Heliyon 10 (2024) e37754

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Tropical peat soil changes across successive oil palm generations in Sarawak, Malaysia

Jicqueline Ratai [a,b], Christopher Boon Sung Teh [b,*], Ngai Paing Tan [b], Hasmah Mohidin [c], Kah Joo Goh [d], Faustina Elfrida Sangok [a], Lulie Melling [a]

[a] Sarawak Tropical Peat Research Institute, Kota Samarahan, Sarawak, Malaysia
[b] Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Selangor, Malaysia
[c] Faculty of Plantation and Agrotechnology, Universiti Teknologi MARA, Kampus Samarahan, Sarawak, Malaysia
[d] Advanced Agriecological Research Sdn. Bhd., Kota Damansara, Petaling Jaya, Selangor, Malaysia

ARTICLE INFO

Keywords:
Humification
Oil palm
Physicochemical properties
SOM quality
Tropical peat soil

ABSTRACT

Oil palm is commonly replanted once reaching the end of its productive lifespan. This cyclical planting practice in oil palm plantations could have long-term implications for the humification and properties of tropical peat soil. This study aimed to investigate the changes observed across successive generations of oil palm plantations in Sarawak, Malaysia. Fourier Transform Infrared Spectroscopy (FTIR) was applied to examine the quality of the Soil Organic Matter (SOM), specifically the functional groups, humification index, Hydrophobicity Index (HI), and Degree of Degradation (DDI). Overall, the peat humification trend was in the order of 2nd Gen > Forest >1st Gen. The higher presence of recalcitrant compounds of lignin in the soil was attributed to the higher HI and lower DDI in the 2nd Gen. The relationship between the Pyrophosphate Solubility Index (PSI) and the humification index further revealed a significant increase in the relative abundance of humic substances with the maturity of degraded organic matter. These findings suggest a notable transition, implicating a shift towards a more stable form of SOM over the long-term utilization of tropical peatland for oil palm plantations. This is characterised by a significant increase in the relative abundance of aromatic, phenolic, and carboxylic functional groups. The study also highlights the need for further research on the linkage between these changes and greenhouse gas emissions to enhance our understanding of the long-term biogeochemical cycle of oil palm on tropical peatlands.

1. Introduction

Tropical peatlands cover an area of approximately 60 million hectares (ha.) globally, with 25 million ha. of this total area located in Southeast Asia [1,2]. In Malaysia, tropical peatlands cover close to 2.6 million ha.; Sarawak holds the majority of this (69.1 %), followed by Peninsular Malaysia (26.1 %) and Sabah (4.76 %) [3]. Tropical peat soils naturally consist mainly of slightly decomposed rainforest tree remains, such as branches, roots, leaves, and trunks, which have accumulated over thousands of years [4–6]. Thus, they exhibit low Bulk Density (BD) and high porosity, with chemical characteristics including low pH, high organic matter content, low base

* Corresponding author. Universiti Putra Malaysia, Serdang, Selangor, Malaysia.
E-mail address: chris@upm.edu.my (C.B.S. Teh).

https://doi.org/10.1016/j.heliyon.2024.e37754
Received 4 March 2024; Received in revised form 7 September 2024; Accepted 9 September 2024
Available online 10 September 2024
2405-8440/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

saturation, and low nutrient content [7].

Oil palm (*Elaeis guineensis*) is one of the most extensively cultivated oil crops in the tropical region [8]. The planted area of oil palm on tropical peatland witnessed a steady increase from the 1990s to the early 2000s, propelled by the Malaysian government's endeavours to enhance the economic prospects of the nation [8,9]. However, in recent years, the expansion has experienced a plateau prompted by the government shift in policy prioritising the enhancement of agricultural productivity and sustainability [8,10]. Nevertheless, a considerable expanse of peatland continues to be agricultural land, with replanting being a regular practice in plantations. As a perennial crop, oil palm trees can potentially produce economically viable yields for around 20–30 years. Subsequently, older and unproductive oil palm trees were cut down and replanted with newer oil palm trees to improve the productivity and profitability of plantations [11,12]. As most large-scale oil palm plantations began in the mid-1980s, a substantial area of mature oil palm trees to be cleared and replanted is expected to increase in the coming years [13,14].

The conversion of tropical peatlands into oil palm plantations entails clearing natural forests and subsequent replanting. This process disrupts natural ecosystem functioning and alters the composition and structure of Soil Organic Matter (SOM) within the peatland [15]. Microbial processes are expedited by soil oxygen exposure after drainage following peatland conversion, causing the decomposition of organic matter and influencing the soil properties such as soil pH, BD, and total nitrogen while diminishing the total carbon content [16]. In oil palm planting, agricultural activities such as harvesting, pruning, weeding, and fertilizing on peatlands may increase or decrease the SOM, affecting its quantity and quality over time [17–20]. Humification refers to converting SOM into recalcitrant organic compounds in a gradual and timely process [21]. The end product of this process is humus, which is highly resistant to further decomposition, thus enhancing the soil structure and fertility, water retention capacity, and overall soil health [22]. The understanding of the changes in the humification of SOM across successive generations of oil palm planting on tropical peatlands is essential for assessing this agricultural practice's long-term sustainability and environmental implications.

Numerous studies have demonstrated the application of Fourier Transform Infrared Spectroscopy (FTIR) to evaluate the quality and composition of SOM [23–25]. FTIR relies on the absorption of infrared light, generating a unique spectral fingerprint that facilitates the characterisation of SOM's chemical composition and structural features. This involves identifying functional groups, such as aromatic, aliphatic, phenolic, hydroxylic, carboxyl, and polysaccharide groups [26], eliminating the need for extraction procedures [27,28]. According to Pärnpuu et al. [29], the understanding of the functional groups present in the SOM can aid in recognising changes in SOM composition caused by various factors such as increased carbon and nitrogen concentration in soil, the addition of biochar or crop biomass to the soil and fertilisation. Furthermore, FTIR has been used to ascertain SOM's hydrophobicity and humification index across a wide range of arable soils [25,30,31]. The ratio of aromatic to aliphatic compounds employed by Chefetz et al. [32] and Margenot et al. [33] has been instrumental in describing the extent of degradation and revealing variations in SOM composition among diverse soils.

Most prior research on tropical peatlands mainly concentrated on the differences between intact forests and fully grown oil palm plantations using a binary approach [34–36]. While the impacts of tropical peatland conversion on greenhouse gas emissions and climate change have been widely discussed [37–39], there is a paucity of studies explicitly focusing on the changes in humification and soil properties across successive generations of oil palm planting on tropical peatlands. The present study aimed to investigate changes in humification and properties of tropical peat soil based on the comparison between forests and two generations of oil palm plantation: 1st Gen or newly planted oil palm plantation and 2nd Gen or replanted oil palm plantation in Sarawak, Malaysia. By assessing the quality of the SOM, specifically the functional groups, humification index, Hydrophobicity Index (HI), and Degree of Degradation (DDI), the impact of long-term oil palm plantations on the quality and stability of SOM can be evaluated. The findings of this study will

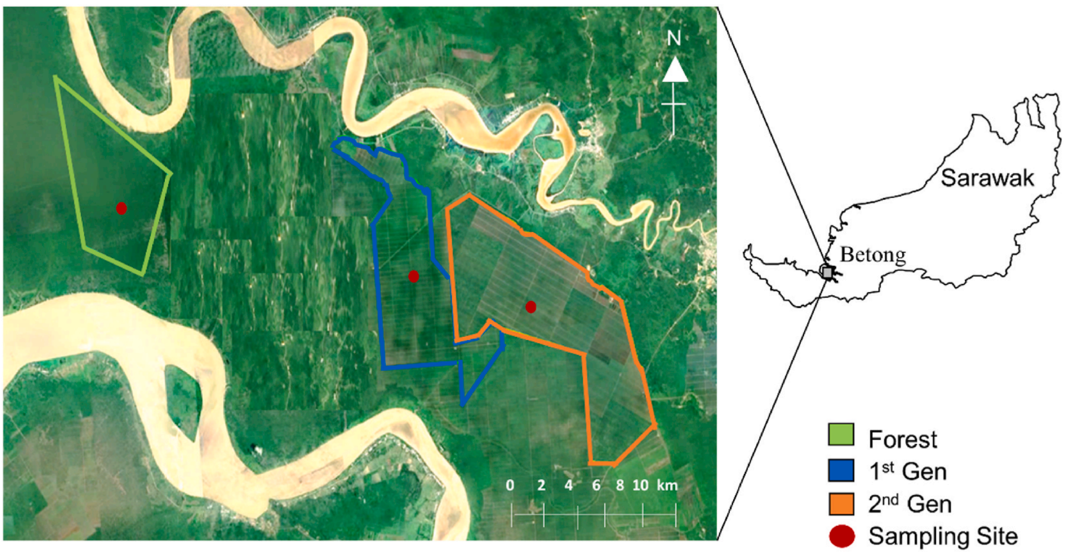

Fig. 1. Location of study sites in Betong, Sarawak, Malaysia.

contribute to our understanding of the sustainability of oil palm cultivation on tropical peatlands and provide insights into land management practices that balance agricultural productivity with environmental preservation.

2. Materials and methods

2.1. Site description

The study site is in Sarawak, Malaysia (Fig. 1: 01° 22′ 29.7948″ N, 111° 34′ 41.2716″ E). The regional climate is humid and tropical, and the site has an average annual precipitation and air temperature of approximately 2700 mm and 32.6 °C, respectively. The soil was classified as Histosol (Fibric, Typic) according to World Reference Base for Soil Resources (4th edition) [40]. The study area encompassed three sites: a forest reserve area (01°28′29.61″ N, 111°19′27.12″ E), a first-generation (newly planted) oil palm plantation (1st Gen) (01°23′31.37″ N; 111°23′48.26″ E), and a second-generation (replanted) oil palm plantation (2nd Gen) (01°22′43.66″ N; 111°28′01.67″ E). The forest site served as a control, representing the original soil condition before any conversion occurred. All sites feature a nearly flat terrain with elevations ranging between 16 and 19 m above sea level. The 1st Gen and 2nd Gen are adjacent to each other, while the forest reserve is located approximately 20 km away from the plantation sites. In Sarawak, peatlands exhibit concentric forest zones known as phasic communities (PC), including Mixed Peat Swamp, Alan Batu, Alan Bunga, Padang Alan, Padang Selunsur, and Padang Keruntum. This forest type is characterized by specific vegetation and peat properties, which influence soil formation and characteristics. According to Melling et al. [41], forest types play a crucial role in determining the type of peat formed and significantly influence both the biophysical and chemical properties of the peat soil. Our study specifically focused on the Alan Bunga Forest type, one of the most prevalent peat forest types in Sarawak [42,43]. The dominant vegetation on the forest site is *Shorea* spp., whereas on the plantation, it is the oil palm crop. The peat depth ranged between 720 and 850 cm at the forest site, 530 and 650 cm at the 1st Gen site, and 550–670 cm at the 2nd Gen site. The water table at the forest site during sample collection was −34.8 cm. In contrast, at the plantation site, the water table was observed at −55 cm at the 1st Gen and −56.8 cm at the 2nd Gen. The water table at 1st Gen and 2nd Gen fall within the typical range for oil palm plantation management, which is typically maintained between −50 and −70 cm to create optimal conditions for oil palm growth. The differences in water table and peat depth between forest and plantations sites were attributed to the establishment of drainage following the conversion of peat forests to oil palm plantations [42,44]. Drainage lowers the water table, creating aerobic conditions essential for the growth of oil palm roots in tropical peatland. Microbial processes were expedited by soil oxygen exposure leading to the decomposition of peat organic matter and resulting in distinct differences in peat depth between forest and plantation sites [16,45,46].

The description of the study sites is presented in Table 1. The 1st Gen, a newly planted oil palm plantation, undergoes the initial transition from a forest to an oil palm plantation. The land preparation began in 2017, with the clearance of forest vegetation and the ploughing of the ground. The drainage was then built, and mechanical compaction was accomplished with a tracked excavator. A groundwater table control was required to ensure adequate water supply for the oil palm throughout prolonged periods of rainfall or dry weather. The oil palm planting for the 1st Gen was completed in 2018. Following this, several oil palm management activities such as pruning of oil palm fronds, weeding, harvesting and fertilizing were carried out in accordance with the plantation's requirements. The 2nd Gen was the replanted oil palm plantation whereby the mature oil palm from the first generation which were initially planted in 2001 had reached the end of their productive lifespan and therefore were cut down and replaced with the new oil palm trees. The land clearance of previously planted oil palm was carried out in 2018 followed by the oil palm replanting in 2019. The replanting land preparation involved the clear-felling of mature oil palms using heavy machinery whereby the trunks of the felled palms (and occasionally the entire trunk) were shredded into smaller sizes and spread over the soil surface and left decomposed. After 6–12 months, preparatory works such as drainage reconstruction, compaction, and watertable control were carried out. Other oil palm management activities, such as pruning, weeding, harvesting and fertilization, were carried out in accordance with plantation requirements. In this study, at the time of field sampling was conducted, both the 1st Gen and 2nd Gen oil palms trees were of the same age, approximately 3 years old. Overall, the duration of land use for oil palm plantation spanned for 4 years for the 1st Gen and 22 years for the 2nd Gen from the initial land clearance in the first cycle to the field sampling. The fertilizer information of the 1st Gen and 2nd Gen oil palm plantations is presented in Table 2. Fertilizers were applied approximately 2 m away from the oil palm trunk. In the 1st Gen, nitrogen (N) fertilizers like Urea (UR) and Ammonium Sulphate (AS) were used. The Rock phosphate (RP) and Muriate of potash (MOP) were also applied providing Phosphorus (P) and Potassium (K) nutrient, respectively. For the 2nd Gen, compound fertilizers with N-P-K-MgO composition such as CPD 55 (15-15-6-4) and CPD 45 (12-12-17-2) were utilized. Other fertilizers such as Copper (Cu), Zinc (Zn), and Boron (B) were also applied in both oil palm plantation as indicated in Table 2.

Table 1
Description of the study sites.

Stages	LC		OP		FS	Oil Palm Age at FS	Time span
	1st Cycle	2nd Cycle	1st Cycle	2nd Cycle			
Forest	–	–	–	–	2021	–	0
1st Gen	2017	–	2018	–	2021	3	4
2nd Gen	2000	2018	2001	2019	2022	3	22

* LC: Land Clearance; OP: Oil Palm Planting; FS: Field Sampling.
**Time span calculated from 1st Cycle of Land Clearance to the year of Field Sampling.

Table 2
Fertiliser information of the 1st Gen and 2nd Gen oil palm plantation.

Fertiliser Type	1st Gen (kg palm^{-1} year^{-1})	2nd Gen (kg palm^{-1} year^{-1})
UR	0.5–1.5	N.A.
AS	1.0–2.0	N.A.
CPD 55	N.A.	0.5–1.0
CPD 45	N.A.	1.0–2.0
RP	2.0–3.0	N.A.
MOP	1.5–2.5	N.A.
Dolomite	N.A	1.0–2.0
Cu	0.1–0.2	0.1–0.2
Zn	0.1–0.2	0.1–0.2
B	0.1–0.2	0.1–0.2

* UR: Urea; AS: Ammonium sulphate; CPD 55: NPK-MgO compound fertilizer 15-15-6-4; CPD 45; NPK-MgO compound fertilizer 12-12-17-2; RP: Rock phosphate; MOP: Muriate of potash; Cu: Copper; Zn: Zinc; B: Borate. All values are in kilogram (kg).

2.2. Peat soil sampling

Field sampling was conducted in June 2021 for Forest and 1st Gen., and in January 2022 for 2nd Gen. Soil samples were collected using a peat auger (Eijkelkamp, Netherlands). Prior to field sampling, the headpiece of the auger was sterilised by wiping down the blades with 70 % ethanol. Samples were collected from depths of 0–50 cm. The peat soil samples taken from this depth represented the soil above the water table level in an oil palm plantation, which was generally controlled between 50 and 70 cm depth. At the forest site, samples were taken randomly at five points whereas at the 1st and 2nd Gen, samples were taken randomly at 5 points of the interrow management zone in the oil palm plantation with three replications for each point. The oil palm plantation was divided into several management zones: the weed circle, frond stack, harvesting path, and interrow zone (Fig. 2). The weed circle, a weed-free area around the oil palm tree, was essential for applying inorganic fertilizers. The frond stack area, located between the palms, was covered with pruned oil palm fronds providing organic nutrient input and facilitating nutrient cycling back into the soil. The harvesting path served as the primary access route for oil palm management activities, frequently used by heavy equipment such as tractors. The soil was sampled from the interrow zone, an area between the rows of the oil palm trees as it was influenced by both inorganic fertilization and the organic decomposition of nutrient-rich fronds from the nearby weed circle and frond stack areas. This area also experiences minimal interference from the movement of heavy equipment compared to the harvesting path. Approximately 2 kg of soil samples were collected at each site. These soil samples were put into labelled polyethylene bags according to their respective sites and the air inside the bag was eliminated as much as possible. Correspondingly, soil samples were air-dried, sieved (<2 mm), and stored at 4°C before analysis.

2.3. Peat soil chemical analysis

Soil pH was determined by weighing 5.0 g of air-dried soil samples into a 50 ml tube containing 12.5 ml of Ultrapure Water (UPW) based on a 2:5 (w/v) soil-to-water ratio. The solution was shaken using an orbital shaker at 300 rpm for 1 h before it was left overnight to allow the suspension to settle and form an aqueous layer. The pH of the soil-water suspension was measured using a pH meter

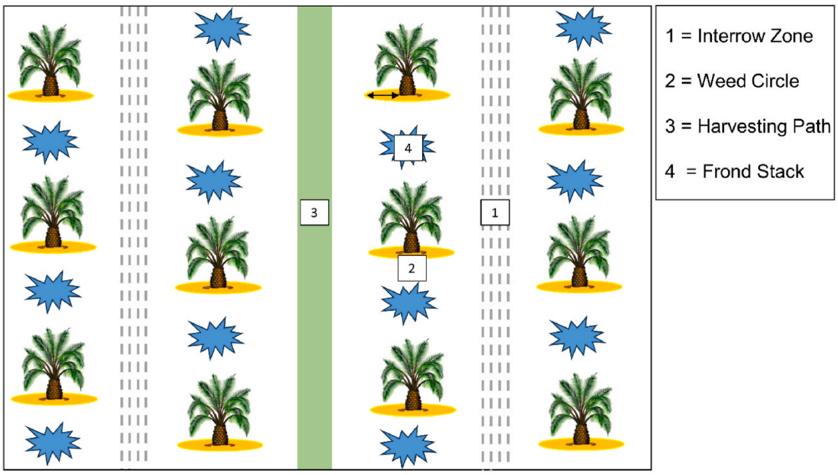

Fig. 2. Layout of the oil palm plantation management zone.

(Metrohm 827; Metrohm, Switzerland). Ash content was obtained from the mass change during the combustion of 1–2 g of dry soil using a thermogravimetric analyser (LECO TGA701, LECO Corporation, San Jose, MI, USA). The degree of humification was determined based on the Pyrophosphate Solubility Index (PSI) measured using an Ultraviolet–Visible Spectrometer (UV/VIS Lambda 25, PerkinElmer, USA). This method is a calorimetric estimation of the degree of humification of organic soil by measuring the colour intensity of an extract obtained by treating the peat sample with sodium pyrophosphate solution, which is able to extract dark-coloured substances quantitatively [47,48]. The Cation Exchange Capacity (CEC) was measured using the ammonium acetate method at pH 7.0, as described by Chapman [49]. It was subsequently analysed with inductively coupled plasma-optical spectroscopy (Optima 7300DV, PerkinElmer, USA). The total Carbon (C) and total nitrogen (N) contents were determined using a TruMac CN analyser (Leco, USA). Total Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Copper (Cu), and Zinc (Zn) were measured using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (Agilent 5800, Agilent Technologies, USA). Soil BD was determined from a peat core sample collected from a depth of 0–50 cm using a peat auger (Eijkelkamp, The Netherlands). The core segment was weighed before and after oven drying at 105 °C for 48 h to calculate BD based on the following formula:

$$Soil\ BD\ \left(g\ cm^{-3}\right) = \frac{Soil\ Dry\ Weight\ (g)}{Soil\ Sample\ Volume\ (cm^{3})} \tag{1}$$

2.4. Spectra of soil samples

The spectra of the soil samples were obtained using an Attenuated Total Reflectance - Fourier Transform Infrared (ATR-FTIR) spectrometer equipped with a diamond crystal (Cary 630, Agilent Technologies, USA). All the spectra were collected at 32 scans with a resolution of 4 cm^{-1} in the range of 4000–650 cm^{-1}. Correspondingly, the ATR crystals were cleaned with anhydrous ethanol between the samples. The spectrum of each sample was ratioed against a fresh background spectrum recorded from the bare ATR crystal and replicated thrice. The peak intensity (by height) was recorded to assess the magnitude of infrared absorption of the selected peaks. The recorded absorption bands were assigned to organic carbon (Table 3).

2.5. Humification index

FTIR was employed to assess variations in humification with depth by examining the relative presence of resilient moieties, such as aromatic, phenolic, and carboxylate compounds. This is in comparison with the abundance of more labile fractions, such as carbohydrates [51]. The ratios of 1620/1030 (aromatic C=C or COO-/polysaccharides), 1420/1030 (OH deformation and CO stretch of phenols), and 1710/1030 (carboxyl C=O and aromatic esters/polysaccharides) were calculated as the humification index [50].

2.6. Hydrophobicity Index

The HI, or SOM repellence, was determined by calculating the ratio of hydrophobic to hydrophilic functional groups [29,52]. The hydrophobic to hydrophilic ratio signifies the presence of (C-H) groups relative to those of the (C=O) group of the peat substrate; thus, hydrophobic and hydrophilic functional groups were estimated using ratio intensities of (2850 + 2920 cm^{-1}) (aliphatic)/1620 cm^{-1} (aromatic). According to Heller et al. [53], a high HI suggests a certain level of SOM protection against microbial degradation.

2.7. Degree of Degradation

The degradation of SOM has traditionally been measured by the proportion of hydrophilic compounds to the combined aliphatic compounds (hydrophobic) [29,32]. As a result, the peak intensity at 1620 cm^{-1}, representing the hydrophilic aromatic components, was divided by the total (2850 + 2920 cm^{-1}) (aliphatic) to determine the DDI of SOM.

2.8. Statistical analysis

All analyses were performed using Rstudio software (Version April 1, 1106) (R Core Team, 2021) and all data were tested for normality using the Shapiro–Wilk test. For the normally distributed data, analysis of variance (ANOVA) was used to test for significant differences, followed by post hoc Tukey's HSD test using the 'aov' and 'TukeyHSD' functions while for the non-normally distributed

Table 3
Peak positions in the FTIR spectra reported in the literature and their proposed assignments [29,50,51].

Peak Name	Wavenumber (cm^{-1})	Assignments/Characteristics
Hydroxyl	3310	O-H vibration of hydroxyl groups
Aliphatic	2850, 2920	Symmetric and asymmetric stretching of aliphatic C-H
Carboxyl	1710	Carbonylic and carboxylic C=O
Aromatic	1620	Aromatic C=C and COO^{-}
Amide	1510	Aromatic C=C or C=O of amides
Phenolic	1420	O-H deformation and CO stretch of phenols
Polysaccharide	1030	C-O stretching of polysaccharidic structures

data the Kruskal-Wallis test was utilized. The Pearson correlation and linear regression were used to describe the relationship between humification levels with PSI values and soil properties. The differences were considered statistically significant at $P < 0.05$. The relationship between soil properties at different sites was visualized using principal component analysis (PCA).

3. Results

3.1. Soil properties

The significant differences in soil properties are shown in Table 4. The selected soil properties and macro- and micronutrients of the peat soils at each site are presented in Fig. 3(a–f) and 4 (a-h). The soil pH was not significantly different ($P > 0.05$) between the sites (Table 4, Fig. 3(a)). BD, CEC, PSI, and CN ratios were significantly higher ($P < 0.05$) in the 2nd Gen compared to the Forest and 1st Gen (Table 4, Fig. 3(b–d-f)). In contrast, ash content was significantly higher ($P < 0.05$) in the 1st Gen than in the Forest and 2nd Gen (Table 4, Fig. 3 (c)).

Total C content was significantly higher ($P < 0.05$) in the Forest and 2nd Gen compared to the 1st Gen (Table 4, Fig. 4 (a)). In comparison, the total N content was significantly higher ($P < 0.05$) in the 1st Gen than in the Forest and 2nd Gen (Table 4, Fig. 4 (b)). Total P and Mg contents were significantly lower ($P < 0.05$) in the 2nd Gen than in the Forest and 1st Gen (Table 4, Fig. 4(c–f)). In contrast, total K, Ca, Cu, and Zn were significantly higher ($P < 0.05$) in 2nd Gen than in the Forest and 1st Gen (Table 4, Fig. 4 (d–e, g-h)).

3.2. Principal component analysis (PCA)

The PCA results illustrated a clustering between the soils at different sites in response to their distinct soil physicochemical properties (Fig. 5). The first principal component, PC1 (x-axis), explained 52.4 % of the total variation in the soil physicochemical properties at different sites and separated the 2nd Gen from Forest and 1st Gen. The variables that contributed significantly to the discriminatory power of PC1 included PSI, BD, CEC, CN ratio, and macro- and micronutrients, such as total K, total Ca, total Cu, and total Zn. The second principal component, PC2 (y-axis), explained 15.8 % of the total variation and distinguished the forest and 1st Gen from the 2nd Gen. The variable scores associated with PC2 included the ash content, total C, total N, total P, and total Mg.

3.3. Correlation between PSI and soil properties

The correlation between PSI and soil properties is presented in Table 5. A significant positive correlation was observed between PSI and pH, BD, CEC, CN ratio, total K, Ca, Cu, and Zn ($P < 0.05$) (Table 5). Additionally, a significant negative correlation was observed between PSI and total N, P, and Mg ($P < 0.05$) (Table 5). PSI was also observed to be negatively correlated with ash content and positively correlated with total C. However, the correlation was not statistically significant ($P > 0.05$) (Table 5).

3.4. Spectra of soil samples

The spectra of the functional groups present in the soils of the study sites are presented in Fig. 6. Common major absorptions were observed in all spectra. General characteristics include a broad and intense band at 3310 cm^{-1} (Fig. 6, Table 3), which is generally attributed to the hydrogen-bonded hydroxyl (O-H) stretch. Distinct peaks ascribed to aliphatic CH stretching vibrations were observed at 2920 and 2850 cm^{-1} (Fig. 6, Table 3). Spectral band vibrations indicative of carboxylates, which include the contribution of aromatic (C=C) and aliphatic carboxylates (R-COO-), were present at 1620 cm^{-1} and 1710 cm^{-1} (Fig. 6, Table 3). Additionally, a

Table 4
Significant differences in soil properties (n=45).

Soil properties	F	p-value
pH	2.962	0.063
Bulk Density (g cm^{-3})	34.120	0.000[b]
Ash content (%)	32.420	0.020[a]
CEC	9.298	0.002[b]
C/N Ratio	50.828	0.000[b]
PSI	65.094	0.000[b]
Total C (g kg^{-1})	23.308	0.000[b]
Total N (g kg^{-1})	61.314	0.035[b]
Total P (mg kg^{-1})	20.275	0.001[b]
Total K (mg kg^{-1})	16.980	0.001[b]
Total Ca (mg kg^{-1})	46.439	0.040[a]
Total Mg (mg kg^{-1})	25.724	0.050[a]
Total Cu (mg kg^{-1})	90.248	0.000[b]
Total Zn (mg kg^{-1})	180.185	0.000[b]

[a] $P < 0.05$.
[b] $P < 0.01$.

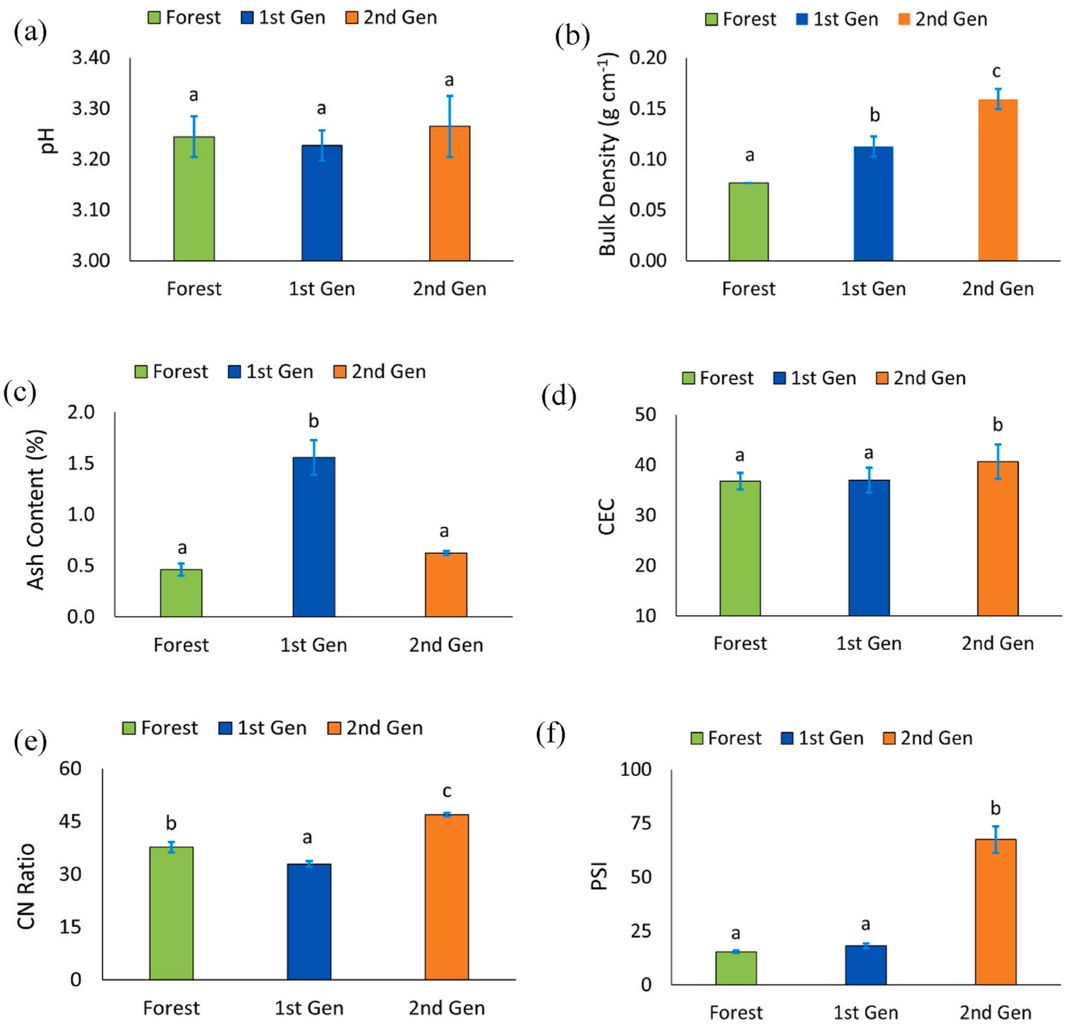

Fig. 3. Soil pH (a), bulk density (b), ash content (c), CEC (d), CN ratio (e), and PSI (f) values according to the site, with the vertical bar indicating the Standard Deviation (SD). Note that different letters indicate significant differences (P < 0.05).

decrease in polysaccharide markers at 1030 cm^{-1} and a relative increase in aromatic C=C or C=O of amide and O-H deformation of the phenolic group at 1510 cm^{-1} and 1420 cm^{-1} were observed at the 2nd Gen (Fig. 6, Table 3). A higher aromatic composition in the 2nd Gen indicated the primary outcome of humification (Fig. 7).

The organic matter characteristics of soil samples from different sites are shown in Table 6. Higher humification indexes of (A_{1620}/A_{1030}), (A_{1420}/A_{1030}), and (A_{1710}/A_{1030}) were observed at 2nd Gen followed by the forest and 1st Gen. HI was also higher at 2nd Gen followed by the forest and 1st Gen. In contrast, DDI was higher at 1st Gen compared to the forest and 2nd Gen. Consequently, linear regression analysis showed a positive relationship between PSI and the humification indexes of (A_{1620}/A_{1030}), (A_{1420}/A_{1030}), and (A_{1710}/A_{1030}) (Fig. 8(a–c)).

4. Discussion

4.1. Changes in the peat soil properties

The soil humification degree, as reflected by the PSI [47], was higher at the 2nd Gen, followed by the forest and 1st Gen soil. These results suggest that the plant residues were more degraded, and the soil nutritional status was higher in the 2nd Gen. After the initial land clearance at the 1st Gen, the accumulation of oil palm biomass, such as frond and leaflet residues, occurred within the top layer of soil due to pruning and mulching activities [54]. According to Elias et al. [55], oil palm litter decomposed approximately 40 % faster than all forest litter, as the litter had the highest foliar P concentrations and lowest lignin to N ratios. The gradual decomposition of oil palm biomass over time, starting from the 1st Gen to the 2nd Gen, leads to higher humification and is attributed to the higher PSI in the 2nd Gen [56].

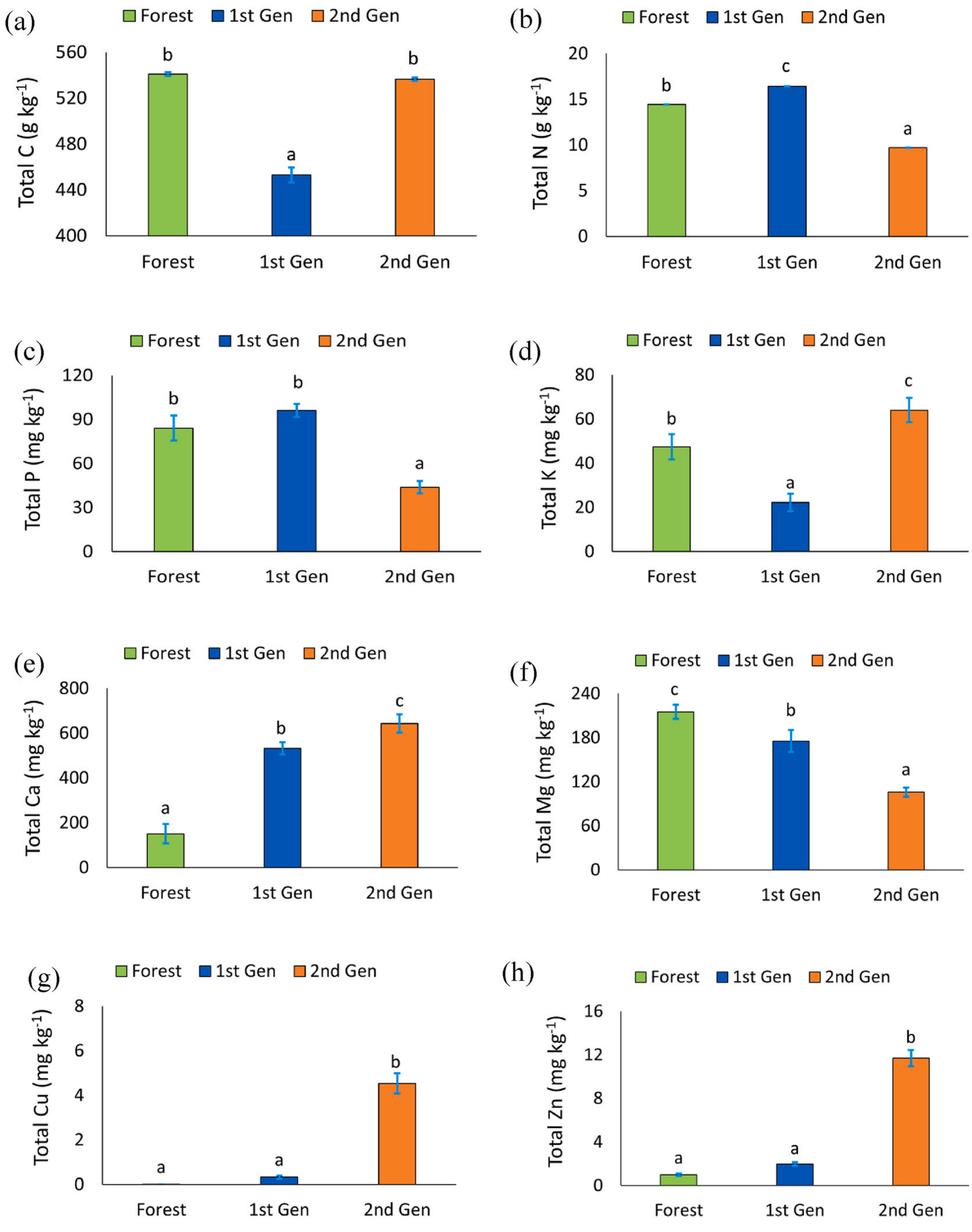

Fig. 4. Means of soil macro- and micronutrients (a)–(h) according to the site, with the vertical bar indicating the Standard Deviation (SD). Different letters indicate significant differences (P < 0.05).

BD was higher at 2nd Gen, probably due to the increased compaction frequency following conversion to oil palm plantation and subsequently following oil palm replanting. During conversion to oil palm plantation, tropical peatlands are generally compacted by heavy machinery to increase the BD and provide better root anchorage to reduce leaning problems for oil palm on peat. The soil particles were consolidated during mechanical compaction, and the total porosity decreased, leading to a high capillary rise and increased soil moisture content and water retention [57,58]. Furthermore, higher soil humification in the 2nd Gen may reduce soil particle size, potentially promoting higher soil BD following mechanical compaction [59].

When peat soils have higher water retention, it increases the mobility of ions within the soil matrix, where ions are more readily exchanged between the soil particles and surrounding solution, and increases the CEC [60]. Higher CEC in 2nd Gen leads to enhanced retention of many positively charged elements in the soil, as observed in this study for K, Ca, Cu, and Zn. The increase in these

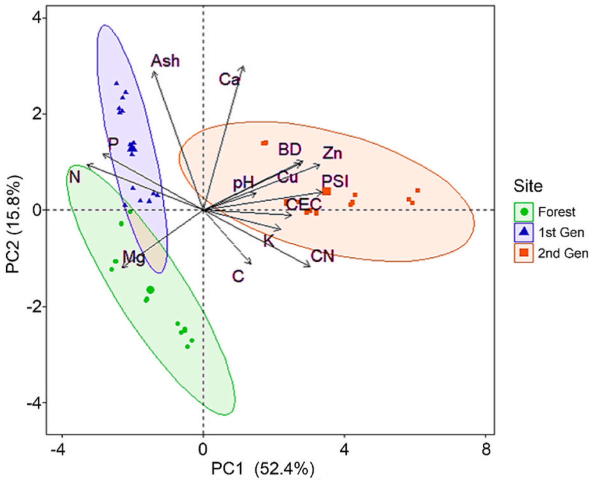

Fig. 5. Principal Component Analysis (PCA) biplot of the relationship between soil properties, where the clusters correspond to different sites. Soil physicochemical properties are indicated in the text, and arrow lengths indicate the strength of the relationship.

Table 5
Pearson's correlation test of PSI with soil properties (n=45).

Soil Properties	PSI
pH	0.542[b]
Bulk Density (g cm^{-3})	0.876[b]
Ash content (%)	−0.293
CEC	0.738[b]
CN Ratio	0.707[b]
Total C (g kg^{-1})	0.277
Total N (g kg^{-1})	−0.877[b]
Total P (mg kg^{-1})	−0.725[b]
Total K (mg kg^{-1})	0.614[b]
Total Ca (mg kg^{-1})	0.331[a]
Total Mg (mg kg^{-1})	−0.644[b]
Total Cu (mg kg^{-1})	0.716[b]
Total Zn (mg kg^{-1})	0.947[b]

[a] $P < 0.05$.
[b] $P < 0.01$.

properties is also visualized in the PCA, which separated the 2nd Gen from the forest and the 1st Gen. Furthermore, a higher proportion of positively charged elements might increase cationic competition and contribute to a decrease in the presence of other positively charged elements in the soil. Mg was significantly lower in the 2nd Gen, which indicated that cationic competition exists between Ca^{2+} and K^{+} with Mg^{2+}, causing a decrease in the concentration of Mg in the 2nd Gen soil [61].

The forest soil exhibited the highest total C content, likely attributed to the input of organic matter predominantly derived from aboveground and belowground litter [62,63]. Total C was higher in 2nd Gen compared to 1st Gen, possibly contributing to root exudates and root turnover over time and the long-term decomposition of oil palm biomass [55,64]. The oil palm replanting of 2nd Gen involved the clear-felling of oil palm trees by heavy machinery [65]. The boles of the felled palms (and sometimes the trunk) are then shredded and distributed on the soil surface where the young oil palms are replanted [9]. Thus, the decomposition of the palm-shredded plant litter during the clear-felling process during replanting may also influenced the higher total C in the soil at 2nd Gen compared to the 1st Gen.

On the contrary, total N and P were significantly higher at 1st Gen soil. The lower BD and higher porosity in 1st Gen increase N leaching losses, causing a higher build-up of residual N within a shorter time [66]. A lower CN ratio at 1st Gen soil indicates more evidence of a relatively high proportion of N in the soil. The higher amount of N in the soil may increase phosphatase enzyme activity and mineralisation rate and, subsequently, increase total P in the soil [67]. As the oil palm matures and develops a more established root system, more N could be taken by the oil palm [68], causing lower N concentration in the soil over time as observed at 2nd Gen. Besides, the mobile NO_3^- in soil solution is susceptible to nitrogen leaching losses which likely to occur during oil palm replanting in the clear-felling process and re-construction of drainage, resulting in the decrease of total N at the 2nd Gen [69].

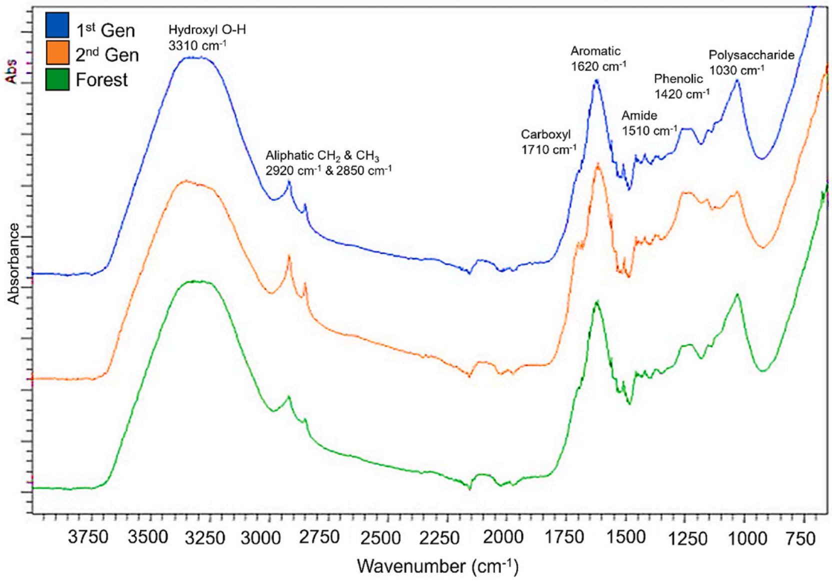

Fig. 6. FTIR spectra on components presented at Forest, 1st Gen, and 2nd Gen.

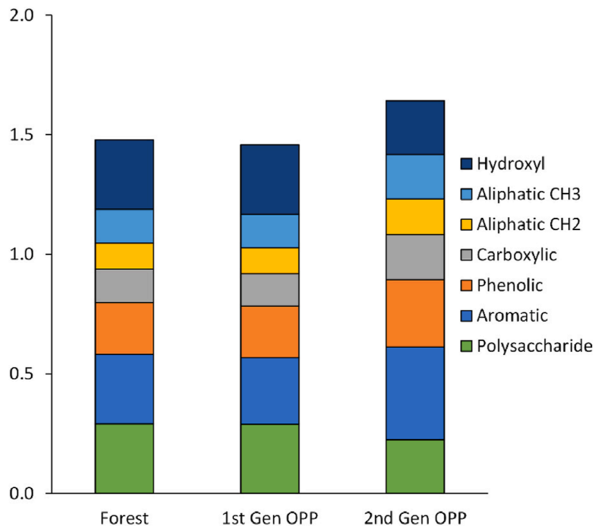

Fig. 7. Composition of the components in the FTIR spectra.

Table 6
(Means ± SE) of organic matter characteristics of soil samples from different sites.

Site	Humification Index$_{(A1620/A1030)}$	Humification Index$_{(A1420/A1030)}$	Humification Index$_{(A1710/A1030)}$	HI	DDI
Forest	1.20 ± 0.032	0.88 ± 0.017	0.58 ± 0.015	1.05 ± 0.009	0.95 ± 0.008
1st Gen	1.11 ± 0.042	0.85 ± 0.026	0.54 ± 0.017	0.88 ± 0.019	1.13 ± 0.023
2nd Gen	1.36 ± 0.045	1.32 ± 0.064	0.86 ± 0.032	1.14 ± 0.033	0.87 ± 0.024

* HI: Hydrophobicity Index; DDI: Degree of degradation.

4.2. Functional groups and SOM composition

In general, the absorbance of functional groups was comparable among soils from different sites. However, they differed in the analysis of peak intensity (specifically, the height of specific peaks). The absorbance at 3310 cm^{-1} originated from stretching the O-H groups of clay minerals [70] and is mainly influenced by the clay content [71]. A decrease in polysaccharide content and a relative

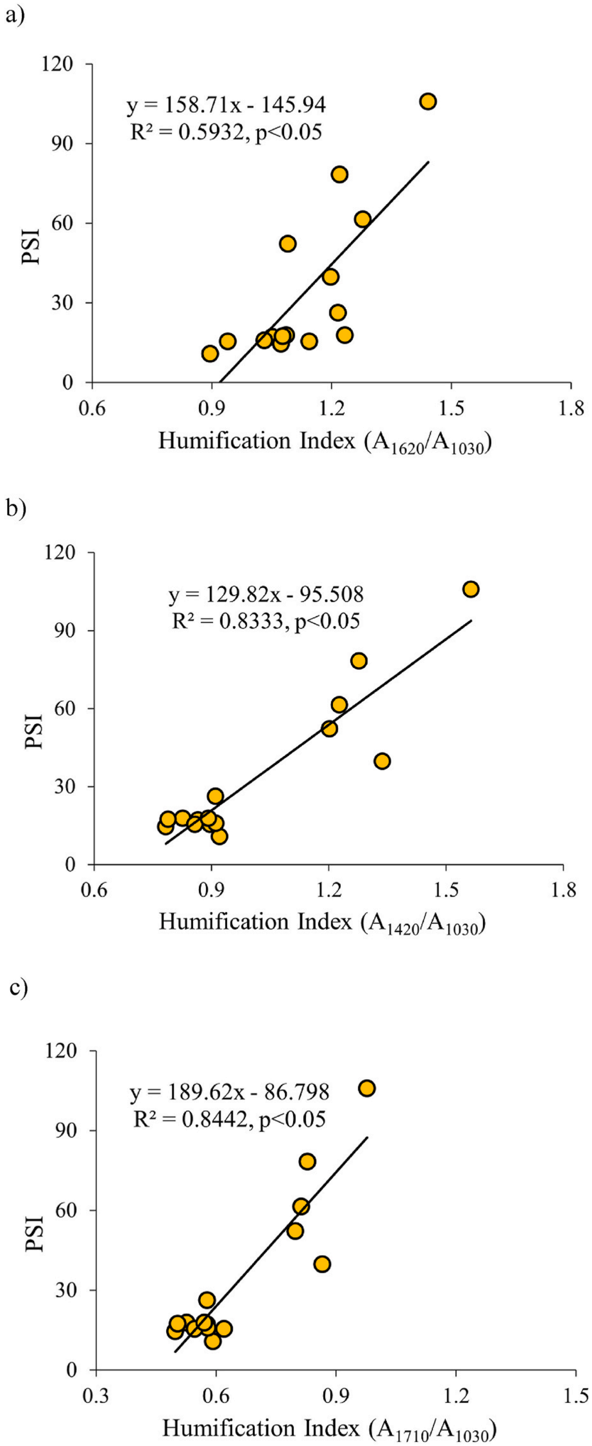

Fig. 8. Linear regression of the relationship between PSI and humification index of (A_{1620}/A_{1030}) (a), (A_{1420}/A_{1030}) (b), and (A_{1710}/A_{1030}) (c).

increase in aromatic, phenolic, and carboxylic spectra at 2nd Gen suggested the highest humification among the sites [25]. As humification advances, the humic matter is typically enriched with aromatic and carboxylic characteristics, indicative of more persistent lignin moieties over polysaccharides [72]. Higher aliphatic methyl and methylene groups attributed to changes in the molecular structure of the alkyl groups, indicating a transformation of the organic matter from a simpler form to a more resistant aliphatic methyl and methylene group. The 2nd Gen and forest exhibited higher aliphatic methyl and methylene groups, suggesting an increase in the decomposition of more easily degradable carbohydrates as compared to the 1st Gen.

The lower HI observed at the 1st Gen soil can be ascribed to the increased microbial activity under aerobic conditions, leading to an elevated C=O group content and the subsequent formation of stable microbial carbohydrates [32]. The forest demonstrated greater HI than the 1st Gen, which was attributed to the long-term additional organic matter input from litter falls, tree debris, and the deep root system of the plants in the forest. In the 2nd Gen, higher HI resulted from organic matter input, specifically from the oil palm-shredded plant litter during the clear-felling process and over the long-term accumulation of oil palm biomass. According to Kalbitz et al. [73], this additional organic matter input contributes to the higher aromatic and lignin-derived compounds of organic matter, which explains the higher HI exhibited at 2nd Gen and forest soil. Likewise, the 2nd Gen exhibited a relatively higher humification index of the aromatic/polysaccharide component ratio (A_{1620}/A_{1030}), signifying a pronounced aromatic compound attribute [72]. Aromatic compounds contain benzene rings or similar structures, although generally indicate hydrophobic groups, can show hydrophilic properties if they are conjugated with C=O groups [29,52].

A positive correlation ($R^2 = 0.59$, $p < 0.05$), ($R^2 = 0.83$, $p < 0.05$), and ($R^2 = 0.0.84$, $p < 0.05$) between PSI and the humification index of the aromatic/polysaccharide component ratio (A_{1620}/A_{1030}), phenolic/polysaccharide component ratio (A_{1420}/A_{1030}), and carboxylic/polysaccharide component ratio (A_{1710}/A_{1030}) suggested that the relative abundance of humic substances increased with the maturity of degraded organic matter. Essentially, humification occurs in two stages. The initial process entailed microbial degradation, which breaks down simpler organic substances into smaller ones, followed by the transformation into a stable humic substance that withstands further degradation and gradually accumulates in soil over time [74]. The extent of degradation was more pronounced in the 1st Gen, followed by the forest and 2nd Gen, possibly due to more favourable degradation conditions driven by the enhanced aerobic decomposition of phenolics and lignin [27,75]. The long-term accumulation of organic matter input counterbalances the effect, resulting in lower DDI in the 2nd Gen compared to the 1st Gen soil.

5. Conclusion

Our findings suggest that successive generations of oil palm planting have varying effects on the humification and the properties of tropical peat soils. Specifically, the soil from 2nd Gen soil exhibited the highest level of humification, as indicated by the PSI, which also impacted BD, CN ratio, CEC, and the availability of micro- and macronutrients such as total K, Ca, Cu, and Zn in the soil. Overall, the peat humification trend was in the order 2nd Gen > Forest >1st Gen. The increased presence of resistant lignin compounds in the soil was associated with the higher HI and lowered DDI observed in the 2nd Gen. Additionally, the relationship between PSI and humification indexes revealed a significant increase in the relative abundance of humic substances with maturity of degraded organic matter. These findings imply a significant transition towards a more stable form of SOM over the long-term utilization of tropical peatland, marked by significant increase in the relative abundance of aromatic, phenolic and carboxylic groups. Further research is needed to understand the linkage between these changes and greenhouse gas emissions, enhancing our understanding of the long-term biogeochemical cycle of oil palm on tropical peatlands. The implications of these findings underscore the importance of sustainable land management practices in oil palm plantations for both environmental preservation and agricultural productivity. It is important to note that this study did not measure peat soil subsidence, which is a known phenomenon in cultivated peatlands and can provide valuable insights into peat decomposition rates. Subsequent studies should also consider incorporating measurements of peat subsidence to provide a more comprehensive understanding of the physical changes occurring in these ecosystems. While the 3-year period since replanting in the 2nd Gen may be relatively short for observing some long-term soil composition changes, it provides valuable insights into the immediate effects of the replanting process and the cumulative impact of long-term oil palm cultivation on tropical peatlands. Longer-term monitoring of replanted areas should be considered to capture the full trajectory of soil property changes across multiple oil palm cultivation cycles.

Funding

This study was supported by the Sarawak State Government.

Data availability statement

Data presented in this paper are available from the corresponding author, upon request.

CRediT authorship contribution statement

Jicqueline Ratai: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Christopher Boon Sung Teh:** Writing – review & editing, Supervision. **Ngai Paing Tan:** Writing – review & editing. **Hasmah Mohidin:** Writing – review & editing. **Kah Joo Goh:** Writing – review & editing. **Faustina Elfrida Sangok:** Writing – review & editing. **Lulie Melling:** Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to acknowledge the technical assistance and fieldwork support provided by members of the Sarawak Tropical Peat Research Institute (TROPI). We acknowledge the permission granted to us to conduct our field experiments in the oil palm plantations.

References

[1] G. Applegate, B. Freeman, B. Tular, L. Sitadevi, T.C. Jessup, Application of agroforestry business models to tropical peatland restoration, Ambio 51 (4) (2022 Apr) 863–874.
[2] M. Ruwaimana, G.Z. Anshari, L.C. Silva, D.G. Gavin, The oldest extant tropical peatland in the world: a major carbon reservoir for at least 47 000 years, Environ. Res. Lett. 15 (11) (2020 Oct 21) 114027.
[3] J. Vijayanathan, M.F. Ishak, I. Parlan, H. Omar, A. Osumanu Haruna, M. Lion, M.G. Hassan, R.M. Jong, A.K. Samah, Temporal patterns control carbon balance in forest and agricultural tropical peatlands in North Selangor, Malaysia, iFor. Biogeosci. For. 14 (4) (2021) 362.
[4] J.A.R. Anderson, The flora of the peat swamp forests of Sarawak and Brunei, including a catalogue of all recorded species of flowering plants, ferns and fern allies, Gardens Bulletin Singapore 29 (1964) 131–228.
[5] S.E. Page, J.O. Rieley, Ø.W. Shotyk, D. Weiss, Interdependence of peat and vegetation in a tropical peat swamp forest, Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 354 (1391) (1999 Nov 29) 1885–1897.
[6] S.B. Hodgkins, C.J. Richardson, R. Dommain, H. Wang, P.H. Glaser, B. Verbeke, B.R. Winkler, A.R. Cobb, V.I. Rich, M. Missilmani, N. Flanagan, Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance, Nat. Commun. 9 (1) (2018 Sep 7) 3640.
[7] L. Melling, Peatland in Malaysia, Tropical peatland ecosystems (2016) 59–73.
[8] D.J. Murphy, K. Goggin, R.R. Paterson, Oil palm in the 2020s and beyond: challenges and solutions, CABI agriculture and bioscience 2 (2021 Dec) 1–22.
[9] R.H. Corley, P.B. Tinker, The Oil Palm, John Wiley & Sons, 2015 Dec 21.
[10] N.A. Busman, L. Melling, K.J. Goh, Y. Imran, F.E. Sangok, A. Watanabe, Soil CO2 and CH4 fluxes from different forest types in tropical peat swamp forest, Sci. Total Environ. 858 (2023 Feb 1) 159973.
[11] D. Ernawati, B. Mulyanto, K. Munibah, Spatial tipology of forest and land fire characteristics: case study in Central Kalimantan Province, in: InIOP Conference Series: Earth and Environmental Science, vol. 393, IOP Publishing, 2019 Dec 1 012071, 1.
[12] E. Barcelos, S.D. Rios, R.N. Cunha, R. Lopes, S.Y. Motoike, E. Babiychuk, A. Skirycz, S. Kushnir, Oil palm natural diversity and the potential for yield improvement, Frontiers in plant science 6 (2015 Mar 27) 190.
[13] C.R. Woodham, A.A. Aryawan, S.H. Luke, P. Manning, J.P. Caliman, M. Naim, E.C. Turner, E.M. Slade, Effects of replanting and retention of mature oil palm riparian buffers on ecosystem functioning in oil palm plantations, Frontiers in Forests and Global Change 2 (2019 Jun 6) 29.
[14] J.L. Snaddon, K.J. Willis, D.W. Macdonald, Biodiversity: oil-palm replanting raises ecology issues, Nature 502 (7470) (2013 Oct 10).
[15] M. Armanto, Comparison of chemical properties of peats under different land uses in South Sumatra, Indonesia, Journal of Ecological Engineering 20 (5) (2019).
[16] A. Kunarso, M.T. Bonner, E.W. Blanch, S. Grover, Differences in tropical peat soil physical and chemical properties under different land uses: a systematic review and meta-analysis, J. Soil Sci. Plant Nutr. 22 (4) (2022 Dec) 4063–4083.
[17] O. Sedlář, J. Balík, J. Černý, M. Kulhánek, M. Smatanová, Long-term application of organic fertilizers in relation to soil organic matter quality, Agronomy 13 (1) (2023 Jan 5) 175.
[18] P. Ojanen, T. Penttilä, A. Tolvanen, J.P. Hotanen, M. Saarimaa, H. Nousiainen, K. Minkkinen, Long-term effect of fertilization on the greenhouse gas exchange of low-productive peatland forests, For. Ecol. Manag. 432 (2019 Jan 15) 786–798.
[19] L.W. Szajdak, A. Jezierski, K. Wegner, T. Meysner, M. Szczepański, Influence of drainage on peat organic matter: implications for development, stability, and transformation, Molecules 25 (11) (2020 Jun 2) 2587.
[20] K.F. Darras, M.D. Corre, G. Formaglio, A. Tjoa, A. Potapov, F. Brambach, K.T. Sibhatu, I. Grass, A.A. Rubiano, D. Buchori, J. Drescher, Reducing fertilizer and avoiding herbicides in oil palm plantations—ecological and economic valuations, Frontiers in Forests and Global Change 2 (2019 Nov 5) 65.
[21] A. Łachacz, B. Kalisz, P. Sowiński, B. Smreczak, J. Niedźwiecki, Transformation of organic soils due to artificial drainage and agricultural use in Poland, Agriculture 13 (3) (2023 Mar 7) 634.
[22] N. Vikram, A. Sagar, C. Gangwar, R. Husain, R.N. Kewat, Properties of humic acid substances and their effect in soil quality and plant health, in: InHumus and Humic Substances-Recent Advances, IntechOpen, 2022 Sep 5.
[23] J.E. Palozzi, Z. Lindo, Boreal peat properties link to plant functional traits of ecosystem engineers, Plant Soil 418 (2017 Sep) 277–291.
[24] S.F. Sim, M.E. Wasli, C.M. Yong, P.S. Howell, C. Jumin, N.A. Safie, B. Samling, Assessment of the humification degree of peat soil under sago (Metroxylon sagu) cultivation based on Fourier Transform Infrared (FTIR) and Ultraviolet-Visible (UV-Vis) spectroscopic characteristics, Mires Peat 19 (2017 Jan 1), 1-0.
[25] R.R. Artz, S.J. Chapman, A.J. Robertson, J.M. Potts, F. Laggoun-Défarge, S. Gogo, L. Comont, J.R. Disnar, A.J. Francez, FTIR spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands, Soil Biol. Biochem. 40 (2) (2008 Feb 1) 515–527.
[26] H.T. Hsu, C.R. Lawrence, M.J. Winnick, J.R. Bargar, K. Maher, A molecular investigation of soil organic carbon composition across a subalpine catchment, Soil Systems 2 (1) (2018 Feb 1) 6.
[27] A.S. Obeng, J. Dunne, M. Giltrap, F. Tian, Soil organic matter carbon chemistry signatures, hydrophobicity and humification index following land use change in temperate peat soils, Heliyon 9 (9) (2023 Sep 1) e19347.
[28] M.H. Bernier, G.J. Levy, P. Fine, M. Borisover, Organic matter composition in soils irrigated with treated wastewater: FT-IR spectroscopic analysis of bulk soil samples, Geoderma 209 (2013 Nov 1) 233–240.
[29] S. Pärnpuu, A. Astover, T. Tõnutare, P. Penu, K. Kauer, Soil organic matter qualification with FTIR spectroscopy under different soil types in Estonia, Geoderma Regional 28 (2022 Mar 1) e00483.
[30] D. Hanke, D.P. Dick, Organic matter stocks and the interactions of humic substances with metals in Araucaria moist forest soil with humic and histic horizons, Rev. Bras. Ciência do Solo 41 (2017) e0160368.
[31] E.S. Vogelmann, J.M. Reichert, J. Prevedello, C.O. Consensa, A.É. Oliveira, G.O. Awe, J. Mataix-Solera, Threshold water content beyond which hydrophobic soils become hydrophilic: the role of soil texture and organic matter content, Geoderma 209 (2013 Nov 1) 177–187.
[32] B. Chefetz, Y. Chen, Y. Hadar, P.G. Hatcher, Characterization of dissolved organic matter extracted from composted municipal solid waste, Soil Sci. Soc. Am. J. 62 (2) (1998 Mar) 326–332.
[33] A.J. Margenot, F.J. Calderón, T.M. Bowles, S.J. Parikh, L.E. Jackson, Soil organic matter functional group composition in relation to organic carbon, nitrogen, and phosphorus fractions in organically managed tomato fields, Soil Sci. Soc. Am. J. 79 (3) (2015 May) 772–782.
[34] P. Srisunthon, S. Chawchai, Land-use changes and the effects of oil palm expansion on a peatland in southern Thailand, Front. Earth Sci. 8 (2020 Nov 24) 559868.
[35] T. Santika, S. Budiharta, E.A. Law, R.A. Dennis, A. Dohong, M.J. Struebig, H. Gunawan, E. Meijaard, K.A. Wilson, Interannual climate variation, land type and village livelihood effects on fires in Kalimantan, Indonesia, Global Environ. Change 64 (2020 Sep 1) 102129.
[36] M. Könönen, J. Jauhiainen, P. Straková, J. Heinonsalo, R. Laiho, K. Kusin, S. Limin, H. Vasander, Deforested and drained tropical peatland sites show poorer peat substrate quality and lower microbial biomass and activity than unmanaged swamp forest, Soil Biol. Biochem. 123 (2018 Aug 1) 229–241.
[37] E. Swails, J. Drewer, J. Hartill, L.P. Comeau, L.V. Verchot, K.A. Hergoualc'h, Soil nitrous oxide and methane fluxes from a land-use change transition of primary forest to oil palm in an Indonesian peatland, Biogeochemistry 167 (4) (2024 Apr) 363–381.
[38] K. Ribeiro, F.S. Pacheco, J.W. Ferreira, E.R. de Sousa-Neto, A. Hastie, G.C. Krieger Filho, P.C. Alvalá, M.C. Forti, J.P. Ometto, Tropical peatlands and their contribution to the global carbon cycle and climate change, Global Change Biol. 27 (3) (2021 Feb) 489–505.

[39] J. Leifeld, L. Menichetti, The underappreciated potential of peatlands in global climate change mitigation strategies, Nat. Commun. 9 (1) (2018 Mar 14) 1071.
[40] IUSS Working Group WRB, World Reference Base for Soil Resources: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, fourth ed., International Union of Soil Sciences (IUSS), Vienna, Austria, 2022, p. 234.
[41] L. Melling, K.J. Goh, R. Hatano, Characterization of tropical peatland and its influence on carbon emission, in: Proceedings of the 9th International Conference of the East and Southeast Asia Federation of Soil Science (ESAFS9), 2007. Korea. Preprint.
[42] F.E. Sangok, N. Maie, L. Melling, A. Watanabe, Evaluation on the decomposability of tropical forest peat soils after conversion to an oil palm plantation, Sci. Total Environ. 587 (2017 Jun 1) 381–388.
[43] L. Melling, Peatland in Malaysia, Tropical peatland ecosystems (2016) 59–73.
[44] G.Z. Anshari, E. Gusmayanti, M. Afifudin, M. Ruwaimana, L. Hendricks, D.G. Gavin, Carbon loss from a deforested and drained tropical peatland over four years as assessed from peat stratigraphy, Catena 208 (2022 Jan 1) 105719.
[45] Decena SC, Avorque C, Macasait Jr D, Arribado A. Diversity and Assemblage of Mangroves along the Carigara Bay in Leyte, Philippines.
[46] J. McCalmont, L.K. Kho, Y.A. Teh, M. Chocholek, E. Rumpang, L. Rowland, M.H. Basri, T. Hill, Oil palm (Elaeis guineensis) plantation on tropical peatland in South East Asia: photosynthetic response to soil drainage level for mitigation of soil carbon emissions, Sci. Total Environ. 858 (2023 Feb 1) 159356.
[47] S.P. Dom, M. Ikenaga, S.Y. Lau, S. Radu, F. Midot, M.L. Yap, M.Y. Chin, M.L. Lo, M.S. Jee, N. Maie, L. Melling, Linking prokaryotic community composition to carbon biogeochemical cycling across a tropical peat dome in Sarawak, Malaysia, Sci. Rep. 11 (1) (2021 Mar 19) 6416.
[48] A. Kaila, Determination of the degree of humification in peat samples, Agricultural and food science 28 (1) (1956 Jan 1) 18–35.
[49] H.D. Chapman, Cation-exchange capacity, Methods of soil analysis: Part 2 Chemical and microbiological properties 9 (1965 Jan 1) 891–901.
[50] T. Broder, C. Blodau, H. Biester, K.H. Knorr, Peat decomposition records in three pristine ombrotrophic bogs in southern Patagonia, Biogeosciences 9 (4) (2012 Apr 20) 1479–1491.
[51] C. Cocozza, V. D'Orazio, T.M. Miano, W. Shotyk, Characterization of solid and aqueous phases of a peat bog profile using molecular fluorescence spectroscopy, ESR and FT-IR, and comparison with physical properties, Org. Geochem. 34 (1) (2003 Jan 1) 49–60.
[52] R.H. Ellerbrock, H.H. Gerke, C. Böhm, In situ DRIFT characterization of organic matter composition on soil structural surfaces, Soil Sci. Soc. Am. J. 73 (2) (2009 Mar) 531–540.
[53] C. Heller, R.H. Ellerbrock, N. Roßkopf, C. Klingenfuß, J. Zeitz, Soil organic matter characterization of temperate peatland soil with FTIR-spectroscopy: effects of mire type and drainage intensity, Eur. J. Soil Sci. 66 (5) (2015 Sep) 847–858.
[54] G. Formaglio, E. Veldkamp, M. Damris, A. Tjoa, M.D. Corre, Mulching with pruned fronds promotes the internal soil N cycling and soil fertility in a large-scale oil palm plantation, Biogeochemistry 154 (1) (2021 May) 63–80.
[55] D.M. Elias, S. Robinson, S. Both, T. Goodall, N. Majalap-Lee, N.J. Ostle, N.P. McNamara, Soil microbial community and litter quality controls on decomposition across a tropical forest disturbance gradient, Frontiers in Forests and Global Change 3 (2020 Jul 16) 81.
[56] Bader C. Peat Decomposition Rates from Managed Organic Soils in Switzerland (Doctoral dissertation, ETH Zurich).
[57] M.I. Nugraha, A. Kurnain, Capillary action of water on peat soil applied subsurface water retention technology membranes in different land uses, Jurnal Solum 20 (2) (2023) 54–61.
[58] R. Walczak, E. Rovdan, B. Witkowska-Walczak, Water retention characteristics of peat and sand mixtures, Int. Agrophys. 16 (2) (2002).
[59] T. Keller, I. Håkansson, Estimation of reference bulk density from soil particle size distribution and soil organic matter content, Geoderma 154 (3–4) (2010 Jan 15) 398–406.
[60] M. Khorshidi, N. Lu, Intrinsic relation between soil water retention and cation exchange capacity, J. Geotech. Geoenviron. Eng. 143 (4) (2017 Apr 1) 04016119.
[61] A. Gransee, H. Führs, Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions, Plant Soil 368 (2013 Jul) 5–21.
[62] A. Upton, C.H. Vane, N. Girkin, B.L. Turner, S. Sjögersten, Does litter input determine carbon storage and peat organic chemistry in tropical peatlands? Geoderma 326 (2018 Sep 15) 76–87.
[63] C.L. Lyons, Z. Lindo, Above-and belowground community linkages in boreal peatlands, Plant Ecol. 221 (7) (2020 Jul) 615–632.
[64] F.A. Dijkstra, B. Zhu, W. Cheng, Root effects on soil organic carbon: a double-edged sword, New Phytol. 230 (1) (2021 Apr) 60–65.
[65] A. Ashton-Butt, S. Willcock, D. Purnomo, Aryawan AA. Suhardi, R. Wahyuningsih, M. Naim, G.M. Poppy, J.P. Caliman, K.S. Peh, J.L. Snaddon, Replanting of first-cycle oil palm results in a second wave of biodiversity loss, Ecol. Evol. 9 (11) (2019 Jun) 6433–6443.
[66] S. Rasouli, J.K. Whalen, C.A. Madramootoo, Reducing residual soil nitrogen losses from agroecosystems for surface water protection in Quebec and Ontario, Canada: best management practices, policies and perspectives, Can. J. Soil Sci. 94 (2) (2014 May) 109–127.
[67] M.R. Arenberg, Y. Arai, Nitrogen species specific phosphorus mineralization in temperate floodplain soils, Sci. Rep. 11 (1) (2021 Aug 31) 17430.
[68] M. Pérez-Sato, Á. Gómez-Gutiérrez, F. López-Valdez, F. Ayala-Niño, E. Soni-Guillermo, M. González-Graillet, H. Pérez-Hernández, Soil physicochemical properties change by age of the oil palm crop, Heliyon 9 (6) (2023 Jun 1) e16302.
[69] I. Comte, F. Colin, J.K. Whalen, O. Grünberger, J.P. Caliman, Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review, Adv. Agron. 116 (2012 Jan 1) 71–124.
[70] A. Bartos, W. Szymański, M. Klimek, Impact of conventional agriculture on the concentration and quality of water-extractable organic matter (WEOM) in the surface horizons of Retisols—a case study from the Carpathian Foothills in Poland, Soil Tillage Res. 204 (2020 Oct 1) 104750.
[71] J. Lehmann, J. Kinyangi, D. Solomon, Organic matter stabilization in soil microaggregates: implications from spatial heterogeneity of organic carbon contents and carbon forms, Biogeochemistry 85 (2007 Aug) 45–57.
[72] B.O. Nordén, E. Bohlin, M. Nilsson, Å. Albano, C. Röckner, Characterization of particle size fractions of peat. An integrated biological, chemical, and spectroscopic approach, Soil Sci. 153 (5) (1992 May 1) 382–396.
[73] K. Kalbitz, A. Meyer, R. Yang, P. Gerstberger, Response of dissolved organic matter in the forest floor to long-term manipulation of litter and throughfall inputs, Biogeochemistry 86 (2007 Dec) 301–318.
[74] J. Lehmann, M. Kleber, The contentious nature of soil organic matter, Nature 528 (7580) (2015 Dec 3) 60–68.
[75] C. Aarti, M.V. Arasu, P. Agastian, Lignin degradation: a microbial approach, Indian J Biol Sci 1 (2015) 119–127.