Liberica coffee as an alternative cropping system for sustainable farming on Indonesian Peatlands

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Abstract: Indonesian peatlands are a fragile ecosystem, and to protect it, growing Liberica coffee is a promising way for both the environment and the economy. This study aimed to evaluate the performance of the liberica coffee on peatland with different water tables and develop an improved cultivation system in this ecosystem. The study area was in Tanjung Jabung Barat District, Jambi Province, Indonesia. The plant age is greater than 15 years and the average plant density was about 1000 trees/hm^2. The study was conducted in two stages. The 1st stage was a survey to identify and characterize smallholder liberica coffee farming at three peatland zones, namely 0-100 m, 200-300 m, and >400 m from the principal drainage canal, and the 2nd stage was a field experiment to test the effectiveness of amendments in improving liberica coffee growth and improving degraded peatland. The treatments were arranged in a randomized complete block design with four replications, including manure (*M*), at the rate of 10 t/hm^2; lime (*L*), 3 t/hm^2; peat surface elevation (*P*), and a farmer's practice (Control) without manure and/or lime as a control. This research revealed that liberica coffee can not tolerate high water table as it may stimulate disease incidence and cause low-quality yield. However, recycling of organic C of about 17.14 t/(hm^2·a) through cherry residue application and litter compensated part of the loss of organic C through CO_2 emissions, coffee bean removal, and maintaining peat fertility for sustainable farming. The low yield of (0.70±0.12) t/(hm^2·a) coffee bean could be increased to (0.87±0.24) and (0.94±0.14) t/(hm^2·a) by adding 3 t/(hm^2·3a) of lime or 10 t/(hm^2·a) of manure, respectively. This research revealed that water table management and amendments are two main factors in liberica coffee farming on peatlands. It is of great significance to study the cultivation technology of coffee in peatland.

Keywords: degraded peat, amendments, water table, cultivation system, liberica coffee, alternative cropping system, sustainable farming, Indonesian Peatlands
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1 Introduction

Liberica coffee (*Coffea liberica* Bull. ex Hiern) is the third most important commercial coffee after arabica and robusta coffee in Indonesia. Consumers of liberica coffee are still limited in Indonesia, and mainly exported to neighboring countries, such as Malaysia, Singapore, and Thailand[1].

Liberica coffee thrives in tropical conditions such as Indonesia, although its origin is natural lowland forests in Africa. Liberica coffee plants are taller than robusta and arabica coffee and can grow into large trees as high as 18 m if not pruned[2]. The coffee cherries and green beans are bigger and the cherries' skin is thicker than that of robusta and arabica coffee[2,3].

Liberica coffee cultivation on peatland in Betara, Tanjung Jabung Barat District has intensified since the 1980s[4]. Generally, farmers plant liberica coffee in a mixed farming system with several other plantation crops, such as areca nut (*Areca cathechu* Burm. f.), coconut (*Cocos nucifera* Linnaeus), oil palm (*Elaeis guineensis* Jacq.), and horticultural crops. According to the farmers, the income from liberica coffee can be higher than that of rubber (*Hevea brasiliensis* Willd. Ex A. Juss.), coconut, or food crops[1].

Jambi Province is one of the provinces in Sumatra having extensive peatland, covering an area of approximately 0.5 million hm^2, while the total area of Indonesian peatland is estimated at about 13.43 million hm^2 distributed in (million hm^2): Sumatra (5.850), Kalimantan (4.540), Papua (3.010), and Sulawesi (0.024) islands[5]. The previous estimate of peatland area on the

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island of Sumatra was around 6.4 million hm^2 and is the largest carbon-storing peat in Southeast Asia[6,7].

In Indonesia, liberica coffee is cultivated mainly on peatlands[3,8,9] with the total area of about 6435 hm^2[9-11], distributed in Jambi, Riau, and Central Kalimantan Provinces. The total peatland area of Tanjung Jabung Barat District, where this experiment was located, is about 155 000 hm^2[10], while the harvested area of liberica coffee in this district is about 2695 hm^2[11].

The peatland is a fragile ecosystem due to the high unstable physical and chemical properties[12]. Under natural forest cover, the organic carbon storage is relatively stable. Degradation, in the forms of escalated above and below-ground carbon losses and peat subsidence, occurs when the peat forest is cleared and drained mostly for agriculture[13]. Burning, associated with land clearing and planting preparation, worsens the carbon losses and peat subsidence[6,7,14-18] causing loss of biodiversity[16]. The peat subsidence was in the range of 1.5 to 3.0 cm/a[17]. Under acacia (*Acacia mangium* Willd.) plantations, for instance, the average peat subsidence is 4.3 cm/a and it occurred not only in the plantations but also extended at least 300 m into adjacent non-drained area. In the decade of the 2000 s, the peat forest loss on the island of Sumatra has been reported at a rate of 5%/a[15].

To preserve peatlands, the development of liberica coffee seems promising environmentally and economically. Peatland should be maintained under near saturation by raising water table. Excessive drainage will change the role of peatland from a carbon store to a source of carbon emissions and encourage nutrient moving into waterways[19,20]. On the other hand, improving the soil fertility to increase yield is also important for the local economy.

There have been criticisms of the unsustainability of farming on drained peatland, especially for crops that require low water table[6,15,19]. Therefore, this study aimed to evaluate whether liberica coffee tolerates high water table, and at the same time, evaluate management systems that potentially improve the production. To the best of our knowledge, there have not been any studies dedicated for increasing the liberica coffee yield and minimizing the environmental impacts through the management under high water table. The objectives of this study were 1) to evaluate the performance of the liberica coffee plant on peatland with different water tables; 2) to develop an improved system for its cultivation in local ecosystem.

2 Materials and methods

2.1 Site description

The study area was located in the peatland of Betara sub-district, Tanjung Jabung Barat Regency, Jambi Province, Indonesia (0°57'18"S-0°57'54"S and 103°21'5"E-103°23'06"E, 5 m above sea level). The peatland area is about 13 755 hm^2 (Figure 1), with peat depth ranged from 0.5 to 1.5 m.

2.2 Climate and hydrology

The climate of the study area is characterized as tropical rain climate zone (Af type, based on Köppen system). The average daily air temperature is 26.9°C, with an average minimum temperature of 21.9°C and a maximum of 32°C; The air humidity range is 80-90%. The average annual rainfall is 2300 mm with 7-9 wet months (>200 mm rainfall) and less than 3 dry months (<100 mm rainfall). The average wind speed range is 11.54-57.55 km/h[20].

The peatlands have been intensively flooded, especially during the rainy seasons before 2017. Information from coffee farmers[21] shows that the areas adjacent to the principal drainage canals are insufficient to drain excess water resulting in flooding that kills the coffee plants[22]. The principal drainage canal is about 6 m wide and 2-3 m deep (based on random measurements in some places) (Figure 2) and was constructed with an excavator. The tidal water of the peatlands has an average pH of 4.91 and electrical conductivity of 168.6 μs/cm. The source of the tidal water is from the Betara River which flows 91.5 km long and 200 m wide[20] and is located 4 km from the research site.

Note: Zone 1: Liberica coffee plantation 0-100 m from the principal drainage canal. Zone 2: Liberica coffee plantation 200-400 m from the principal drainage canal. Zone 3: Liberica coffee plantation >400 m from the principal drainage canal.

Figure 1 Experimental area distribution

Figure 2 The appearance of the main drainage canal

2.3 Methods

The research was conducted in a few stages: 1) A survey to characterize smallholder liberica coffee farming; 2) Measurement of peat hydrology; 3) Characterization of the peat physicochemical properties; 4) A field test of several cultivation technologies, especially the application of amendments and peat surface elevation for improving the fertility of the peatland and the growth and production of liberica coffee.

2.3.1 Characterization of smallholder liberica coffee farming

As shown in Figure 1, the smallholder liberica coffee plantation was divided into three zones. This division was based on the preliminary survey finding of the physical properties of peat, and the growth of Liberica coffee was not the same in the areas at different distances from the prime canal. The study areas are as follows:

Zone 1: Liberica coffee plantation 0-100 m from the principal drainage canal.

Zone 2: Liberica coffee plantation 200-400 m from the principal drainage canal.

Zone 3: Liberica coffee plantation >400 m from the principal drainage canal.

2.3.2 Peatland hydrology

The hydrology of the peatland was studied during survey and field experiments. During the survey in 2019, the water table of peatland was measured manually with a meter stick daily from the peat surface to the surface of flowing water in the drainage ditch, during the low tide around 10:00 a.m. and high tide at 4:00 p.m. local time at each zone. Meanwhile, during the 2020 field experiment, the average water level was recorded in the sub-canal near the experimental site once a week also at low (10:00 a.m.) and high tide (4:00 p.m.).

2.3.3 Physicochemical properties of the peat

Observation of the physical properties of the peat includes: 1) Bulk density, measured with metalcores of 7.3 cm diameter and 4 cm thick from 0-20 cm soil depth. As many as 6 core samples were taken from each zone. The sampling points were chosen randomly with a distance between the sampling points of about 20-30 m. All peat samples were brought to the soil laboratory for oven drying; 2) Peat maturity (consisting of fibric, hemic, and sapri) was observed manually in the field by squeezing method[23] on 30 points and 0-20 cm depth of each zone; 3) Peat depth was observed by a peat auger (Globalindo Teknik Mandiri, Bogor, Indonesia)[24]; 4) Porosity and the water retention characteristics at pF 4.20 (permanent wilting point), 2.54 (field capacity), pF 2.00, and pF 1.00 (water saturation) were measured by a pressure membrane plates apparatus (Royal Eijkelkamp, Sassenheim, Netherlands)[25].

The chemical property analyses of peat of each zone were measured from composite samples collected from at least 10 randomly selected points of peat sampling and replicated four times from the 20 cm top layer. The chemical properties measured in the laboratory were pH with a glass electrode, organic matter and ash content by loss on ignition (LOI) method at 550°C-600°C, total N by the Kjeldahl digestion method, available P by the Bray method, and exchangeable K, Ca, Mg, by 1 mol/L NH_4OAc extraction at pH 7.0[26].

2.3.4 Plant growth and yield

The observation of coffee plant performance, especially vegetative growth, was only focused on individual leaf area (LA) and the frequency of the diseased leaves. The LA was determined manually by measuring the length (L) and width (W) of the 4th leaf from each productive branch represented by four branches, taken crosswise according to the four cardinal directions of each observed tree. Calculating the individual LA of the liberica coffee was by a single power model proposed by Antunes et al.[27] namely $LA = 0.6626(L\times W)^{1.0116}$. The disease infection frequency was recorded by counting the number of the leaves infected by rust (*Hemileia vastatrix* Berk) and or spots (*Cercospora coffeicola* Berk. & Cooke), and the total number of leaves on each representative branch. The leaf rust and/or spots were observed because they are the main plant disease of liberica coffee plant in peatland[28].

Furthermore, in the same branch with LA measurements and disease attacks, this study also observed the yield components, including the number of pods per branch, the number of cherries per pod and per branch, the number of cherries attacked by the borer insect (*Hypothenemus hampei* Ferrari), and the harvesting of ripe cherries (red fruit) to determine the yield (dry seed weight of 100 fresh fruits), the 100 beans weight and the caffeine content using the UV-Vis spectrophotometric method[29]. The observation was on 30 randomly selected plants represented in each Zone.

2.4 Field experiment

The field experiment to test the effectiveness of soil amendments to improve peat soil fertility and increase liberica coffee growth and yield, was conducted in the second year (2020) of the study. The average coffee age was >15 years, the tree spacing was 3 m×3 m and the population was around 1000 trees/hm². This field test was in the liberica coffee planting of Zone 1 only since it was identified as the most severely degraded among the three zones, due to changes in physicochemical properties, such as more compaction, lower porosity, lower available water, and lower fertility than the other zones of peat (discussed in the Results section).

The field research used a randomized complete block design with 4 replications. The experimental plots, each with area of 20 m× 6 m, contained 12 trees. The treatments were:

T1: Manure (M) - Application of manure as much as 10 kg/tree (10 t/hm²).

T2: Lime (L) - Application of lime at as much as 300 g/tree (3 t/hm²/3 a).

T3: Peat surface elevation (P) - Elevate peat surface under liberica coffee canopies (about 3 m diameter) to 10-15 cm high, using the mud from the dredging of the drainage ditch as part of its maintenance.

Control (Farmers' practice) - Liberica coffee is cultivated according to farmers' practice, i.e no amendment, no elevation of peat surface, and no pruning and removing of useless shoots and unproductive twigs.

The application of amendments on peat under the canopy of liberica coffee cultivation was done in March 2020. The applied manure had the characteristics of pH of 7.17, organic C 2.42%, total N 1.35%, total P 0.3%, and total K, Ca, and Mg, 0.28%, 2.51%, and 0.82%. Meanwhile, the lime applied was calcite with 85% $CaCO_3$ content. The basis of lime rate is the measured peat pH[30]. Meanwhile, the treatment of elevating the peat surface under the coffee canopy was intended to raise the peat surface and increase the ash (non-organic matter) content. Pruning and removing unproductive twigs and weeding were conducted every 6 months in all treated plots, except farmer's practice plots.

8 months after treatments, the effects of the treatments on LA, the number of pods and cherries per branch, and the weight of 100 fresh cherries and beans, were monitored. Then, the green beans yield, i.e. the beans without the skin of ripe cherries of liberica coffee, were predicted based on data of the number of cherries per branch, the number of productive branches, the weight of beans in fresh cherries, and plant population per hm². Other observations were the percentages of borer insects attacking the cherries and rust and or spot disease infecting the leaves and also the effect of treatment on several peat chemical properties from samples taken at a depth of 0-20 cm in a composite manner of which peat sampling collected from 6 randomly selected points using a hoe in each experimental plots. During the field experiment in Zone 1, fluctuations in the peat water level were also observed in sub-canal.

2.5 Data analysis

The data on growth and yield of liberica coffee and physicochemical properties of peat were subjected to ANOVA (F-test) and post hoc mean differences were tested using the Duncan's Multiple Range Test using SPSS Statistics 22 software[31].

3 Results

3.1 Liberica coffee cultivation

Based on the field observations and farmers' surveys, the most productive liberica coffee plants were greater than 15 years old. Liberica coffee is generally cultivated in mixed (traditional agroforestry) farming systems, especially with areca nut (*Areca cathechu* Burm. f.), which also functions as shade trees. The spacings of liberica coffee plants are mostly irregular, generally 3 m× 3 m to 3 m×4 m, making the population ranging from 830 to 1100 trees/hm² as reported by Gusfarina[32]. Farmers often replant the trees that die due to disease or waterlogging. The arrangement of areca nut plants as shade trees has the distance between rows of 6 m and within rows of 5 m.

Liberica coffee maintenance by farmers is very minimal, with almost no pruning, no chemical fertilization, and no application of chemicals for pest and disease control. One positive practice of some farmers was to return compost of cherry residues to the peat surface under the coffee canopy. The observation of Hafif and Sasmita[9], which was also part of this study, found that the content of organic C in the litter (leaves, twigs and some cherries) derived from liberica coffee trees was over 50% (Table 1). The amount of organic C returned by the liberica coffee trees aged greater than 10 years old to the peat was 4.70 t/(hm^2·a) through the litter, and 12.40 t/(hm^2·a) through the compost of cherries processing residue could offset the removal of organic C through CO_2 emission from peat as much as 23.70 t/(hm^2·a) (predicted from the change of carbon stock in peat for about 2 years), and the coffee beans about 1.39 t/(hm^2·a) (Table 1). Sometimes farmers also applied manure as much as it was available.

Table 1 Organic C content in biomass of liberica coffee plantation cultivated optimally and its contribution in sequestration of organic C of peat in Betara sub-district, Tanjung Jabung Barat, Jambi Province

No.	Biomass of liberica coffee tree	Production/ t·hm^{-2}·a^{-1}	Organic C content/%	Organic C/ t·hm^{-2}·a^{-1}
1	Litter (leaves, twigs, etc.)	9.00	52.24	4.70
2	Cherries processing residue	23.13	53.81	12.44
	Total input (1+2)	--	--	17.14
3	Coffee beans (brought out)	2.57	54.12	1.39

3.2 Peatland hydrology

The measurement result of the peat water table level in the three observation zones showed that in Zone 1 the water table level was the highest or closer to the peat surface compared to the water table level in Zone 2 and Zone 3 (Table 2). The flowing water level in the drainage ditch to the peat surface in Zone 1 is about 12 cm higher than the water level in Zone 2 at high tide, while at low tide, the difference increases slightly to about 14 cm. Similarly, the water level in Zone 2 was about 13 cm higher at high tide and 11 cm higher at low tide than in Zone 3.

Table 2 Water table at the three zones as affected by the nearby river tides, measured from 8-13 August 2019 (August is in the dry season, Figure 3).

Zone	Tide	Mean±Stdev/cm
Zone 1	High tide	–22.80±0.20
	Low tide	–42.17±0.37
Zone 2	High tide	–34.87±0.39
	Low tide	–56.25±0.49
Zone 3	High tide	–48.20±0.72
	Low tide	–67.63±1.01

Note: High tide was recorded at 16:00 and low tide was at 10:00 local time.

Meanwhile, observations for eight months of fluctuations of water table in the canal of Zone 1 (Figure 3) were strongly influenced by rainfall. During the rainy season (April-May), the high tide brought the water table level to be around –5 to –10 cm on average, while at the low tide, the water level was –56 to –60 cm on average. On the other hand, in the dry season (August and September), at high tide, the water level from the peat surface was on average –41 to –53 cm, and during low tide it reached –137 cm.

3.3 Physicochemical properties of the peat

3.3.1 Chemical properties

The chemical peat analysis showed that the average pH of peat of 4.4 in Zone 1 was higher and significantly different from those in Zones 2 and 3. On the other hand, the percent organic C content of peat in Zone 1 (33.4%) was significantly lower than in Zone 2 (46%) and Zone 3 (49%) (Table 3). There were no significant differences in the measured N and K^+ between the peats in the three Zones, yet the P_2O_5 content was higher in Zone 3 and significantly different from that in Zones 2 and 3. Meanwhile, the Ca^{2+} and Mg^{2+} contents of peat in Zones 2 and 3 were significantly higher than that in Zone 1 (Table 3). The results of this chemical analysis indicated that peat in Zone 1 has a better pH and ash content, but lower total N, potential P, and exchangeable Ca and Mg.

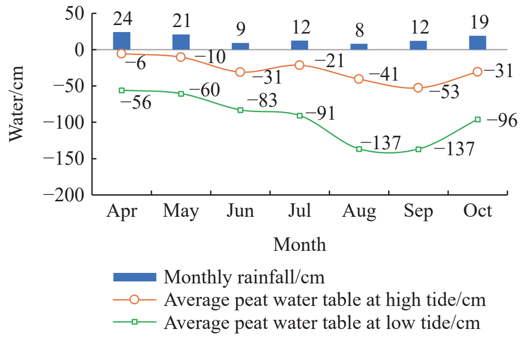


Figure 3 Average peat water table level in some rainy season months (April-June) and in some dry season months (July-September) of 2020 in Zone 1 during the field experiment in Betara sub-district, Tanjung Jabung Barat, Jambi Province

Table 3 Average chemical properties of peat in each Zone in Betara sub-district Tanjung Jabung Barat, Jambi Province

Chemical properties	Mean±Stdev		
	Zone 1	Zone 2	Zone 3
pH	4.40±0.14^a	3.70±0.15^b	3.40± 0.15^c
Organic C/%	33.39±3.30^b	46.06±2.10^a	48.90±3.24^a
Ash content/%	67.76±6.34^a	7.86±2.03^b	11.46±7.63^b
*Total N/%	0.52±0.16^b	1.17±0.50^a	1.13±0.68^a
P_2O_5/mg·L^{-1}	27.40±8.74^c	70.89±8.51^a	47.48±17.23^b
K^+/(cmol(+)·kg^{-1})	0.16±0.02	0.20± 0.06	0.19±0.04
Ca^{2+}/(cmol(+)·kg^{-1})	0.87±0.13^b	3.13±0.60^a	3.48±0.66^a
Mg^{2+}/(cmol(+)·kg^{-1})	0.64±0.06^b	1.99±0.29^a	2.13±0.56^a

Note: Numbers in the same row followed by different letters were significantly different at $p≤0.05$. *Numbers in the same row followed by different letters were significantly different at $p≤0.10$.

3.3.2 Physical properties

About 55% of the 0-20 cm peat layer in Zone 1 was sapric, 35% was hemic, and 10% was fibric maturities, while in Zone 2 it was around 30 % sapric, 50% hemic and 20% fibric. In Zone 3, about 30% fibric, 50% hemic, and 20% sapric (Figure 4).

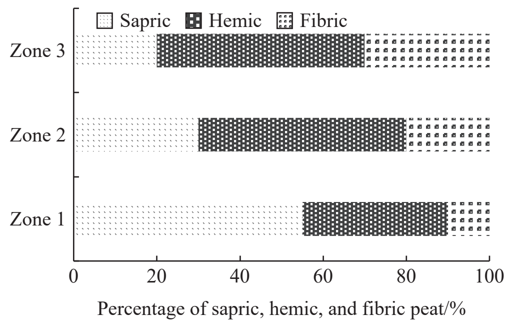


Figure 4 Distribution of peat maturity at a depth of 0-20 cm on each observation Zone in Betara sub-district, Tanjung Jabung Barat, Jambi Province

The physical properties of peat in the three Zones were significantly different, particularly bulk density (BD) and porosity. The highest BD of 0.55 g/cm³ was found in Zone 1, while those in Zones 2 and 3 were significantly lower. The Porosity of peat in Zone 1 (52.9%) was the lowest and significantly different from those in Zones 2 and 3, while the available water pores were the highest in Zone 3 and significantly different from those in Zone 1 at p=0.097 (Table 4).

Table 4 Bulk density, porosity and available water of peat in each Zone in Betara sub-district, Tanjung Jabung Barat, Jambi Province

Physical properties	Mean±Stdev		
	Zone 1	Zone 2	Zone 3
Bulk density/g·cm⁻³	0.55±0.07ᵃ	0.21±0.03ᵇ	0.32±0.05ᵇ
Porosity/% vol	52.90±5.69ᵇ	74.42±5.39ᵃ	70.72±2.30ᵃ
*Available water (pF 2.54-pF 4.2)/% vol	10.37±1.45ᵇ	15.90±2.45ᵃᵇ	16.50±7.20ᵃ

Note: Numbers in the same row followed by different letters were significantly different at $p\leq0.05$. * Numbers in the same row followed by different letters were significantly different at $p\leq0.10$.

3.3.3 Water retention/pF curve

The pF curve (Figure 5) shows the peat water retention at pF 4.2 (15 bar), also known as volumetric moisture content (MCv) at permanent wilting point, was not significantly different between the peat of the three Zones. However, the retention of pF 2.54 (0.33 bar) or pF 2 (0.1 bar) was different between the three zones. Peat of Zone 1 had a lower total pore volume or water content at saturation compared to the other two zones. The average available water pores=$MCv_{pF\ 2.54}$-$MCv_{pF\ 4.2}$[33] was lower in the peat of Zone 1 than in Zones 2 and 3 (Table 4).

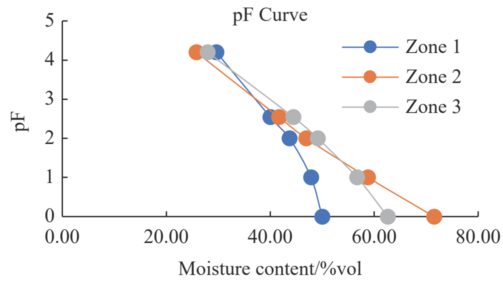


Figure 5 Performance of peat water retention at different pF in each zone in Betara sub-district, Tanjung Jabung Barat, Jambi Province

3.4 Plant growth and yield components

Based on our visual observation and the information from several farmers that coffee growth in Zone 3 was better than those of other zones (Figure 6). The LA of the coffee in Zone 3 was significantly higher compared to that of the other two Zones. Likewise, the number of liberica coffee leaves infected by rusts and/or spots in Zone 3 was significantly lower than those in Zone 1 (Table 5). A lower LA and a higher percentage of rust and or spots infected the leaves in Zone 1 seems to be related to the average peat water table (Figure 4), which is less than −10 cm at high tide in the rainy season (April and May) and only decreased to less than −60 cm at low tide from the peat surface. The high peat water table level, especially during the rainy season created the higher air humidity around liberica coffee trees in Zone 1. It was the atmosphere that encouraged the development of fungi *Hemileia vastatrix* and *Cercospora coffeicola* as a source of rust and spot on leaves, respectively[34].

a. Zone 1 b. Zone 2 c. Zone 3

Figure 6 Liberica coffee cultivation in Zone 1, Zone 2, and Zone 3 in Betara sub-district, Tanjung Jabung Barat, Jambi Province

Table 5 Leaf area, percentage of leaves infected by rust and yield components and quality of green beans of liberica coffee on each observation Zone

Variables	Mean±Stdev		
	Zone 1	Zone 2	Zone 3
Leaf area (LA)/cm²·leaf⁻¹	78.07±30.52ᵇ	78.13±31.06ᵇ	111.43±40.23ᵃ
The leaves infected by rust and or spot/%	26.50±21.01ᵃ	21.50±8.71ᵃ	14.03±9.57ᵇ
Pod number per branch	18.73±8.05	18.4±6.01	19.90±7.28
Cherry number per branch	34.32±15.21ᵃ	20.91±10.6ᵇ	27.08±17.99ᵃᵇ
Weight of 100 cheries/g	335.00±23.91ᵇ	338.00±26.08ᵇ	414.00±47.13ᵃ
Weight of beans in 100 cherries/g	32.48±4.09ᵇ	32.27±3.76ᵇ	40.10±4.93ᵃ
Percentage of beans from fresh cherries/%	9.68±1.11	9.52±1.09	9.67±0.55
Caffeine content of beans/%	0.84±0.02ᵇ	0.91±0.02ᵃ	0.89±0.01ᵃ
Cherry attacked by the borer insect/%	17.17±12.99	16.15±9.55	20.80±16.40

Note: Numbers in the same row followed by different letters were significantly different at $p\leq0.05$.

Meanwhile, the average number of cherries per branch of liberica coffee in Zone 1 was significantly higher than in the other two zones. However, the weight of 100 cherries and coffee beans from 100 cherries was significantly higher in Zone 3 than those of zones 1 and 2. Likewise, the caffeine content of liberica coffee beans from Zone 2 and Zone 3 was higher than that from Zone 1 (Table 5).

3.5 Field experiment

3.5.1 Effects of amendments on liberica coffee growth and yield

The application of manure and lime improved the growth and yield of liberica coffee on peatlands. The two treatments increased the LA significantly relative to the control (the farmers' method). Cherry formation and cherry weight were also improved (Table 6). The application of 10 kg manure /tree increased the number of cherries per branch by about 29%, the weight of 100 coffee beans by 26% and coffee beans yield /hm² by 34% compared to the farmers' method. Meanwhile, the application of 300 g of lime per tree increased the number of cherries and the quality of liberica beans, yet it was not significantly different from the treatments that received manure, raising peat surface, and control. There was no effect of amendment application on the resistance of coffee leaves and berries to pests and diseases (Table 6). However, the raised bed treatment did not improve the coffee growth and production.

Table 6 Effect of treatments on leaf area (LA), leave infected by rust and or spots, yield component and bean yield of liberica coffee tree on peatland of Betara sub-district, Tanjung Jabung Barat, Jambi Province

Variables	Mean±Stdev			
	Peat surface elevation	Manure	Lime	Control
Leaf area (LA)/cm^{-2}·leaf^{-1}	108.40±55.28^{ab}	121.41±48.6^{a}	113.73±29.7^{a}	96.06±30.56^{b}
Leaves infected by deseases/%	21.58±13.84	24.21±13.00	24.61±19.91	21.80±14.68
The pod number/branch^{-1}	38.52±14.04	43.87±22.53	41.72±14.94	37.37±12.77
*The cherry number branch^{-1}	86.37±18.01^{bc}	118.21±46.33^{a}	97.69±44.17^{ab}	83.75±27.58^{c}
The weight of 100 cherries/g	443.33±63.28^{ab}	486.40±68.81^{a}	423.12±54.51^{ab}	387.20±13.69^{b}
Beans weight in 100 cherries/g	45.83±5.63	47.00±7.52	45.90±5.63	41.40±5.08
Cherries attacked by borer insect/%	11.22±7.56	12.77±8.80	13.37±9.17	10.58±7.67
Caffeine content of beans/%	0.75±0.09	0.81±0.09	0.77±0.07	0.74±0.12
Coffee bean yield/t·hm^{-2}·year^{-1}	0.83±0.07^{ab}	0.94±0.14^{a}	0.87±0.24^{ab}	0.70±0.12^{b}

Note: Numbers in the same row followed by different letters were significantly different at $p \leq 0.05$. *The cherry number branch^{-1} between the treaments was significantly different at $p \leq 0.10$.

3.5.2 Effect of amendments on chemical peat properties

Figure 7 shows that eight months after treatments the use of lime and manure increased Ca^{2+} concentration of the peat significantly. However, the effects were not significant for other measured properties.

4 Discussion

4.1 Water level tolerance and implication to the environmental aspects

Liberica coffee farming which has been running for greater than 15 years, will continue because it provides good income to farmers[1]. Even in peat of Zone 1 with relatively highwater table levels, and the peat fertility was also relatively low (Tables 3 and 4), the farmers still maintain the coffee trees. Liberica coffee plants were not tolerant to high water table levels, especially if the average water table is greater than −10 cm at high tide during the rainy season. At this water table level, the incidence of rust and spot diseases was higher, while the yield quality was lower (Table 5).

The growth and yield of liberica coffee trees on peatlands are better under the lower (deeper) water table. The deeper water table could lead to higher CO_2 emissions and rapid peat degradation[35,36]. Nevertheless, liberica coffee has the potential for peat organic C sequestration. As Hafif and Sasmita[9] reported from the liberica coffee plants optimally cultivated, the liberica coffee trees can contribute organic C of about 17.14 t/(hm^2·a), namely from the compost of coffee cherry processing residue 12.44 t/(hm^2·a) and litter 4.70 t/(hm^2·a) to the peatland, while the green beans brought about 1.39 t /(hm^2·a) C through harvest. Other carbon stock can also be observed in the standing trees of liberica coffee, shading trees, and other trees within the agroforestry coffee system, which have not been taken into account. Polzot[37] reported that the coffee production system stored the most amount of carbon per hectare and Otalvaro et al.[38] reported that there were about 8.9 t/(hm^2·a) CO_2 sequestrated by coffee trees. Segura and Andrade[39] revealed that Arabica coffee trees which are smaller than the liberica coffee trees fixed about 8.1 t/(hm^2·a).

On the other hand, the predicted amount of CO_2 emissions from peatlands planted with liberica coffee in Tanjung Jabung Barat was about 23.7 t CO_2e/(hm^2·a)[9] much lower than the CO_2 emissions from oil palm plantations of 43 t CO_2e/(hm^2·a)[40]. These results can increase confidence in the potential of liberica coffee cultivation in peat conservation and sustainable farming.

4.2 Liberica coffee performance and physicochemical characteristics of peat

The long-term high water table level (reaching –10 cm from the peat surface at high tide), especially in the 7-9 months rainy season in Zone 1 disturbed the growth and production of the liberica coffee plant. The low LA, high rust and/or spots incidence on leaves, lower yield and lower beans quality indicated by the lower weight of 100 cherries and beans, and lower measurable caffeine content were an indication that the peat fertility in Zone 1 was lower, seemingly caused by the longer roots submerged in water due to the relatively high water level compared to peatland in Zone 2 and 3 (Figure 2).

The high frequency of flooding, especially during the rainy season in the years before 2017[22] was the principal cause of peatland degradation in Zone 1. The floods seemed to have transported a lot of fertile top layers of peat that reduced the C, P_2O_5, Ca^{2+}, and Mg^{2+} contents (Table 3). On the other hand, uncontrolled drainage will not only remove organic acids, and hence increase the pH, but also remove a lot of organic matter, which contains a lot of carbon[41], as well as wash other essential minerals[20]. The prolonged high water table level in Zone 1 stimulated the development of white root fungus, causing root rot which resulted in the death of the liberica coffee plant[28].

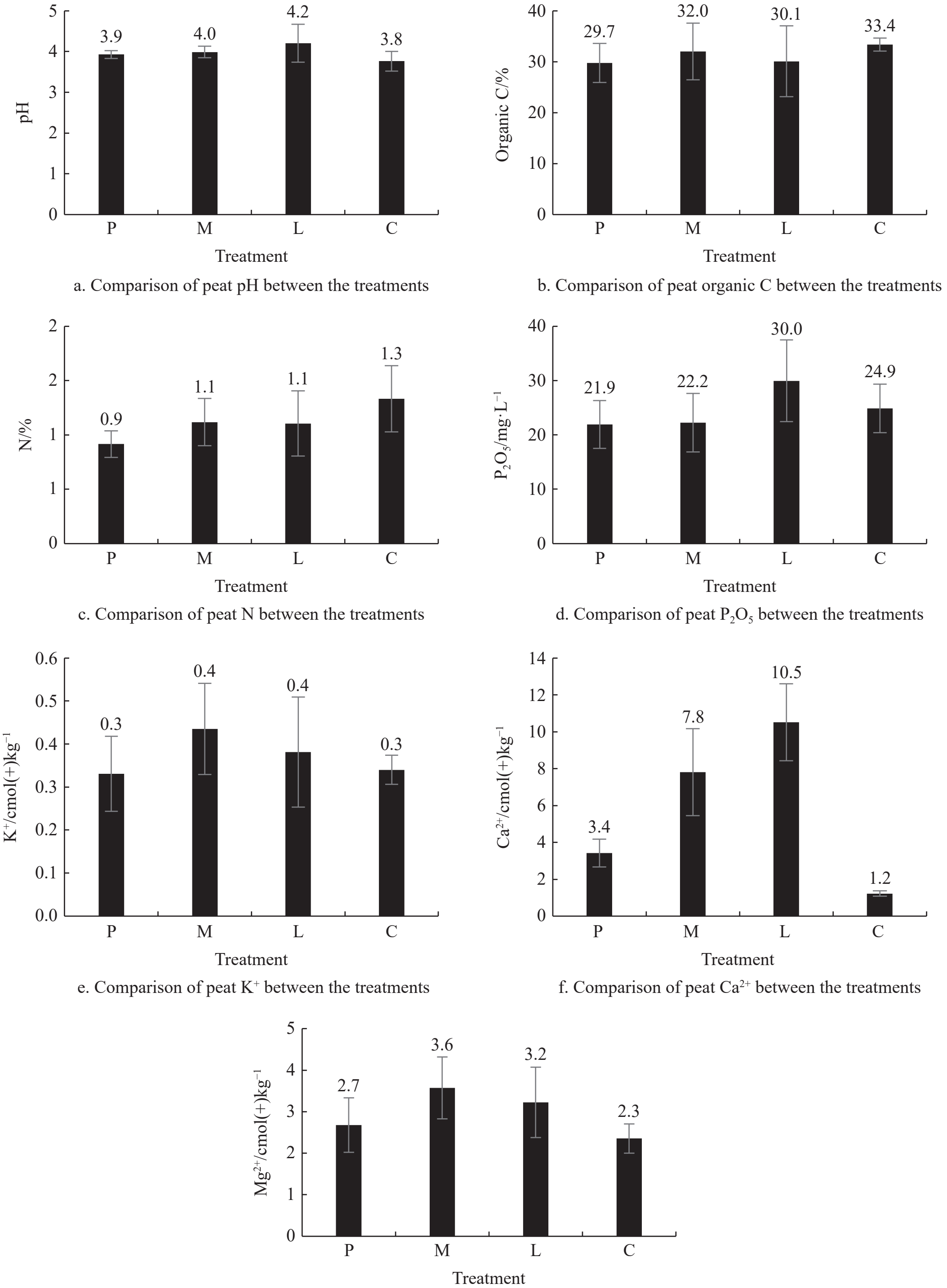
Although there was a decrease in the content of peat nutrients such as P_2O_5 in Zone 1, it was not yet to the level that limited the growth of liberica coffee because it was still within the high content category[27]. Other nutrients in Zone 1, such as Ca^{2+} also decreased to very low, while in peatland Zones 2 and 3 it was still in low category. The level of Mg^{2+} was measured as a moderate category in Zone 1 while in Zones 2 and 3, it was a high category (>2 cmol (+)/kg) (Table 3)[27].

Peat in Zones 2 and 3 was not disturbed by abundant water and seems to be able to maintain peat fertility. As stated by Salim et al.[42], peat management can increase the pH, and the content of P_2O_5, K, Ca, and Mg. On the other side, the artificial drainage for plant cultivation should be kept to a minimum depth to moisten the land[43].

Higher BD, lower porosity, and decreased water absorption of peat in Zone 1 compared to Zones 2 and 3 (Table 4) were the other indications of disturbed peat sustainability in Zone 1[42]. Drzymulska[44] stated the peat degradation can be indicated by an increase in BD and a decrease in peat water holding capacity[41,45,46]. The better physicochemical properties of peat in Zones 2 and 3 (Tables 3 and 4) also indicated that liberica coffee cultivation can preserve peat and was a sustainable farming system in peatland.

4.3 Effect of amendments on growth, productivity, and quality of peat

A test on the use of amendments to improve degraded peat, carried out in Zone 1, showed that the application of manure and lime increased the growth and production of liberica coffee. Manure application of 10 kg/tree or the equivalent of 10 t/hm^2 could significantly improve the growth and increase the yield of liberica



a. Comparison of peat pH between the treatments

b. Comparison of peat organic C between the treatments

c. Comparison of peat N between the treatments

d. Comparison of peat P_2O_5 between the treatments

e. Comparison of peat K^+ between the treatments

f. Comparison of peat Ca^{2+} between the treatments

g. Comparison of peat Mg^{2+} between the treatments

Note: P: Peat surface elevation; M: Manure; L: Lime; C: Control (conventional); ⌶: standard deviation.

Figure 7 Chemical peat properties at eight months after treatment

coffee by as much as 34%. Application of lime 300 g/tree and raised peat treatment also increased the growth and yield of liberica coffee beans by 24% and 18.6%, respectively (Table 6). The use of lime only increased the Ca^{2+}, pH, and the indigenous available P of peat[47], while the application of manure added nutrients to the peat so that the growth and yield of liberica coffee increased significantly. Maftu'ah et al.[48] also reported that using manure in combination with mineral fertilizers increased the number and weight of chilly fruits on degraded peatland. Meanwhile, Salim et al.[40] showed that the use of manure of 2.5 t/hm^2 in horticultural cultivation, besides increasing crop production, can also maintain the chemical properties of peat. Using lime on peat can also increase the bulb of shallot[49] and paddy yield[50].

A study on the effect of amendment application on the chemical properties of peat under liberica coffee plants needs further research. Effect of manure and lime on the nutrient status of peat after eight months was not yet conclusive. The measured nutrient content such as N, P_2O_5, K^+, and Mg^{2+} was still on the same criteria in all plots[27], although on average available P_2O_5 was the highest in the lime treated plots (Figure 7). The only difference in chemical properties was the amount of Ca^{2+}, which was in the medium category under the application of lime and manure, while in the peat surface elevation and control treatments they were in the low category (3.43 cmol(+)/kg) and very low (1.23 cmol(+)/kg), respectively (Figure 7). N status was higher in the control than in the amendment treatment, possibly due to the high N uptake by plants that grew better under the amendment application even though they were all in the high category[27].

Research to further increase liberica coffee production requires testing on a combination of manure with chemical fertilizers so that liberica coffee plants get sufficient nutrients. Meanwhile, adding lime can be done periodically, for example, once every 6 years[51].

Changes in the use of peatlands in the tropics without understanding the properties of peat leads to degradation, as has happened in Kalimantan (Borneo) and other islands in Indonesia[17]. From 1992 to 2022, Indonesia's peatland degradation due to deforestation was reported to be around 60%[52], and about 31% or 41 000 km^2 of which are located in Sumatra and Kalimantan. The degraded peatlands have been reclaimed into agricultural land and plantations of either smallholder or industrial exploitations[53]. In 2022, 25% of Indonesia's peatland was severely degraded. Therefore, besides capturing CO_2 as a consensus to preserve peat[40], research to identify and characterize the potential of cultivated plants, especially for smallholder plantations that can improve the welfare of the community and save peatlands, needs to be carried out. As stated by Watanabe et al.[54], peatland is one of the principal sources of greenhouse gases, and improper management can accelerate the humification of peat organic matter and increase greenhouse gas emissions.

However, obtaining in-depth information on the potential of cultivated plants developed on peatlands, such as coffee liberica, both in improving the welfare of the community, and saving peat from damage, requires a long-term research so that the research results reveal the potential of plants in influencing various biophysical and socio-economic aspects of peatland management.

5 Conclusions

Liberica coffee plant appears not to tolerate high water tables as it is associated with disease incidence and low-quality yield. However, liberica coffee can recycle organic C through compost application from cherry processing residue and the litter, approximately 17.14 t/(hm^2·a) and partially offset the loss of organic C through CO_2 emissions from peat as much as 23.7 t CO_2e/(hm^2·a), and from coffee beans removal as much as 5.1 t CO_2e/(hm^2·a) (organic C 1.39 t/(hm^2·a)). This process seemed to have maintained peat fertility and liberica coffee cultivation for greater than 15 years.

Application of nutrients through manure or other sources is very important for increasing peat fertility and crop yield. The yield of coffee beans at Zone 1 in the degraded peatland could be increased from (0.70±0.12) t/(hm^2·a) to (0.87±0.24) and (0.94±0.14) t/(hm^2·a) by adding 3 t/(hm^2·3a) of lime or 10 t/(hm^2·a) of manure, respectively. It is possible to increase the potential further yield by combining amendments and fertilizer. However, the further research is still needed in the future.

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