research results, the composition of peat material is rather similar, being mostly rich in wood containing high content of lignin that varies from 65 to 80% for the peats of Jambi, and 78 to 93% for the peats of Central Kalimantan. The content of cellulose was mostly less than 10%, while hemi-cellulose and protein were not detected. The main organic acids, as a result of lignin biodegradation and the sources of C-release, are of aromatic group consisting mainly of derivative phenolic acids. The concentration of such organic acids ranging from the highest to the lowest is as follows: ferulic acid \approx synapic acid $>$ *p*-coumaric acid $>$ *p*-hydroxybenzoic acid $>$ vanilic acid $>$ syringic acid. The drying and wetting processes on the peat materials affected the stability of organic acids, which was indicated by the loss of C through CO_2 and CH_4 releases. The release of CO_2 and CH_4 from fibric peat was higher than that from hemic and sapric peats. To solve such problems, the addition of metal ion (Fe^{3+}) as an ameliorant to the peat at a certain dosage was used. In the field experiments, the use of mineral soil and basic slag at the rate of 5% maximum Fe^{3+} -sorption decreased the total of C-emission from peat of about 28 to 31%.

Key words: Indonesian peat, peat material composition, derivative phenolic acids, C-release.

1. Introduction

Recently, the peat-land utilization in Indonesia for agriculture has received much attention although the peat mostly contains: (i) poor to very poor in nutrients for plant growth and (ii) organic materials which are rather similar in composition, being very rich in wood, i.e. more or less decomposed trunks and branches derived from the former vegetation covers [Sabiham, 1988]. Several investigators have demonstrated that the composition of peats is related to the forest structure and the characteristics of vegetation cover. The use of peat forest for agricultural activities has led to widespread declines in organic carbon (C) and hence in peat quality. The declines occur because, in such activities, the loss of organic-C is not offset by the gains of C through the deposition of biomass.

The important physical properties of peat are high porosity [Sabiham, 2000] and very high content of water. Therefore, peat is naturally in anaerobic condition. Because peat materials have an irreversible drying property, however, the peat function as hydrologic controller would easily be disturbed. On the irreversible drying condition, particularly after a drainage system in peat land is constructed, a part of peat materials will not be able to reabsorb water. In fact, peat materials are the primary storehouse of organic-C. The loss of C through the reduction and oxidation of peat in the forms of CH_4 and CO_2 respectively is mostly emitted to the atmosphere. Yagi and Minami [1990] reported that the highest rate of CH_4 emission during cultivation period ($44.8 \text{ g CH}_4 \text{ m}^{-2}$) was in rice field consisting of peat. The drainage of peat releases oxygen (O_2) into the surface, which promotes decomposition. It means that since peat deposits are a pile of carbon (C), they became potential materials of C-release that could be emitted to the atmosphere. The current annual average emission from Indonesian peat between 2000 and 2006 is estimated to be 903 MtCO_2 [BAPPENAS, 2009]. This condition shows that peat is very fragile and easily destroyed. The destruction rate will be faster if peat is poor in alkali and/or metal cations and below the peat layer there are old soil formations or sand (quartz) layers. In an anaerobic condition, the decomposition of organic matter in peat can actually occur even though it is at a very slow rate.

1.1. Nature of the Research Problem

The studies on the chemistry of C-emission in Indonesia have been given very little attention compared with the activities of peat utilization. Therefore, it could be understood that the reclamation of peat lands in the country has always been a matter of some controversies. Since the 1960s the Indonesian Government has started agricultural development on peat lands through the transmigration program, and from 1980s private companies started to open the lands for plantations. However, as a result of initial drainage, the stability of peat decreased and its land surface subsided due to the presence of high C-release from peat to atmosphere [WWF, 2008]. This means that the development of peat for agricultural activities has been hampered by the very little understanding of the people about the process of peat degradation.

Recognizing such problems particularly understanding of Indonesian peat properties in relation to the chemistry of C-emission has apparently become more important. The chemical composition of peat, critical water content, surface charge and adsorption characteristics of cation are the key factors that strongly affect the chemistry of C-emission. Low contents of water and cation in peat are also highly potential causes of C-losses.

1.2. Methodology Employed

The sites selected chosen for the study were the eastern part of Jambi, Sumatra and the center and southern parts of Central Kalimantan. The experiments, both in the laboratory and the experimental sites, were conducted during the period of 1999 until 2004. Peat deposits here are mostly situated inland of the coastal plains [Polak, 1975]. Therefore, peat samples were taken from the representative areas with different environments: marine, brackish and fresh water environments, which are characterized by a condition of water salinity in each environment. Peat land influenced by water inundation having water salinity of 1.0 to more than 2.0 mmhos cm^{-1} is categorized into marine environment, and the land influenced by that having water salinity of 0.5 to 10 mmhos cm^{-1} is categorized into brackish environment. The land classified into fresh water environment if it is influenced by water inundation having water salinity of less than 0.5 mmhos cm^{-1} .

The research was divided into two steps. The first (laboratory experiments) activities were focused on the inherent properties of peat, namely: (i) chemical compositions of peat in relation to the organic acids as the sources of C-release, for which organic acid measurement focused on derivative phenolic acids was conducted with the method of partition separation using reversed-phase column of C_{18} ($\mu\text{Bondapak}^{\text{TM}}$ 2.9x300 mm) and UV detector with D2-lamp at the wave of 280 nm; HPLC (High Performance Liquid Chromatography) was used to determine derivative phenolic acids, (ii) critical water content in relation to the process of irreversible drying determined by using the methods of Bisdom *et al.* [1993], (iii) adsorption characteristics of Fe^{3+} in peat, for which the methods of Fox and Kamprath [1971] modified by Widjaja-Adhi *et al.* [1990] and Syers *et al.* [1973] were used to select the cation that has high reactivity with organic acids, and (iv) measurement of CO_2 and CH_4 releases through reduction and oxidation processes. The second (field experiments) activities were focused on the interaction of organic acids and mineral materials containing high Fe^{3+} and its influence to rice production and C-emission.

2. Results and Discussion

2.1. Chemical Composition of Peat

Table 1 shows several physical and chemical characteristics of peats in Jambi and Central-Kalimantan. The degree of sapric, hemic and fibric decomposition was determined by using the data of fiber volume and pyrophosphate index [Lynn *et al.*, 1974]. There are several interesting results to discuss. Based on the ash content, the peats in Jambi and Central Kalimantan, which have the loss of ignition of mostly more than 95%, could be categorized as poor peats. C/N ratio of peats in both areas is still very high (more than 50%). The peat composition is dominated by lignin of 65% to 80% for the peats of Jambi, 78% to 93% for the peats of Central Kalimantan. The content of cellulose in all peat

samples was mostly less than 10%, while hemi-cellulose and protein were not detected. Lignin, as the dominant peat composition, is categorized as a thermoplastic system, highly aromatic polymers, derived from guaiacyl propane monomers [Tan, 1998]. Plant lignin in most Indonesian peats consists of three types of basic monomers, namely: (i) lignin from grasses and palm, in which the type of basic monomer is derived from 4-hydroxy phenyl propane, (ii) lignin from softwood derived from 3-methoxy-4-hydroxy phenyl propane, and (iii) lignin from hardwood derived from 3-5-dimethoxy-4-hydroxy phenyl propane as can be seen in Fig. 1. Orlov [1995] showed the processes of lignin disintegration that result in several derivative phenolic acids. In relation to plant growth, of 18 derivative phenolic acids as stated by Stevenson [1994], only five to six were the most important derivative phenolic acids found in the peats of Jambi and Central Kalimantan [Sabiham, 1997; Mario and Sabiham, 2002]: ferulic, synapic, *p*-coumaric, vanilic, syringic, and *p*-hydroxybenzoic acids (Fig.2).

Table 1. Physical and chemical characteristics of peats in Jambi and Central-Kalimantan

Peat properties	Marine peat			Brackish peat			Fresh water peat		
	S-ric	H-mic	F-ric	S-ric	H-mic	F-ric	S-ric	H-mic	F-ric
Jambi									
Organic-C (%)	54.9	56.9	-	55.8	56.5	57.4	54.8	56.0	55.8
Ash content (%)	5.26	2.08	-	5.62	3.53	3.73	3.75	2.68	1.09
Total-N (%)	1.06	1.04	-	0.82	0.94	0.78	0.86	0.76	0.71
C/N ratio	51.8	54.7	-	68.1	60.1	73.6	63.7	73.7	78.6
Lignin (%)	71.6	65.6	-	73.4	74.0	80.0	77.8	75.4	79.2
Cellulose (%)	5.9	9.6	-	6.84	5.4	3.4	5.2	2.6	4.8
Central Kalimantan									
Organic-C (%)	54.3	55.7	53.5	55.5	57.0	57.1	57.7	57.7	57.8
Ash content (%)	4.62	8.71	6.14	4.53	2.02	1.83	0.63	0.62	0.58
Total-N (%)	0.91	0.60	0.71	0.71	0.76	0.65	0.77	0.60	0.61
C/N ratio	59.7	92.8	75.4	78.2	75.0	87.8	74.9	96.2	94.8
Lignin (%)	78.8	86.7	82.8	87.5	91.5	90.5	93.0	92.0	92.2
Cellulose (%)	10.9	4.6	4.9	5.3	3.9	1.7	2.3	4.8	3.1

Notes: 1. In Jambi, marine fibric-peat could not be found due to intensive cultivation by local people.
 2. S-ric = sapric peat; H-mic = hemic peat; F-ric = fibric peat.
 3. Hemi-cellulose and protein contents in the peats of Jambi and Central Kalimantan were not detected.

Table 2 shows the concentrations of most important derivative phenolic acids found in the studied areas. Based on the concentration of the acids, ferulic and synapic acids are the highest, and the lowest was syringic acid. Such a series of the acid concentrations could be listed as follows: ferulic acid \approx synapic acid $>$ *p*-coumaric acid $>$ *p*-hydroxybenzoic acid $>$ vanilic acid $>$ syringic acid. These acids were categorized as the main sources of C-release due to the high content of carboxyl ($-\text{COOH}$) and methoxy ($-\text{OCH}_3$) groups. COOH could be broken down completely into CO_2 and H_2O through the processes of oxidation-reduction. CO_2 could also be released when the methoxy groups ($-\text{OCH}_3$) changed into $-\text{OH}$ groups during the phenol-OH formation through the processes of demethylation, hydroxylation and oxidation. The other important gas, methane (CH_4), is produced by strict anaerobic bacteria (methanogens) [van der Gon and Neue, 1995]. The rate at which anaerobic decomposition of peats proceeds as well as the resulted ratio of CO_2 to CH_4 particularly depended on soil pH. A major pathway in anaerobic condition produces CH_4 through the reduction of CO_2 with H_2 or organic molecules (H_2A) as the H donor if soil pH is very low [Neue and Scharpenseel, 1985], as follow:



Although atmospheric CH_4 concentration is much lower than the atmospheric concentration of the most important greenhouse gas, CO_2 , the rising atmospheric CH_4 concentration may significantly affect global temperature. The importance of CH_4 as a greenhouse gas is, for example, due to its relatively large annual concentration increase of approximately 0.8% [IPCC, 1992].

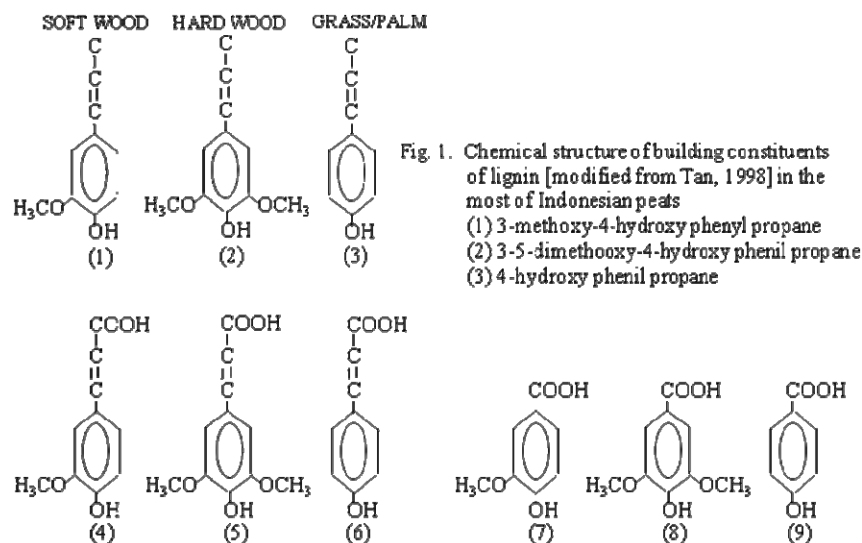


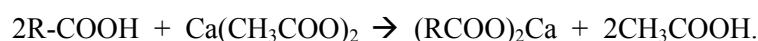
Fig. 2. The most important derivative phenolic acids in the peats of Jambi and Central Kalimantan: (4) Ferulic acid; (5) Synapic acid; (6) *p*-Coumaric acid; (7) Vanillic acid; (8) Syringic acid; and (9) *p*-Hydroxybenzoic acid.

Table 2. Concentrations of the most important derivative phenolic acids (mM) in the peats of Jambi and Central Kalimantan

Peat properties	Marine peat			Brackish peat			Fresh water peat		
	S-ric	H-mic	F-ric	S-ric	H-mic	F-ric	S-ric	H-mic	F-ric
Jambi									
<i>p</i> -Hydroxybenzoic acid	0.33	0.32	-	0.28	0.43	0.20	0.53	0.35	0.24
Vanillic acid	0.32	0.24	-	0.27	0.39	0.12	0.45	0.38	0.22
Syringic acid	0.31	0.24	-	0.40	0.29	0.15	0.37	0.30	0.13
<i>p</i> -Coumaric acid	0.33	0.53	-	0.53	0.35	0.18	0.70	0.45	0.32
Ferulic acid	1.10	0.83	-	1.21	0.29	0.10	1.10	0.80	0.52
Central Kalimantan	Composite sample			Composite sample			Composite sample		
<i>p</i> -Hydroxybenzoic acid		0.65			0.80			0.91	
Vanillic acid		0.66			0.78			0.84	
Syringic acid		0.58			0.71			0.84	
<i>p</i> -Coumaric acid		1.33			1.54			1.83	
Ferulic acid		1.42			1.65			2.24	
Synapic acid		1.35			1.76			2.32	

Notes: 1. In Jambi, marine fibric-peat could not be found, and synapic acid was not analyzed
2. S-ric = sapric peat; H-mic = hemic peat; F-ric = fibric peat.
3. In Central Kalimantan, peat samples were not separated between sapric, humic and fibric peats.

To determine the amount of COOH groups in peats, Ca acetate procedure [Tan, 1998] was used. The Ca acetate method made use of the reaction in which acetic acid (CH₃COOH) was formed and released according to the reaction as follows:



COOH content was determined by titration of the CH₃COOH solution with 1N NaOH, followed by calculation using the formula of:

$$COOH \text{ groups (me g}^{-1} \text{ of peat)} = [(V_s - V_b) \times N] / \text{weight of peat sample,}$$

where: V_s = volume of CH_3COOH solution; V_b = volume of blank; and N = normality of NaOH.

The analysis result of the COOH content can be seen in Table 3.

Table 3. The content of COOH functional groups (me g^{-1} peat) in the peats of Jambi and Central Kalimantan

Decomposition degree	Peat of Jambi			Peat of Central Kalimantan		
	Marine	Brackish	F. water*	Marine	Brackish	F. water*
Fibric peat	0.51	0.48	0.35	0.51	0.39	0.39
Hemic peat	0.34	0.36	0.33	0.50	0.30	0.34
Sapric peat	0.33	0.40	0.29	0.50	0.30	0.30

Notes: *) F. water = Fresh water.

2.2. Critical Water Content and Irreversible Drying

The most important factor that influenced the COOH groups in peat was critical water content. The value of critical water content was calculated by making the relationship between the water content at certain levels and the proportion of irreversible drying.

Irreversible drying was determined by the method of “water drop penetration time”. A model used for such relationship was $Y = ae^{-bX}$. To analyze the proportion of irreversible drying, peat samples were dried at 50 °C in an electric oven with time intervals of 15, 30, 45, 55, 65, 75, 90, 105, 135 and 150 minutes. The results showed that in all environmental conditions, namely marine, brackish and fresh water environments, fibric peat with the high values of critical water content (Table 4) needed a shorter period to reach an irreversible drying condition compared with hemic and sapric peats.

Table 4. Irreversible drying (ID) period and the value of critical water content (CWC) in the peats of Jambi and Central Kalimantan

Peat properties	Peat of Jambi			Peat of Central Kalimantan		
	Marine	Brackish	F. water	Marine	Brackish	F. water
Fibric peat						
ID period (minute)	90	90	90	90	90	90
CWC (%)**	336.8–450.9	316.5–423.7	308.9–413.5	290.6–388.9	273.0–365.5	346.6–464.0
Hemic peat						
ID period (minute)	120	120	105	120	105	105
CWC (%)**	165.5–221.6	245.0–327.9	318.3–426.5	202.7–271.4	178.0–238.3	191.7–256.6
Sapric peat						
ID period (minute)	135	105	120	135	135	120
CWC (%)**	186.8–250.0	280.6–375.7	238.2–318.9	192.0–257.0	224.4–300.4	232.0–310.6

Notes: *) F. water = fresh water

**) Below the critical water-content level, peat materials could not reabsorb water.

In fact, the fibric peat that is categorized into a suborder of fibrist according to Soil Taxonomy [Soil Survey Staff, 1999] mainly consists of plant remains which are not totally destroyed yet. A part of botanical origin of peat materials could be readily recognized, and consists mostly of the partly decomposed wood with small amount of the plant remains of leave and grasses. As a consequence, colloidal organics in fibric peat are very small, so the peat could not absorb more water. On the other hand, the perfectly decomposed plant remains, such as sapric peats, produced more organic acids as colloidal organics which could tightly bind the water molecules, so that the water did not easily lose from its colloidal surface. Hemic peat consists of plant remains which have degrees of decomposition in between fibric and sapric peats.

Based on Table 4 it can be mentioned that the higher the critical water content of peats, the more rapidly the peat materials would dry toward irreversible drying. Conversely, peat with low critical water content became very slow to dry. The high content of COOH groups (Table 3) might be one of the reasons why the above facts occurred. Tschapek *et al.* [1996] reported that functional groups of COOH are polarity and hydrophilic, so they can be helpful in the process of adsorbing water.

2.3. The adsorption characteristic of Fe^{3+}

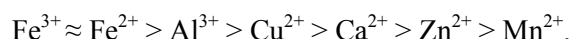
Based on pH_{ZPC} and pH actual (Table 5), it can be mentioned that the surface of colloidal organic of peats mostly indicated as negative charge. In Indonesian peats which are mostly in acid condition, the charge is generally controlled by phenolic-OH and COOH groups. However, Tan [1998] noted that 54% of the exchange capacity of organic acids was attributed to COOH groups and they started to dissociate its H^+ at pH 3–5.5. This condition was very important for colloidal organic in the process of attracting cations, which lead to complex reaction (chelation). This fact was used to solve the problem in relation to the disintegration of organic matter through C-release.

Table 5. pH_{ZPC} and pH actual of the peats of Jambi and Central Kalimantan

Decomposition degree	Peats of Jambi						Peats of Central Kalimantan					
	Marine		Brackish		Fresh water		Marine		Brackish		Fresh water	
	pH_Z^*	pH_A	pH_Z	pH_A	pH_Z	pH_A	pH_Z	pH_A	pH_Z	pH_A	pH_Z	pH_A
Fibric	4.56	4.67	3.16	3.51	3.31	3.40	4.48	4.75	3.86	4.00	3.76	3.97
Hemic	4.13	2.48	3.24	3.47	3.28	3.35	4.28	4.33	3.43	3.78	3.51	3.02
Sapric	5.01	5.12	3.36	3.56	3.33	3.54	4.53	4.82	3.15	3.52	3.30	3.41

Notes: *) $\text{pH}_Z = \text{pH}_{\text{ZPC}}$ (pH at zero point of charge) is soil pH at which the surface charge of the colloidal organic is electrically neutral.

The use of selected cation of Fe^{3+} as an ameliorant for increasing peat stability was based on the previous research [Sabiham, 1997] in which the method of Langmuir curve according to Fox and Kamprath [1971, modified by Widjaja-Adhi *et al.*, 1990] and Syers *et al.* [1973] was adopted to select seven cations of Fe^{3+} , Fe^{2+} , Cu^{2+} , Ca^{2+} , Zn^{2+} , Mn^{2+} and Al^{3+} . Based on this research, the effectiveness of Fe^{3+} reaction with the colloidal organic to form the complexes is highest. Such a series of cation listed in the decreasing order of preferential interaction in the formation of complexes is as follows:



Maximum adsorption of Fe^{3+} in different pH increased, as presented in Table 6, with the increasing soil pH. Because the pH of peat is categorized as pH dependent charge, the increase in pH has caused the rise of negative charges due to the presence of functional group (COOH) dissociation, causing the increase in cation (Fe^{3+}) adsorption.

Table 6. The average of Fe^{3+} -sorption ($\mu\text{g g}^{-1}$) in different soil pH of the peats in Jambi and Central Kalimantan

Location	Environmental unit	Soil pH				
		-0.25 pH_{ZPC}	pH_{ZPC}	$\text{pH}_{\text{actual}}$	+0.5 pH_{ZPC}	+1.0 pH_{ZPC}
Jambi	Marine	16,446.6	22,208.5	23,533.9	26,554.9	29,735.3
	Brackish	12,351.7	17,630.2	19,520.9	20,931.3	24,049.2
	Fresh water	10,000.7	15,613.4	15,933.4	16,751.3	17,952.7
Central Kalimantan	Marine	12,287.0	19,706.9	20,143.7	23,659.7	24,650.5
	Brackish	8,660.0	12,081.0	16,349.0	17,029.8	18,594.8
	Fresh water	8,706.3	9,017.5	10,943.4	11,204.9	11,567.9

With such formation, peat would be more resistant to decomposition process, thereby reducing the production of CO₂ and CH₄.

Table 8. Effect of the application of Fe³⁺ on the CO₂ and CH₄ productions (μg g⁻¹ h⁻¹) and the soluble Fe (ppm) in composite-peat samples from Jambi and Central Kalimantan

Rate of Fe ³⁺ * (% max. sorption)	Peats of Jambi			Peats of Central Kalimantan		
	CO ₂	CH ₄	Fe-solution	CO ₂	CH ₄	Fe-solution
2.5	36.2	17.8	16.3	37.0	16.7	16.2
5.0	30.9	15.2	18.5	30.5	14.1	18.9
7.5	28.6	14.8	26.3	28.0	13.4	27.6

Notes: *) Given in the form of FeCl₃.6H₂O

2.5. Interaction of organic acids and mineral materials containing high Fe³⁺, and its influence on rice production and C-emission

It has long been my contention that the production of agricultural crops planted on peats is always lower than those planted on mineral soils. The low productivity of peats is mainly caused by the constraint of high content of organic acids, particularly derivative phenolic acids which are phytotoxic to plants. Peats are also very easy to get destroyed due to the high loss of organic-C upon reclamation. Rieley *et al.* [1997] stated that peats in Southeast Asia are formerly forests and are of only marginal use for growing crops, yet with the conversion to agriculture together with non-sustainable logging, are a major and increasing threat.

Recently, however, many scientists have conducted research in cultivated peatlands in order to solve the constraints. In the present paper, I argue that a method to decrease the derivative phenolic acids by changing the environment from anaerobic into aerobic conditions should be considered. The addition of mineral soil enriched with basic slag containing high levels of Fe³⁺ is expected to be able to reduce the harmful effects of such acids, meaning that the productivity and stability of peats can be increased. The experiments were carried out in three locations of Central Kalimantan's peatlands: marine peatland located in Samuda, brackish peatland in Sampit, and fresh water peatland in Berengbengkell. A combination of mineral soil containing Fe³⁺ of about 22.06% of Fe₂O₃ and basic slag of about 42.6% of Fe₂O₃ on various levels was given to the peat as ameliorants based on 5% of the maximum adsorption of Fe³⁺. The combinations of such ameliorants were MBS₀ = without treatment; MBS₁ = 100% mineral soil (ms), MBS₂ = 50% ms + 50% slag (bs); MBS₃ = 100% bs.

The research results showed that the concentration of observed derivative-phenolic acids, namely: ferulic, synapic, *p*-coumaric, vanilic, syringic and *p*-hydroxybenzoic acids in peats decreased with the addition of mineral soil or basic slag, or the combination of both materials (Table 9). The higher the mineral soil in peats, the more interaction would actually emerge between organic and mineral materials containing high Fe³⁺. Sabiham [1997] stated that the proportion of Fe³⁺ in peats is mainly distributed in the forms of chelation and strong bond which varies from 55.1 to 78.6% of the total extracted Fe³⁺.

The addition of ameliorants also increased the rice production, as can be seen in Table 10. Based on the observation results, however, rice did not seem to be able to grow well on fresh water peat; without ameliorant, plant growth was totally hampered, so after 42 to 49 days of transplanting the rice died. Tadano *et al.* [1992] reported that derivative phenolic acids, such as ferulic, synapic, *p*-coumaric, and *p*-hydroxybenzoic acids are phytotoxic for rice, particularly during the first stage of plant growth. He also mentioned that ferulic acid in peat is more toxic compared to the other derivative phenolic acids. Tsutsuki *et al.* [1994] stated that the concentration of phenolic acids at the range of 0.6 to 3.0 mM could hamper the root growth of rice up to 50%.

Based on Table 10, the production of rice in marine peat is higher compared to that of rice in brackish and fresh water peats. Marine peat is categorized as eutrophic peat [Andriess, 1988], rich in nutrients due to very close to the marine environment, so the peat could support plant growth well. On the other hand fresh water peat categorized as oligotrophic peat, in which the source of nutrients is

mostly derived from rain water, does not seem to be easy to bring into agricultural activities. Therefore, it could be suggested that the natural fresh-water peat not converted into agricultural use, as it is extremely acid and infertile.

Table 9. Average of the observed derivative-phenolic acids in peat of Central Kalimantan treated by some combinations of mineral soil and basic slag containing high content of Fe^{3+}

No	Treatment	Derivative phenolic acid (mM)					
		Ferulic	Synapic	<i>p</i> -coumaric	Vanilic	Syringic	<i>p</i> -HB*
1. Marine peat							
	MBS ₀ **	1.43	1.35	1.33	0.66	0.58	0.65
	MBS ₁	0.76	0.91	0.91	0.43	0.35	0.49
	MBS ₂	0.92	0.97	1.06	0.51	0.43	0.51
	MBS ₃	0.99	1.02	1.10	0.53	0.44	0.52
2. Brackish peat							
	MBS ₀	1.65	1.76	1.54	0.78	0.71	0.80
	MBS ₁	0.93	1.19	0.95	0.55	0.48	0.58
	MBS ₂	1.21	1.30	1.20	0.63	0.59	0.65
	MBS ₃	1.22	1.40	1.17	0.65	0.60	0.67
3. Fresh water peat							
	MBS ₀	2.25	2.32	1.83	0.84	0.84	0.90
	MBS ₁	1.51	1.49	1.46	0.64	0.61	0.66
	MBS ₂	1.70	1.73	1.56	0.68	0.70	0.72
	MBS ₃	1.81	1.82	1.59	0.69	0.73	0.72

Notes: *) *p*-HB = *p*-hydroxybenzoic

***) MBS = combination of mineral soil and basic slag as ameliorant: MBS₀ = without ameliorant; MBS₁ = 100% mineral soil (ms); MBS₂ = 50% + 50% basic slag (bs); MBS₃ = 100% bs.

Table 10. The effect of ameliorants on the weight of rice grain of IR-64 (t ha^{-1})

Treatment	Peats of Central Kalimantan		
	Marine peat	Brackish peat	Fresh water peat
MBS ₀ *	4.09	2.12	0.00**
MBS ₁	4.18	2.27	0.00
MBS ₂	5.17	4.78	1.15
MBS ₃	5.62	5.08	1.56

Notes: *) MBS = combination of mineral soil and basic slag as ameliorant: MBS₀ = without ameliorant;

MBS₁ = 100% mineral soil (ms); MBS₂ = 50% + 50% basic slag (bs); MBS₃ = 100% bs.

***) Rice plant died at 42 – 49 days after transplanting.

Table 10 shows that although the treatment of MBS₃ (100% basic slag or bs) produced the highest level of yield, the production resulting from the treatment of MBS₂ at the same environment is not so much different. Based on the practical aspect, it can be suggested that the treatment of MBS₂ (50% ms + 50% bs) is more useful for improving the peat productivity.

In fact, undisturbed naturally forested peatlands either have a balanced C-budget or show a net accumulation of C through the natural process of peat formation. Therefore, peat in natural condition can be categorized as a stable peat, meaning that the accumulation of C is higher than its loss through decomposition process. The C-sequestration rate from natural peatlands in Indonesia has been estimated to be up to $0.8 \text{ t C ha}^{-1} \text{ yr}^{-1}$ [Page *et al.*, 2004]. In cultivated peatlands, however, most agricultural crops grown there have always required drainage of peat, even though the drainage releases oxygen into the surface which promotes decomposition. As a consequence, the peat stability is disturbed, and C-release from the peat increases.

To measure the flux of CO₂ and CH₄ in the field, a chamber for trapping the gases made from the fiberglass with the size of 1 m x 0.5 m x 0.5 m, was used. Syringes were used to take the samples of gases from the chamber. The samples were then put on the vacuum bottles. In this research, Gas Chromatography Shimadzu 14-B and Chromatopac Shimadzu C-R6A were used to determine the CO₂ and CH₄ emissions. The emissions were calculated by using the following equation [Boer *et al.* 1996]:

$$\Phi_M = ((\delta[\text{CO}_2/\text{CH}_4]\delta t \times h_U \times 16.123 (44.01) \times 273.2 \times (60/22.41))/(t_U + 273.2) \text{ mg m}^{-2} \text{ h}^{-1}$$

where: $\delta[\text{CO}_2/\text{CH}_4]\delta t$ = change of the concentrations of CO₂ and CH₄ in chamber after the period of t minute(s);

h_U = the height of chamber;

t_U = the average of air temperature in chamber;

Value of 16.123 = the weight of CH₄ molecule; 44.01 = the weight of CO₂;

Value of 273.2 = temperature in Kelvin; 22.41 = volume of gas molecule; and

Value of 60 means 60 minutes (1 hour).

Based on the research results, the average of total C-losses through CH₄ and CO₂ emission from the peats in Central Kalimantan where IR-64 is continuously planted in submerged condition is estimated be about 2.09 t C ha⁻¹ yr⁻¹ in fresh water peat, 1.99 t C ha⁻¹ yr⁻¹ in brackish peat, and 1.97 t C ha⁻¹ yr⁻¹ in marine peat. However, by using the ameliorants of (50% ms and 50% bs) the total C-loss decreased to about 1.49 t C ha⁻¹ yr⁻¹ (28%) in fresh water peat, 1.38 t C ha⁻¹ yr⁻¹ (30%) in brackish peat, and 1.34 t C ha⁻¹ yr⁻¹ (31%) in marine peat. In fact, these calculation results of C-emissions are still lower than those reported by Maltby [1997], i.e. up to 5 – 42 t C ha⁻¹ yr⁻¹.

3. Conclusion

The Indonesian peats, represented by the peats of Jambi and Central Kalimantan, are mostly easy to get destroyed, meaning that the stability of such peats is very low. The low stability is characterized by the C-release in the form of CH₄ and CO₂ emissions as a result of the decomposition process. To maintain the stability of peats, water content should always be kept higher than the critical water content. Peats treated by ameliorants containing high Fe³⁺ in submerged condition are relatively resistant to decomposition. By using the ameliorants at the rates (50% ms + 50% bs) as the basis of 5% maximum sorption Fe³⁺, derivative phenolic acids as the dominant organic acids in peats and as the sources of C-emission would decrease and peat productivity would increase. Cation metal of Fe³⁺ has potential as Cation Bridge to enhance the polymerization of derivative phenolic acids by linking the individual phenolic molecules together to yield a chain-like structure, and it results in the increase of peat material stability. The decrease of C-emission is 0.60 t C ha⁻¹ yr⁻¹ (28%) in fresh water peat, 0.61 t C ha⁻¹ yr⁻¹ (30%) in brackish peat, and 0.63 t C ha⁻¹ yr⁻¹ (31%) in marine peat.

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