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THE ROLE OF COMPACTION ON PYHSICOCHEMICAL PROPERTIES AND CARBON EMISSIONS OF TROPICAL PEAT SOILS: A REVIEW

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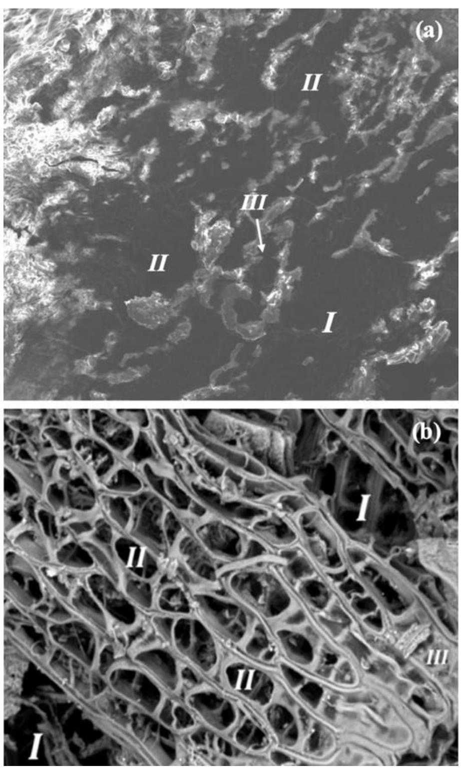
Graphical abstract



Abstract

The peat compaction method is currently adopted by Malaysia oil palm companies to mitigate the uprising environmental issues. This method is claimed to be effective in minimising the risk of fire through enhancement of soil moisture due to capillary effect. In this review, the authors discussed on the peatland function in global perspective, the important of peat soil compaction, emergence of potential peat compaction in oil palm plantation establishment, peat compaction processes and the effects of compaction on physicochemical properties and carbon emission via peat surface and fire. Authors also found that compaction terminology on tropical peatland should be defined wisely, as it closely depends on the initial water table level and the peat quality. Thus, the retrieved information could serve as basic platform to further probe into the highlighted aspects and may as well function as a guide for management of these sensitive ecosystems, particularly in light of carbon loss mitigation.

Keywords: Carbon emission, mitigation, peat compaction, physicochemical properties, oil palm plantation

Abstrak

Kaedah pemadatan gambut kini diadaptasi oleh syarikat kelapa sawit Malaysia untuk mengurangkan masalah persekitaran yang membimbangkan. Kaedah ini dikatakan efektif bagi meminimumkan risiko kebakaran melalui peningkatan kelembapan tanah akibat kesan kapilari. Dalam tinjauan ini, penulis membincangkan mengenai fungsi kawasan gambut tropika dari sudut pandangan global, kepentingan pemadatan tanah gambut, kemunculan pemadatan gambut yang berpotensi di ladang kelapa sawit, proses pemadatan gambut serta kesan pemadatan terhadap sifat fizik kimia dan pelepasan karbon melalui permukaan gambut dan api. Penulis juga mendapati bahawa terminologi pemadatan gambut harus ditentukan secara hemat kerana ia bergantung kepada paras permukaan air dan kualiti gambut. Jesteru, maklumat yang didapati boleh dijadikan sebagai platform asas untuk menyiasat lebih jauh aspek yang diketengahkan, malah dapat berfungsi sebagai panduan untuk pengurusan ekosistem sensitif ini, terutama dalam mempertimbangkan mitigasi pengurangan kehilangan karbon.

Kata kunci: Perlepasan karbon, mitigasi, pemadatan gambut, sifat fizikokimia, perladangan kelapa sawit

1.0 TROPICAL PEATLAND

Peatlands are vital for ecological function as terrestrial carbon sequestration. These ecosystems are characterised by waterlogged, high organic matter environments where reduced oxygen levels in the soil result in slow and only partial decomposition of the organic matter produced by the vegetation growing upon them [1–4]. As a result, there is a net gain in in organic matter, high in carbon which accumulates over thousands of years [1, 5, 6]. This fragile ecosystem is therefore completely dependent on both the waterlogged (high water table) conditions and the vegetation growing above [1, 7, 8]. In their natural state, peatlands actively sequester carbon and, as such, play a globally significant role in mitigating against climate change [9]. Wetland International have estimated that this ecosystem stores up to 550 Gt of the world's carbon pool under, of which approximately 247,778 km^2 or 68.5 Gt distribution across Southeast Asia [10]. In fact, Malaysia alone reported a *ca.* 9.1 Gt carbon pool which contributes approximately 60% to the total forest carbon pool [10]. Nonetheless, these peatland areas have been exploited intensively due to deforestation, drainage, and burning activities. The main driver for this land use change is oil palm.

To date, expansion of oil palm has increased due to demand from the food industry domain. The United Nations Development Programme (UNDP) [11] reported that the trend of edible oil demand has escalated exponentially in line with the increasing world population. By the year of 2050, 240 Mt yr^{-1} of edible oil is needed to accommodate 9.2 billion population across the globe. Precisely in Malaysia, the share of vegetable oil export (crude palm oil is part of vegetable oils) by the year 2024 has been expected to increase by 25%, when compared to other origins and second to Indonesia by 12%. These figures signify high crude palm oil production due to expansion of oil palm across tropical peatland, especially Indonesia and Malaysia with 15.0 Mha and 2.5 Mha of peatland area, respectively [6, 12]. Until recently, expansion of oil palm took place on mineral soil lowlands (either as previous forms of agriculture - primarily rubber) [13], or through the deforestation of lowland tropical forest [14]. However, in the last 15 years or so, much of the expansion of plantations has been undertaken into tropical peatlands. These areas were often considered 'unproductive wastelands' [15], ripe for development.

As oil palm cannot grow in waterlogged conditions, to undertake conversion, areas must be cleared of forest (often undertaken using fire) and drained [16]. This process exposes the soils to oxygen, speeding up decomposition via aerobic microbial activity. This in turn releases vast quantities of GHGs to the atmosphere. The C loss is not then replaced by organic matter inputs as the forest cover has been removed. As such, converted tropical peatlands become enormous net sources of GHGs to the atmosphere, especially CO_2. The present carbon loss due to conversion from peatland to oil palm, according to Carlson *et al*. [5] using integration of modelling mass balance at -70.0 cm water table level and based on a number of references (see[17–20]), results in an estimated 13.3 Mt yr^{-1} of carbon loss from 666,038 hectares (year 2009) of oil palm areas in Malaysia alone. Furthermore, this model is solely applicable for carbon loss estimation excluding other carbon loss pathways (i.e., fluvial and soil surface) or other species (i.e., CO_2 and CH_4). Based on Carlson's *et al*. [5] estimation, one can conclude that carbon loss from tropical peatland has been underestimated when compared to the estimation made by Intergovernmental Panel of on Climate Change (IPCC) from oil palm land use. Thus, the amount of carbon loss was placed fourth in the 2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories [21].

While full rehabilitation is in the long-term the only route towards achieving full ecosystem sustainability [15], this approach requires rewetting and reforestation of peatlands, meaning agriculture is no longer possible. This approach has proved successful, for example, in a study using validated field inventory and remote sensing to generate 3D models of peat dome hydrology, the rewetting of 590 km^2 was found to mitigated emissions of 1.4 to 1.6 Mt CO_2 yearly [22]. In contrast, raising water tables in previously developed peatlands to the surface may trigger, in the short term, other adverse effects, such as P and N mobilisation (P-rich water resulted in further eutrophication), algal blooms, and heightened CH_4 (28 times more potent gas than CO_2 based on global warming potential (GWP), CO_2, and dissolved organic emissions [23]. With many established plantations on peat, any changes to management which can decrease the environmental impacts of these developed systems should be explored.

2.0 PEAT SOIL COMPACTION

A new technique that has been introduced recently during land opening practices for oil palm establishment on tropical peatland refers to active peat compaction [24–26]. While in the early stage of land preparation, peat compaction occurs 'naturally' by oxidation of peat materials during drainage or by mechanical force of heavy machinery (especially in industrial scale plantations) during timber clearance, this approach seeks to actively increase compaction by additional mechanical exertion with the intention of increasing peat bulk density to a minimum of 0.20 g cm^{-3}. As it will be discussed in greater detail throughout this review, the physical alteration that takes place upon changing macropores to micropores has been reported in non-peer reviewed manuscripts to increase soil water holding capacity and bulk density, restrict oxygen concentration, and force habitat stress to pests [24, 25, 27]. This change is thought to result in water-nutrient retention that enhances mechanical anchorage, apart from preventing risk of fire and pest infestation [25, 27, 28].

The effects of peat compaction (either derived passively though conversion or as an active aim) do not only occur at the early stage of oil palm cycle, but continuously throughout the oil palm cycle due to management activities [27–30]. However, it is not known if this effect is more pronounced in specific areas within a plantation (e.g., closer to palms or closer to palm frond piles). These microsites may lead to heterogeneity, particularly in terms of soil properties, which may vary over the life of a plantation cycle. As such, as while drained tropical peatland under agriculture is susceptible to carbon depletion due to peat oxidation and deposition alteration to soil moisture, bulk density and soil pore size, and other factors associated with compaction have the potential to alter the levels of oxidation, and therefore GHG gas emission extent and signature over both time and space. Proper research-based assessment of these changes is needed before any recommendations of compaction promotion or avoidance are promoted for wiser peat management.

Information on alteration to the quantity and signature of carbon losses due to peat compaction is scarce due to several biotic and abiotic factors that are inter-related. For example, moisture content, oxidation and associated microbial activity, nutrient availability and hydrological connectivity are all likely to be influenced by level of compaction [31–34]. Therefore, compartmentalising its effect to management outcomes is a challenge. Most mitigation options discussed to date on tropical peatland focus only on hydrological restoration as a key mechanism to hinder adverse emission (through air, water, and fire) from drained peat [22]. However, it must be emphasised here that the present application of peat compaction has become defined within industry practitioners an essential practice for oil palm establishment [35], especially to stabilise soils for movement of traffic property of peat soil, but increasingly with the concept that compaction will reduce CO_2 emissions, and reduce fire ignitability risk of dry peat soil [24, 25]. While theoretically, this technique retains and regains water due to peat pores space restriction that enhance rise of peat capillary. Critically, no study has comprehensively investigated the above-mentioned claims despite the wide application of the approach across Malaysia [26, 36].

3.0 CONVERSION OF PEATLAND PRIOR TO COMPACTION

The two general approaches for land clearing on oil palm are zero burning and slash-and-burn. Land clearance through zero burning has been practised mostly by oil palm companies via manual mechanical vegetation clearance (e.g., pristine forest, secondary forest, bushes dominated by *Imperata sp.*, or conversion from another crop cultivation). This manual mechanical technique incorporates several practices, such as slashing → cutting → chopping → piling/staking or with integration of pesticide spraying. This technique creates an open "wound" to the topsoil as the work of pilling does not promote decomposition of woody biomass and results in soil compaction on the peat surface, primarily due to heavy load from the machinery utilised.

Cambi *et al*. [37] mentioned that the evolution of heavy machinery usage to work efficiently involves heavier and more powerful machinery. This increases the intensity of compaction effort on soil due to traffic flows. Information regarding peat compaction through this clearing method is limited but is mainly due two main factors: shrinkage by lowering water table level, and heavy machinery usage. However, the drawbacks are addressed within certain time period due to plasticity and compressibility properties or rebound effect [38], so long thresholds are not exceeded [39] especially on matured peat that consist of collapsed pores structure [38]. From the economic stance, this technique is cost-ineffective, but environmentally less polluting, when compared to burning practice [16].

In contrast, slash and burn is conservative as it has been commonly practised by small holders across the globe for centuries. Typically, this method does not require high-end technology and consumes minimal operational cost. However, it is far less widely practiced and is often banned due to the volatile substances released from fires and escaped fires causing transboundary haze pollution that affects the neighbouring communities and countries [40]. Yet despite the impacts, several country's policies still allow for this approach where it involves small-scale plantation on their own native land. This clearing technique does not guarantee success due to the massive remaining undecomposed and wet woody materials buried under peat soil or large tree stumps. Consequently, this may result in unsuitable minor slopes for crops plantation, unless heavy machinery is introduced for land clearance. However, this approach has been considered by oil palm companies as it is potentially beneficial beyond cost reduction, for the reduction of *Ganoderma boninense* Pat., a damaging oil palm fungal disease, and other pests, that threaten palm oil [41,42]. After clearance, compaction is undertaken. This is addressed below in detail.

4.0 PEAT SOIL COMPACTION – THE PROCESS AND JUSTIFICATION

After clearing has been completed, land preparation for oil palm seedlings is carefully implemented through the compaction approach. First, peat compaction can be induced by heavy machinery usage during land clearance practices [43, 44] (Figure 1). Specifically, this technique involves land clearing and construction of water canals to control the level of water table [45,46] and to prepare the land for oil palm seedling planting [27].

Figure 1 The use of excavator for land clearing and the preparation of oil palm plantation site in Sibu, Sarawak, Malaysia

Second, peat compaction continuously occurs within the entire palm cycle due to plantation management activities, such as fertiliser and liming application [45], as well as harvesting of FFB and frond piling [30] – though these effects may be heterogeneous in their extent across plantation 'microsites'. Third, apart from anthropogenic activities, the impact from abiotic factors (e.g., rainfall, seasonal variation, and peat maturity) may be considered as minor contribution within this process [47, 48]. Based on these potential sources, both the intensity and the magnitude of peat compaction have been expected to rise as time passes (Figure 2).

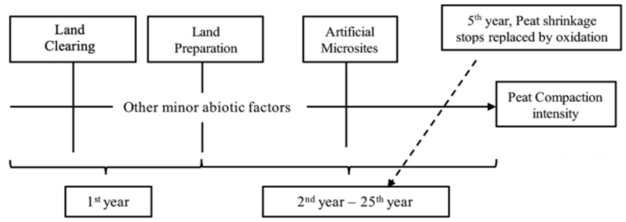


Figure 2 Potential peat compaction sources presented by timeline in a cycle of oil palm cultivation for 25 years

During the past decades, peat compaction across oil palm has become an important practice [26–28]. However, this not implicates for small-scaled holder around Malaysia on the usage of heavy machinery due to limited access [35] than company plantation. Therefore, approximately 36% (*ca* 874,884 hectares) of tropical peatland in Malaysia is under compaction. This can be estimated by the distribution of agriculture land uses across tropical peatland that reflects soil compaction, wherein 76% (*ca.* 666,038 hectares) were planted with oil palm by large-scaled plantation, when compared to other crops, such as pineapple and vegetable crops, on peatlands (Wetland International Malaysia, 2010). The heavy machinery usage for plantation is important as this approach enhances mechanical anchorage for oil palm root system and prevents "love syndrome" among mature palms. Love syndrome refers to the state of oil palm falling over towards each other and resulting in unfavourable growth (Figure 3).

Figure 3 The "love syndrome" among palms at maturity stage (26 years old). Picture was taken (with permission) at drained and shallow tropical peat, Malaysian Oil Palm Board (MPOB) Research Station, Sessang, Sarawak

Further, the compaction approach has also been claimed to increase the available nutrients and water supply by improving capillary rise and water holding capacity [25, 49–51]. Limiting nutrients translocation over oil palm vary across a plantation according to water movement and specific microsite heterogeneity [52]. In order to maintain and retain nutrients at a specific site, the hole-in-hole practice is applied via peat compaction up to 1.0 m from the initial surface level [27]. This practice is an innovative mechanical efforts to initiate direct distribution of agricultural inputs e.g. fertiliser due to the impact of rainwater [26]. As a result, the fertiliser in oil palm is concentrated around the palm circle with minimal distribution laterally [52].

As water retention capability is enhance after peat compaction, the risk of fire is stated to be greatly reduced [25, 27, 53]. However, no specific research or data towards this conclusion has been undertaken to supported this notion [36]. Compressed peat is also said to controls pest, such as termites and white ants. This is due to the inducement of habitat stress that targets oxygen availability and food sources. According to Beylich *et al*. [31], the effective compaction threshold to affect soil fauna and microorganism is above 1.70 g cm^{-3}, as measured in bulk density. Yet, attaining such levels of compaction and bulk density in peat soil to that value is almost impossible due to high organic content [54]. The maximum bulk density of tropical peat soil in natural and agricultural ecosystems is approximately below 1.0 g cm^{-3} without any amendment of other mineral soil [55–58]. As such, this statement can also be questioned.

The other main claims for this approach are the reduction particularly in CO_2 emissions from sites. As presented in [25], during workshop on 'Haze and Biomass in Asia – A Systems Perspective to Reveal Opportunities with Benefits for Long-Term Transformations' at Bandung, Indonesia on 4 to 5th October 2018; who asserted that the increasing of bulk density value by 0.02 gcm^{-3} within the range of 0.13 to 0.15 g cm^{-3}, could reduce CO_2 flux by 15% from the former of un-compacted oil palm plantation (Table 1). Irony, contradicting with their own finding, the reduction of CO_2 emission will only take effect by the value of bulk density that more than 0.24 g cm^{-3}, but below than that; within the range from 0.14 to 0.22 g cm^{-3}, the CO_2 emissions are not affected [24]. Beside, although mean water table level at peat swamp forest is obviously higher than that of compacted oil palm plantation by 45.6 cm, the value of water filled pore space (WFPS) is much lower than compacted oil palm plantation, which tentatively in contrast with the results by several authors [13, 59–61] who suggested that the capillary rise will be disconnected when the distance between the water table and the surface ground is too far. Furthermore, the CH_4 and N_2O emissions that considered the second and third important gas of which 28 to 36 and 265 to 298 times more potent gas to global warming potential was not measured- as the impact of CO_2 reduction due to O_2 depletion and water content increases as a result from compaction could lead another possible effect such as higher CH_4 and N_2O emissions [62]. Therefore, there is need to understand better the relationship between the CO_2 emissions and bulk density or other parameters that associated with water content, pores condition as well as degree of decomposition.

Table 1 Comparison between compacted oil palm plantation (COPP), un-compacted oil palm plantation (UOPP), and peat swamp forest (PSF) in the form of CO_2 and CH_4 emissions (Retrieved from Melling and Tang [25])

Parameter	Ecosystem		
	COPP	UOPP	PSF
Mean water table (-cm)	60.7	59.8	15.1
Water-filled pore space (%)	83.3	71.3	75.1
Bulk density (g cm^{-3})	0.15	0.13	0.11
Soil CO_2 (t C ha^{-1} yr^{-1})	9.5	11.2	12.5
Soil CH_4 flux (t C ha^{-1} yr^{-1})		N/A	

Note: N/A is not available.

5.0 PEAT SOIL COMPACTION AND SUBSIDENCE

Soil compaction refers to incremental increase of bulk density because of macro pores reduction from either single or multidirectional loads. Adapting the theory of tropical peat soil compaction processes initiated by Hooijer *et al*. and Alakukku [45], [63], the two main forces that induce peat compaction are external and internal forces. External load is a static and dynamic load that derives from the lateral forces to the soil surface, while internal load refers to the process that occurs due to alteration of soil physical changed by water suction gradient [64].

Hooijer *et al*. [45] explained peat compaction in relation to of peat subsidence. In general, compaction in peat can occur with or without peat oxygen availability (i.e., aerobic, and anaerobic) at peat horizons that are divided into three main components (see Figure 4). The first component (C1) is a combination of compaction and shrinkage, which is considered as an entity of peat subsidence in the aerobic layer beside peat oxidation that can increase the bulk density value. At the unsaturated soil peat layer (aerobic layer), the induced loads may be immediate or temporary. The impact on the peat surface could be caused by several factors, such as heavy machinery wheels [65], rainfall drops [66], and animal tracks [67]. The second and third components are associated within anaerobic layer at saturated peat (anoxic horizon), which are described as primary and secondary consolidation. The primary consolidation (C2) is induced by rapid decrease of moisture regime, whereas the secondary consolidation (C3) is linked with resistance of peat materials to compaction. Since soil consolidation is affected within the saturated soil peat layer or anaerobic horizon [44], the load is applicable over a longer time period and continuous, for example, over a wetting and drying cycle or with long-term water table fluctuation.

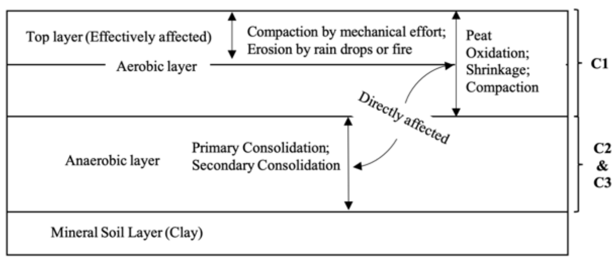


Figure 4 Tropical peat subsidence mechanisms or compaction described by Hooijer *et al*. [45]

Yet grouping subsidence and compaction together has led to some confusion. The application of tropical peatland compaction as a subsidence index has increased. For example, peat subsidence has been used as a measurable indicator to determine carbon loss by observing changes to peat depth [13]. van Asselen *et al*. [43] argued that the compaction process of natural peat ecosystems does not always represent peat subsidence. This is because of incompressible layers that dominate peat subsurface, that compaction does not always mean peat loss and the fact that the peat expands and contracts in response to water table fluctuation level due to high porosity and buoyancy characteristics, also independently of carbon loss. As such, data on peat subsidence and surface level growth is heavily dependent on water table level and should not be interpreted as a measure of carbon loss without being corrected against soil bulk density.

The complexity underlying compaction magnitude is derived from several factors, such as abiotic, biotic, and anthropogenic factors (man-made compaction). Nevertheless, the combination of compaction and shrinkage as an entity seems very difficult to distinguish. Most literature works (see [26, 27, 29, 45]) defined tropical peat compaction based on the nature of the study site. For instance, in logged-over or drained forest ecosystems, peat compaction source is always described as a result from water table fluctuation between seasonal variations [68] that causes shrinkage (bulk density increase), or oxidation (by microbial activity), which decreases bulk density [45]. As for developed peatland ecosystems, such as agri-systems, most of the authors (see [26, 29, 45, 69]) described peat compaction as a coupled process caused by heavy machinery or shrinkage by drainage, which contribute to increased bulk density. This particular landscape-based definition leads to confusion towards the clarity definition mechanism of compaction on tropical peatland among researchers. Therefore, to better understand the terminology of 'peat compaction', future research should initiate to separate the first component (C1) from oxidation and C loss effects, but rather, considers compaction caused by heavy machinery and shrinkage as a single entity.

6.0 EFFECT OF COMPACTION ON TROPICAL PEAT SOIL

6.1 Physicochemical Properties Change by Compaction

In general, compaction practice on soil affects its integrity by causing forced deformation on the macro structure of the soil. This condition causes reconfiguration of soil pores, reduction in soil volume, restriction on the available oxygen, decreased water infiltration, and increased water content (e.g. gravimetric and volumetric water content and water-filled pore space) [30, 48, 64, 70, 71]. Kuncoro *et al*. [56] asserted that deformation of physical structures in compacted soils can affect air and water transportation in various ways, depending on the connectivity of macro pores.

The characteristics of temperate and tropical peats in term of pores distribution are different, mainly depending on the origin plant biomass [38]. Hence, the magnitude of compaction towards tropical peats maybe varied. Temperate peats have heterogeneous and anisotropic structures, wherein pores are arranged in vertical and horizontal paths for air-water and solute transportations [38, 72]. Samuel *et al*. [73] determined the pore size of peat for Sarawak's tropical peat at MARDI, Saratok, Sarawak (see Figure 5(a)), within the depth profile of 40 cm using scanning electron microscope (SEM) incorporated with image analyst software [ImageJ; National Institutes of Health (NIH) and the Laboratory for Optical and Computational Instrumentation (LOCI, University of Wisconsin)]. They revealed that the physical configuration of anisotropic pores traits of tropical peat pores is consistent with sphagnum sample across temperate regions (see Figure 5(b)).

This is despite the fact that tropical peat aggregate is somewhat larger, more clumped, and more amorphous (completely decomposed woody material) than with sphagnum, and there is a large variation in pore diameters (sphagnum is measured between 0.1 and 0.4 mm [38], while tropical peatland between 0.005 and 0.1 mm [73]. As such, both systems would have the potential to be differently impacted by compaction in terms of pore deformation. This is also in agreement to the study by Katimon and Melling [49], who claimed that tropical peat soils differ from those found across temperate regions, with tropical peat behaving more similarly to sand and clay loam, which hold more water by 50 to 60% after treatment with permanent wilting point (-150 kPa). Subsequently, tropical peat maybe successful to compact due to cohesion and adhesive characteristics which are similar to sand and clay loam that susceptible to compaction [74,75].

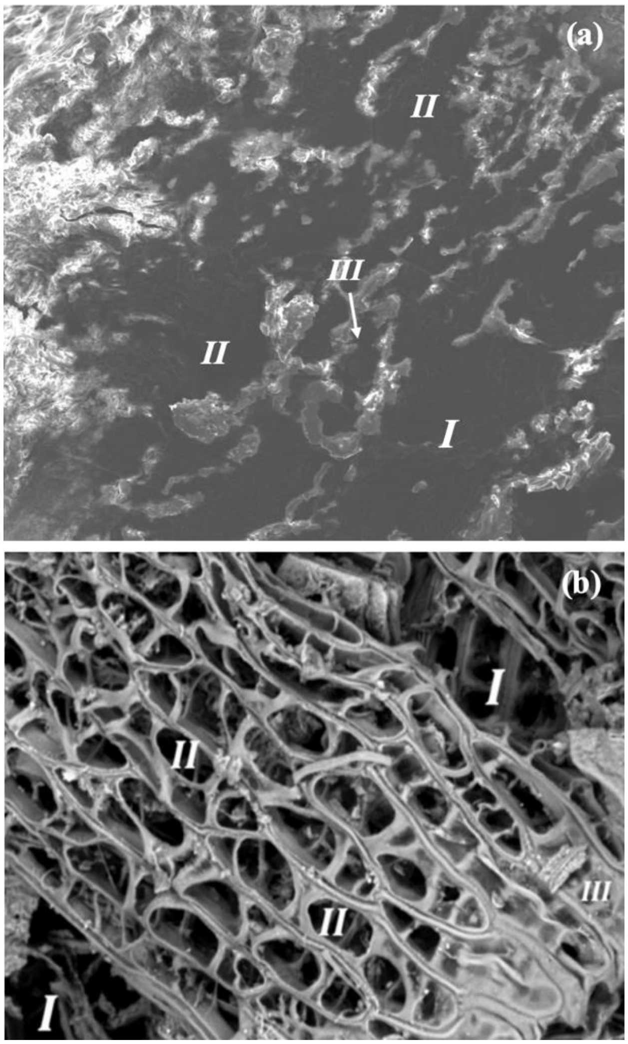


Figure 5 The heterogeneous configuration of **(a)** tropical peat by Samuel *et al*. [73] and **(b)** temperate peat (Sphagnum) by Rezanezhad *et al*. [38], both in vertical cross-section view. The images show differentiation of pore path distribution; evidence of existence of (I) Open and connected macropores, (II) closed or partially closed macropores, (III) dead-end or isolated pores spaces called hyaline cells."

Overall, the alteration of tropical peat physicochemical properties by compaction, especially those associated to agriculture activity, is rarely reported [76]. This is because; most peat is commonly used as soil conditioner to repair and stabilise compacted mineral soil due to its high clay content [56, 77, 78]. Its characteristics as a soil conditioner is derived from the peat itself as peat is formed through the semi- or complete decomposition of botanical material – resulting in high porosity of more than 80% and compressibility of 400% from its initial state [38]. Peat is capable to a certain extent of returning to its original state after compression due to plasticity and active pores composition [38, 54]. As such, the methods and concepts used to generalise the porous media properties are based on assessments of mineral soils with peat additions, which may often be insufficient [79].

6.2 Soil Gas Emissions Properties Change by Compaction

Changes in physical habitat particularly altered pore-size distribution may lead to restriction of oxygen diffusion in compressed peat. Regulate and induce new conditions or habitable pores to the native peat decomposition microbial communities [80]. For instance, during the oxygen depletion that marked by redox potential level [24] or water-filled porosity (WFS) of above 60% [81], the activities of microbes would lead to population succession from which predominated by aerobic to anaerobic communities. Subsequently, the CO_2 production would decrease linearly. In contrast, Shestak and Busse [82] discovered poor link between physical and biological indices of soil health due to the fact that broad tolerance of microbial communities from contrasting soil textures (mineral soils) to compaction (75 to 3800 Kpa). Thus, the impact of peat pore reconfiguration due to compaction on microbial communities contribute to the ambiguous response, which is another reason for future study to be undertaken.

Compaction mechanism involves in compression of peat and could possibly decrease peat depth although as abovementioned the peat could rebound back due to high plasticity trait unless the pores is inactive due to high decomposition level [83]. Consequently, the decrease of peat depth may lead to in close proximity to water table level and controlling carbon emission by manipulating aerobic and anaerobic condition within peat horizon. With increment in the oxic level of the peat soil due to water table fluctuation, spontaneous oxidation in terms of CO_2 gas production by peat materials and microbial activities may occur [84,85]. For instance, the change in compacted peat structure during wetting and drying influences activity in peat soil, apart from playing crucial roles in the emission and sequestration of carbon in peatlands. Nonetheless, most literature mentions that water table fluctuation is the main control for carbon emission in tropical peatland regardless of compacted or uncompacted peat (see [5, 13, 17, 22, 45, 86]). Altered water levels by drainage leads to continuously fluctuations over time, aside from releasing CO_2 and CH_4 gases [87]. This means that gas exchange depends on periodic oxic and anoxic environment, as well as micro-topography within the peat horizon [88].

Peat surface respiration is composed of two types of O_2 consumption and release: autotrophic respiration (AR) (by roots) and heterotrophic respiration (HR) (microbial activities). Combined, these two sources make up total soil respiration (SR). To understand the true impact of land use on peat emissions, the peat-only (HR) emissions need to be isolated. There are several techniques to partitioning total soil respiration (SR). For instance, the trenching technique [13, 89–94] severs active roots from a sampling zone and in doing so isolates HR by measuring CO_2 from soil respiration only. However, this approach when undertaken often then assume that the remaining heterotrophic emissions signature from the soil within a plantation will be uniform in its character and that randomised replication will capture any natural variation in a given area. The common approach at this point is to upscale the average emission by plantation area to give the total HR emissions per hectare. This method does not account for potential consistent variation between microsites within a given area. For example, the results may vary (in a predicable way) as the peat biophysical itself and other regulatory factors, such as fertiliser input or farming management practices, varied levels of compaction and existence of focal litter piles [95].

The specific nature of soil physiological changes and the associated emissions signature may in fact rely on site specific conditions that may be found according to oil palm designated layout and following the planting density. Specifically, each area between the row of palms has a key role based on the management plan with specific perimeter area affected [96]. For example, the palm circle or 'under canopy' (UC) is usually treated for fertiliser input and hole-in-hole compaction in the first year with a radius of 1.3 m. The frond pile (FP) or frond stack is on average 1.3 m beside UC. The far from palm (FF) is situated beside UC (1.3 m radius) and FP (1.0 m) with passive plantation management activities due to buried plant biomass during the first year of land clearing activity. Lastly, the harvesting path (HP) is located beside other microsites (UC, FP, and FF) and this can be considered as the active path for management activities. As such, these microsites have significant potential to influence the emissions signatures from sites in what would then be a predictable (and critically) up-scalable fashion.

6.3 Soil Gas Emissions Properties (Via Peat Fires) Change by Compaction

Tropical peatland fire occurrences have recorded huge devastating impacts not only upon environment, but also on human health due to the particulate matter and other hazardous volatile contents [97]. Peat soil after drainage can be hydrophobic due to irreversible drying effects and susceptible to risk of fire. When compared to the process of peat oxidation from peat decomposition, volatile substances from peat fire emissions contain 30% more carbon monoxide (CO), 20% more hydrocarbons, but less CO_2 due to the smouldering nature of peat fires [98].

Peat ignition may occur naturally caused by lightening [98], especially during dry period (April-October) or due to anthropogenic activities, such as the land clearing technique mentioned previously. Peat ignitability depends on several characteristics, such as botanical properties that attribute to fuel quality [99]. Consequently, affects the spread of smouldering peat fire that ascribed as multidirectional including in-depth vertical and surface lateral distribution [100]. Peat fire's thermal mechanism reactions play a crucial role during peat utilization processes. Basically, peat fire has three main thermal processes phases of weight loss such as dehydration, oxidative pyrolysis and combustion. The peat burning processes consist of several stages that differentiated by temperature [101]; Figure 6).

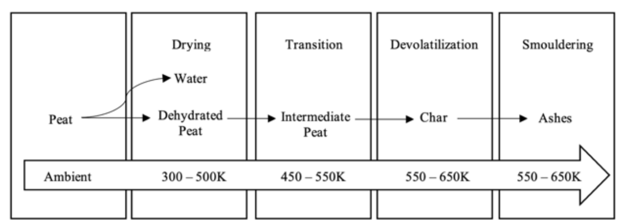


Figure 6 Schematic illustration of the decomposition of peat as a function of temperature in Kelvin (K) by Leroy-Cancellieri *et al.* [101]

The temperature threshold between transition of each phases are different between tropical and boreal peats [101, 102]. This is probably due to the minor components of chemical factors and inorganic compounds present in peat origin; thus, affect the spreading of peat fire once successfully ignited (Table 2).

Table 2 Comparison between boreal and tropical peats on thermal decomposition temperature in Celsius (°C) range between transition phrases

Peat thermal decomposition phase	Boreal peat	Tropical peat
	Temperature range (°C)	
Dehydration	27 - 226	28 - 210
Oxidative pyrolysis	226 - 377	210 - 350
Combustion	377 - 627	350 - 550

Further, it is important to determine the thermal decomposition properties of peats when talking about peatland fire management. Most of the works have focused on characterising volatile products and evaluating yields from carbon decomposition on boreal, sub-tropic and tropical peats [69, 101–106]. Despite emission factors quantification from peat fire events; only limited information are available on the effects of peat property changes by human intervention on the fuel arrangement such as compaction [69, 102]. In addition, the effect of compaction on peat fire is fairly limited [36]. A recent study on tropical peat in Pahang and Selangor, Peninsular Malaysia suggested a trend of emissions signatures being linked to level of peat compaction, as marked by bulk density value [69].

Ground water level, moisture content, and fuel arrangement appear to be the main factors preventing a smouldering fire from burning into deeper layers of peat soil [100, 102]. In fact, the overhang thickness formation during fire occurrence is found to increase with moisture and wind speed (oxygen), while the spread rate decreases with moisture and increases with wind speed [107]. Thus far, water conservation, such as rewetting approach, is essential to mitigate fire risk at drained peatland. Peat fire ignitability can be hindered by manipulating water table level to increase peat moisture content [108]. A model approach using integrated metadata from Tropical Rainfall Measuring Mission by GES-DISC NOAA, ground water level and historical satellite of fire reoccurrence by NASA-EODIS; suggested that fire reoccurrence can be prevented as long as ground water level be maintained at - 10 cm or higher [108]. The control of ground water level in peatlands is not always possible in dry season periods (especially in tropical countries). This is often due to the over drainage of the peatlands and their reduced capacity to hold water throughout the dry season post conversion as they can develop water repellent or hydrophobicity traits on incessant drought conditions [109, 110]. During peat fire episode, there are two important transitions that frequently occur simultaneously during a fire such as flaming combustion and smouldering. Flaming combustion converts the C, H, N, and S in the fuel into highly oxidized gases such as CO_2, H_2O, NO_x, and SO_2, respectively, and produces most of the elemental carbon particles [111]. Meanwhile, smouldering produces most of the CO, CH_4, NMOC, and primary organic aerosol. However, future study should be focused on the three main peat fire carbon emission by-products in the form of carbon emission (CO_2, CH_4, and CO) or emission factors. The emission factor index value is useful to determine and quantify the impact of peat fire occurrence especially in the IPCC report. These volatile gases can be determined in-situ by using Fourier-transform infrared (FTIR) spectroscopy approach, as described by Smith *et al*. and Wilson *et al*. [69, 99] in peat fire investigations on tropical peatland. Emission factor for tropical peatland is one of the most important variables for determining total emission of carbon released by peat fires.

Despite the importance of these fires in terms of environmental, social, economic, and political impacts, little is known about what factors control the variability in emissions signatures of quantity. Large-scale modification to soil characteristics (e.g. via compaction) may have a significant impact on future fires. Yet despite this, this practice has been promoted widely without any evidence or empirical investigation to-date into the impact of active compaction and resulting high BD of peats on the signature and quantification of peat fire emissions.

7.0 CONCLUSION

At present, the idea of compaction derives from the personal opinion highlighted by Melling *et al*. [51], citing presumed capillary rise. Growing momentum and support for this approach [53] enthusiastically promote this technique to mitigate fire events. However increasing doubts by the scientific community (e.g., [36]) due to the lack of scientific assessment of the impacts of the approach as well as a consideration of the long-term implications to ecosystem function and habitat rehabilitation post oil palm (in-line with long-term goals suggested by RSPO BMP 2019 and the Indonesian Restoration Agency, BRG) have captured some attention due to limited comprehension pertaining to peat compaction (e.g., JakartaPost.com "Soil compaction puts peatland at risk, agency says"). In general, there is a pressing need to reduce knowledge gaps associated with potential compaction. Better understanding of the impact of physicochemical alteration due to compaction in tropical peatland should consider both the changes in soil physicohemistry and resulting emissions but should also account for the issues associated with the potential permanent loss of unique soil structures and water-sensitive properties of these complex environments.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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