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REVIEW

Differences in Tropical Peat Soil Physical and Chemical Properties Under Different Land Uses: A Systematic Review and Meta-analysis

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Abstract

Drainage and conversion of natural peatlands, which increases fire frequency, haze air pollution and carbon emissions, also affects the physical and chemical properties of peat soils. Although there has been continued interest in research on tropical peat soil properties, no attempt has yet been made to synthesise these results. We conducted a systematic literature review and meta-analysis of sixty-six papers published in English language academic literature to explore the current state of knowledge of peat soil properties of Southeast Asia and to compare physical and chemical peat properties (e.g. bulk density, carbon content, pH) under different land uses and depths. Most of these studies were undertaken in Indonesia (56.1%) and Malaysia (28.8%), where substantial tracts of peat soils occur. We extracted data from these papers to calculate the mean of each peat property and compare results between land uses and depths. Linear mixed-effects models were used to test the significance of land use and depth on each peat property. We found that bulk density (44 papers), carbon (C) content (43 papers), pH (42 papers) and nitrogen (N) content (39 papers) were the most widely reported, while other properties remain less studied. Bulk density, pH, phosphorus (P) and calcium (Ca) showed significant differences between land uses and depths. Fibre fraction, potassium (K), iron (Fe) and zinc (Zn) levels showed a significant difference between land uses only, while N differed significantly only between soil depths. Other physical properties such as hydraulic conductivity, porosity, woody fraction, amorphic fraction and chemical properties such as electrical conductivity (EC), C, ammonium (NH_4^+), nitrate (NO_3^-), available nitrogen (available N), magnesium (Mg), aluminium (Al), copper (Cu), manganese (Mn), sulphur (S) and silicon (Si) showed no significant differences between land uses or depths. This review identifies key research gaps, including underrepresented geographic areas and peat properties and highlights the need for standardised methodologies for measuring peat soil properties.

Keywords Drainage · Tropical peatland · Peat properties · Southeast Asia

1 Introduction

Tropical peatlands cover an area of approximately 44 Mha (~11% of known peatlands area globally), of which about 25 Mha (56%) are located in Southeast Asia (Page et al. 2011). The important role of tropical peatlands in the global carbon balance and provision of many valuable ecosystem services is widely acknowledged (Page et al. 2011; Uda et al. 2017; Van Eijk and Leenman 2004). However, rapid human population growth in Southeast Asia has led to increasing demands for food and fibre, resulting in drainage of natural peatland ecosystems for conversion to agricultural use (Koh et al. 2011; Miettinen et al. 2011; Nurulita et al. 2015; Page et al. 2002).

Tropical peatlands are formed by an accumulation of partially decayed woody vegetation under waterlogged conditions, where oxygen deficiency limits decomposition of organic materials (Page and Baird 2016; Page et al. 2011). Under undisturbed conditions, peatlands are characterised by high organic matter with high acidity, low nutrient content and dominance of macropores that

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facilitate water movement (Cole et al. 2022; Kurnianto et al. 2019; Mustamo et al. 2016). Peatland drainage accelerates degradation of peat soil by lowering the water table and thereby increasing the thickness of the oxidative peat layer (Anshari et al. 2010). Drying leads to shrinkage of organic materials, resulting in compression of peat layers (Nurulita et al. 2015; Sinclair et al. 2019). The combination of oxidation, shrinkage and compaction causes subsidence of the peat soil surface, reducing pore space and increasing bulk density (Hooijer et al. 2012; Sinclair et al. 2019). Land use change associated with drainage may affect nutrient concentrations and alter nutrient cycling by means of vegetation change and consequent changes in organic matter turnover (Könönen et al. 2015).

Drainage and conversion of natural peatlands have affected the physical and chemical properties of peat soil. Numerous comparison studies conducted in tropical peatlands have recorded that physical and chemical properties differed between land uses, particularly at the surface layer. For example, higher values of bulk density, pH, EC and cation exchange capacity have been observed in drained peatlands relative to undrained peatlands (Anshari et al. 2010; Armanto 2019; Könönen et al. 2015; Sinclair et al. 2019; Tonks et al. 2017). Conversely, properties such as organic C, porosity and hydraulic conductivity tend to be lower in drained peatlands in comparison with undrained peat swamp forest (Armanto 2019; Kurnianto et al. 2019; Wasis et al. 2019).

Understanding of tropical peat soils is developing rapidly, largely due to the relatively recent commencement of formal research on the topic. Research on cold climate northern hemisphere peat soils dates back to the first years of the nineteenth century, initiated by demands for agricultural expansion (Eggelsmann and Blankenburg 2009; Gorham 1957). Research on Southeast Asian peat soils only began at the beginning of the 1940s, as documented by Polak, who studied peat properties in Indonesia (Andriesse 1988). After interruption by the Second World War, agronomic studies resumed on tropical peats in Southeast Asia in the 1950s (Andriesse 1988). Studies on the impact of drainage on peat soil began in the early 2000s (Hadi et al. 2001), in response to the extensive drainage and conversion of natural peatland that occurred during this period (Miettinen et al. 2011). A comparison study conducted by Hadi et al. (2001) set out to evaluate the effect of drainage on peat soils in order to develop restoration strategies, improve conservation management and mitigate fires and carbon emissions. More recently, an overview of the engineering properties of peat soils in Malaysia (Raghunandan and Sriraam 2017) summarised the properties by geographical location rather than land use.

Information on physical and chemical peat soil properties as a basis for understanding water movement and nutrient conditions of peat soils is important to peatland restoration efforts, including hydrological restoration and revegetation of drained peatlands. For example, peatland management aimed at maintaining the saturation of peat soil requires information on hydraulic conductivity, bulk density and water retention, as these properties are the main regulators of water movement through peat soil (Joosten and Clarke 2002). Chemical properties of peatlands help elucidate the availability of nutrients to support plant growth. Despite their obvious importance, there is no recent review of the academic literature on tropical peat soil properties.

The objectives of this study were to assess the current scientific literature on soil properties of tropical peats in Southeast Asia and to compare physical and chemical peat properties under different land uses and depths. We searched English language academic literature published in peer-reviewed journals and compiled it into a database to determine: (1) where research was conducted; (2) what was assessed, including research designs, methods and peat properties measured; (3) what impacts on peat properties were recorded; and (4) what important knowledge gaps remain. Data provided in this review can be used in hydrological modelling as well as peatland restoration planning and monitoring, to inform sustainable land use decision making.

2 Methods

2.1 Literature Search and Database

A systematic quantitative literature review method (Pickering and Byrne 2014) was used to collate all of the academic English language literature on tropical peat soil properties. Peer-reviewed papers published in academic journals were obtained by searching the following electronic databases: Scopus, J store, Google Scholar and Science Direct. Papers were collected between October 2019 and February 2020 and updated between June and October 2020. The keywords used in this search were "peat properties", and a combination of "tropical", "peat", "soil", "degradation", "disturbance", "conversion", "drainage", "canal", "fire", "forest", "oil palm", "agriculture", "plantation", "timber", "restoration", "development", "swamps" and "lowland". Other literature such as books, book chapters, review papers and conference papers were omitted, although reference lists in this literature and the original papers were used to find additional research papers. Papers related to the study question were included according to the following criteria: (1) study area is located within Southeast Asia (31°17′30.713"N-12°22′31.69915"S and 88°35′39.77837"E-152°56′15.87338"E); (2) studies measured physical or chemical properties of peat associated with land use change or were measured at only one land use; (3) studies that primarily focused on other properties, such as greenhouse gas emissions, soil microbiology, peat subsidence or peat decomposition but also included peat soil properties. Information entered into a database included: author(s), title, journal, year of publication, geographical location with GPS coordinates, sampling methods, selected peat properties (including the number of samples and the measured values), land use and sampling depth. The peat properties included in the review are as follows: (a) physical properties – bulk density, particle density, woody fraction, fibre fraction, amorphic fraction, porosity/total pore space, water retention, hydraulic conductivity; and (b) chemical properties – pH, electrical conductivity (EC), carbon content (C), nitrogen content (N), ammonium (NH_4^+), nitrate (NO_3^-), available nitrogen (available N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminium (Al), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), sulphur (S) and silicon (Si).

2.2 Categorisation

The studies included in the review used more than ten different land use classifications. These included pristine forest, undrained logged-over forest, drained logged-over forest, timber and oil palm plantation in different stages of growth, rubber plantation, rubber jungle, sago plantation, agriculture with different commodities (e.g. rice, maize, yam), intercropping site, restoration site, degraded peatland, burnt peatland and shrubland/fern. In order to compare peat soil properties from biophysically similar land uses, each site from each study was allocated into one of four land use groups: forest, managed perennial vegetation, managed annual crop and regenerating site (Table 1).

The studies presented many variations of depth sampling intervals, from fine-scale sampling at 10-cm depth increments to whole profiles comprising one sampling interval. Some studies collected samples only from the surface layer, others sampled down to the mineral soil. In this review, the sample depth across studies was grouped into three intervals: 0–40 cm, 40–80 cm and > 80 cm. These intervals were selected based on Indonesian Government policy on water level management in peatlands. A water level depth of no less than 40 cm has been recommended as the critical threshold to prevent peat fire (Wösten et al. 2008), and this threshold has also been adopted in Indonesian Government Regulation No. 57 (2016) on protection and management of peatland, which stipulates that peatland is considered damaged if the water table is more than 40 cm below the ground surface. The 0—40-cm interval is expected to sit above the water level throughout most of the year. At this level, chemical and physical processes such as oxidation, shrinkage and compaction are expected to be more prevalent due to changes in hydrological conditions. The surface level is also the main location of litter decomposition and organic matter turnover (Könönen et al. 2015). The second depth interval, 40–80 cm, is the region in which the water level fluctuates during the year and thus it is temporarily saturated, especially in the rainy season. The third interval, > 80-cm depth, is the region that is expected to be water-saturated during most of the year; an exception is drained peatland during El Ñino years, where the water level may fall by more than 1 m (Itoh et al. 2017; Könönen et al. 2015). The depth of 80 cm was chosen based on an average water level in the field, especially in drained peatland or in managed perennial vegetation, where the water level is routinely about 80 cm based on the literature and a decade of field experience by the first author. Research conducted in Southeast Asia's oil palm and acacia plantations recorded an average water level between 68 and 91 cm below the surface (Carlson et al. 2015). Bell (2016) reported that acacia established in peatland requires water levels between 70 and 90 cm below the surface to support productivity. In addition, a new peatland management approach, 'eko-hidro,' promoted by several industry actors and academics, has proposed that water levels in plantations are managed at between 50 and 80 cm below the peat surface to minimise subsidence and reduce carbon emissions (Wetlands International and Tropenbos International 2016).

Table 1 Land use groupings into which land use classifications were pooled in this study

Land use grouping	Land use classification in the papers
Forest	Pristine forest, undrained logged-over peat forest, drained logged-over forest
Managed perennial vegetation	Oil palm plantation, timber plantation, rubber plantation, rubber jungle, sago palm plantation
Managed annual crop	Agriculture with different commodities (e.g. rice, maize, yam)
Regenerating site	Abandoned open shrubland, ferns, revegetation site, degraded peatland and natural regeneration

2.3 Statistical Analyses and Mapping

The average values of selected peat properties within each study were tabulated to perform a quantitative analysis. Some papers present the average values of peat properties from the surface to the mineral layer without stating a sampling interval (Anshari et al. 2010; Shimada et al. 2001), and in these instances, the peat soil property values were included in the > 80-cm sampling depth interval category as the profiles were 0–9 m deep. We used the GetData Graph Digitizer (http://getdata-graph-digitizer.com/index.php) to extract values where data were presented only as graphs.

R software (R Core Team) enabled us to explore differences in peat soil properties between land uses and sampling depths. The 'lme4' package (Bates et al. 2015) was used to fit linear mixed-effects models in order and thereby test the significance of land use and depth on each peat property. As the data comprised a collection of subsets of unique individual conditions originating from different papers, the data structure called for the inclusion of 'paper' as a random grouping variable. Pairwise, group-level comparisons were performed using the 'emmeans' package (Lenth et al. 2021). Where model residuals violated the assumption of normality, we used Gamma or Weibull-distributed generalised mixed-effect models depending on which yielded normally distributed residuals. The 'ggplot2' package was used for graphing (Wickham 2009).

The ArcMap 10 program was used to map the number of papers reporting Southeast Asia's peat soil properties. An image of peatland area of Southeast Asia was retrieved from http://www.aseanpeat.net/ and georeferenced based on a shapefile map of Indonesia as the control point. Country and province/state border shapefiles were retrieved from https://gadm.org/download country_v3.html.

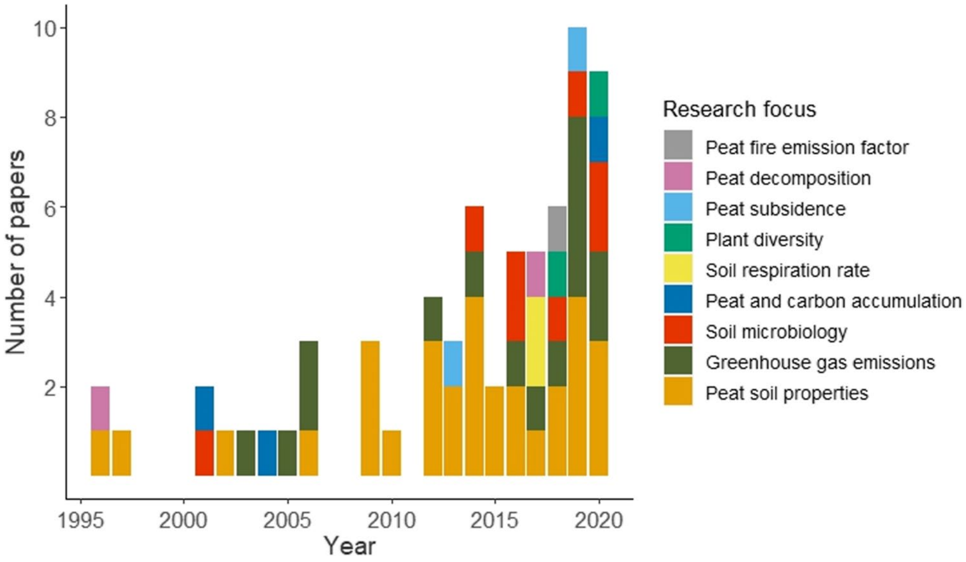
3 Results

3.1 Description of Papers

Assessments of peat properties are relevant to many different fields of study, which is reflected in the diversity of journals that publish papers on this topic. In total, we identified 66 papers that examined the physical and chemical properties of peat soils of Southeast Asia and met the criteria for inclusion. These studies were published in 41 different journals, spanning the disciplines of soil science (29%), environmental science (15%), chemistry (12%), agriculture (11%), biology (8%), wetlands management (8%), earth science (6%), microbiology (5%), biodiversity (2%), engineering (2%), oil palm research (2%) and interdisciplinary research (3%).

Research on peat soil properties of Southeast Asia is a young and rapidly expanding field with a sustained focus on greenhouse gas (GHG) emissions and growing interest in peat soil properties. Nearly half of the papers (31 papers, 46.9%) assessed peat soil properties as the primary focus of research. Fifteen papers (22.7%) had a primary interest in GHG emissions, and eight papers (12.1%) were focused mainly on soil microbiology. A small number of papers with other research foci involved peat subsidence (three papers), soil respiration

Fig. 1 Primary research focus and year of publication of peer-reviewed literature reporting peat soil physical and chemical properties from Southeast Asian peatlands



(two papers), peat and carbon accumulation (two papers), plant diversity (two papers), peat decomposition (two papers) and fire emission factors (one paper) (Fig. 1). The majority (76%) of papers were published between 2012 and 2020 (Fig. 1).

Peat soil properties of Southeast Asia have received wide international research interest. The largest contribution to this body of work has come from Southeast Asia, with a dominance of Indonesian authors — 28% of the 255 authors are affiliated with Indonesian institutions. Other authors were predominantly from Japan (20%) and European countries (19%), but also from other parts of the world: 13 authors were from Australia, six from the USA, four from South Korea and two from South Africa.

3.2 Research Location

More than half of the studies were conducted in Indonesia (37 papers – 56%) in the provinces of Central Kalimantan, South Kalimantan, West Kalimantan, Riau, Jambi and South Sumatra, and close to a third were conducted in Malaysia (19 papers – 29%) in the states of Sarawak, Selangor, Terengganu, Johor and Pahang (Fig. 2). Six papers were from Brunei (the district of Belait), three from Thailand (the provinces of Nakhon Si Thammarat and Surat Thani) and one from the Philippines (the province of Agusan del Sur). Although Vietnam and Myanmar contain approximately 5.6 Mha of peatlands (https://www2.cifor.org/global-wetlands/), no paper could be found reporting peat soil properties from either of these countries. Papers were similarly absent from Papua province in Indonesia, although peat soils cover approximately 3.01 Mha of this province (Anda et al. 2021).

3.3 Research Designs and Methods

Three broad research designs characterised the 66 papers: single site studies, comparison studies between two or more land uses and before-and-after studies. Twenty studies (30.3%) were conducted at only a single site:

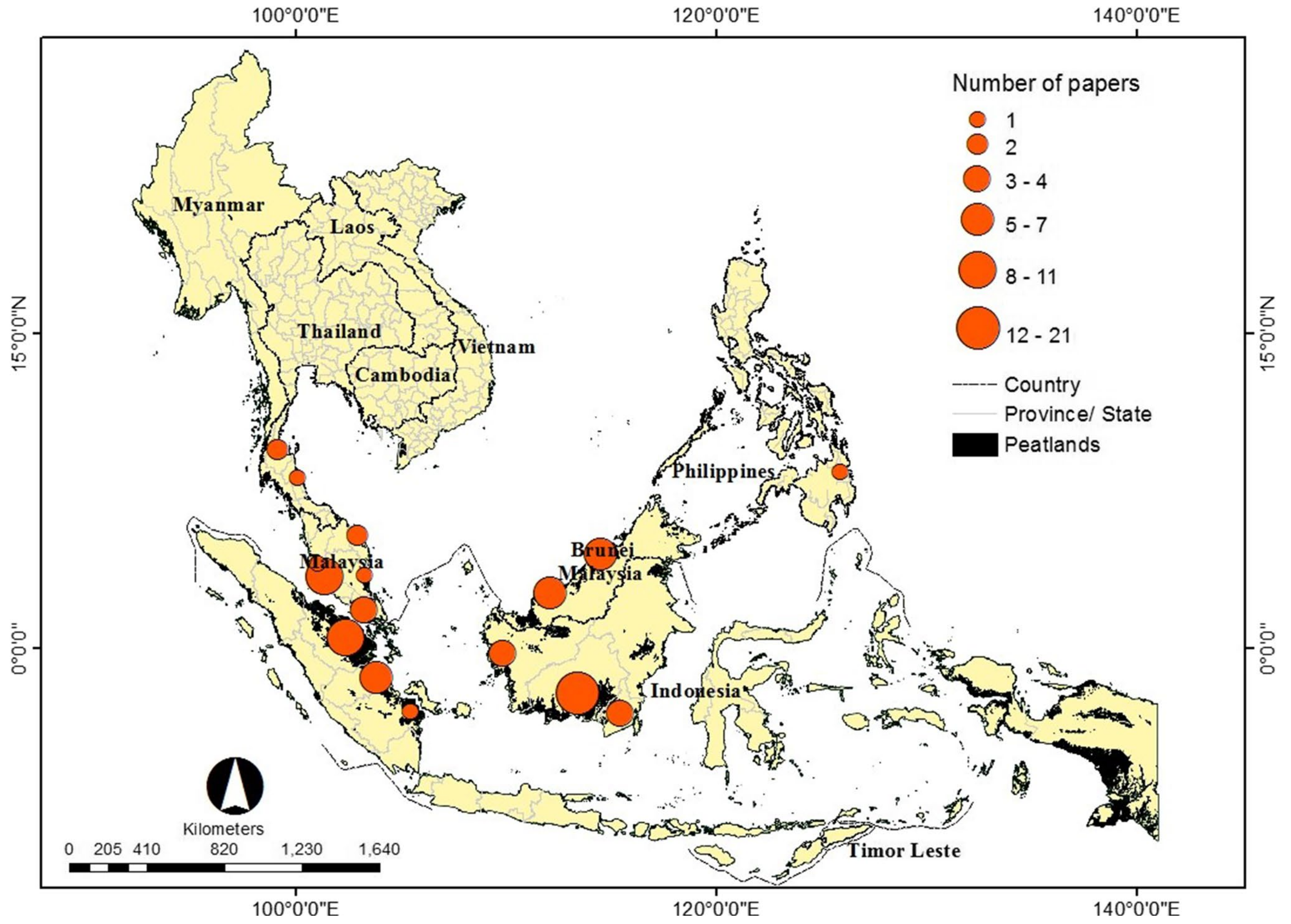


Fig. 2 Study sites of peer-reviewed literature which reported physical and chemical soil properties of Southeast Asian peatlands. Circle sizes indicate the number of papers from a province or state, not the exact study location. Peatland areas are shaded black

nine in forest sites, seven in perennial vegetation sites, three in regenerating sites and one study was conducted in an annual crop site. Forty-six (70%) studies were conducted over two or more land uses and nearly all of these were comparative studies. In the two before-after studies included here, Anda et al. (2009) studied the change of peat properties induced by agricultural land use changes, while Satrio et al. (2009) studied the impact of logging operations. Although comparison research designs were commonly used in predicting the environmental changes, more research will be required to monitor the change of peat properties over time.

There is no standard and commonly accepted method for collecting peat soil samples for physical analysis purposes, and indeed a significant proportion of studies on soil bulk density (16%–7 of the 44 papers on soil bulk density) do not state collection method at all. Half of the studies (22 papers) used ring samplers to collect samples from the surface to 2.5 m down into the peat. Both small (50–100 cm^3) and large steel cylinder rings (402 cm^3) were commonly used. Only one paper used a large box-shaped corer (4480 cm^3) to enclose branches and living roots up to 2 cm thick within the samples (Lampela et al. 2014), while fifteen studies (34%) used peat augers to collect samples down to the mineral soil. Bulk density was the most widely reported physical peat property, and laboratory analyses were performed to provide tabulated values. Most studies (64%–28 of the 44 papers on soil bulk density) used oven-dried samples at 105 °C to provide a constant weight to calculate bulk density. Three papers studied oven-dried samples at 70 °C (Farmer et al. 2014; Kurnianto et al. 2019; Purwanto et al. 2002), and only one paper (Hergoualc'h et al. 2017) used oven-dried samples at 60 °C to calculate bulk density. Another 12 papers did not specify the methodology for drying samples.

Samples for chemical analysis were commonly collected from the same depth as samples collected for physical analysis and stored in plastic bags. Carbon (C) content, pH and nitrogen (N) content were the most widely reported chemical peat properties. The most common methods for measuring C and N content involved elemental analysers (25 and 20 papers, respectively). Other common methods to measure C and N content were the Walkley–Black method (Walkley and Black 1934) — nine papers and Kjeldahl method (Kjeldahl 1883) — 10 papers. Soil pH was most commonly measured with a pH meter and glass electrode (15 and 13 papers, respectively).

3.4 Peat Properties

Bulk density (44 papers), C content (43 papers), pH (42 papers) and N content (39 papers) were the most widely reported peat properties (Fig. 3). Studies on other peat properties were very limited, with only one paper each that recorded woody fraction, amorphic fraction, sodium (Na) content and available N content.

Generating comparable results across land uses and depths required calculating a mean of each soil property. The number of samples of each soil property varied greatly depending on the number of studies reporting

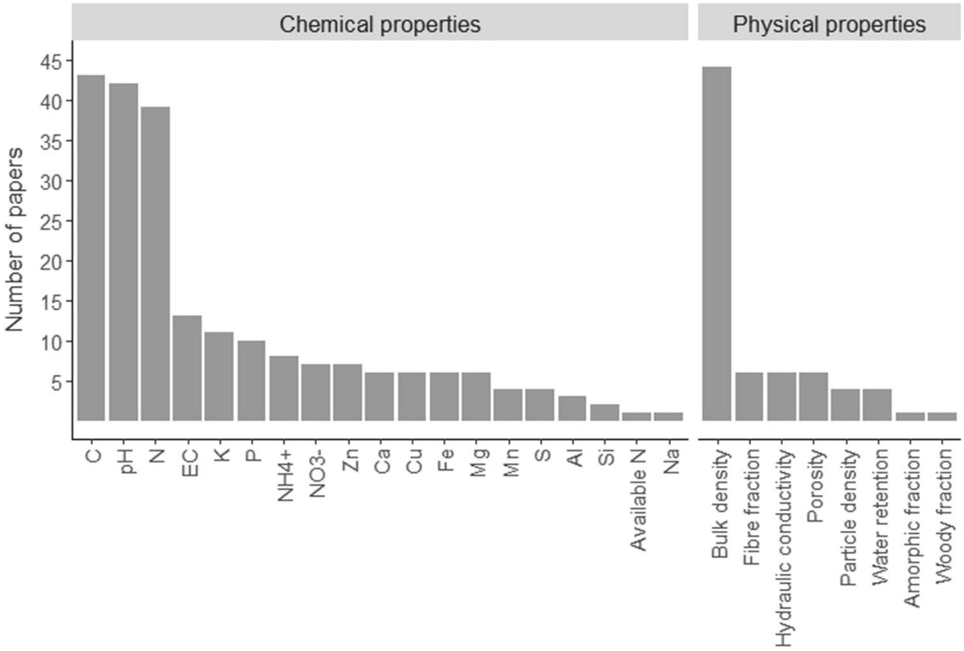


Fig. 3 Physical and chemical peat soil properties directly measured and reported in peer-reviewed literature from Southeast Asian peatlands

Table 2 Physical properties of peat soil from three depths at four land uses (forest, perennial vegetation, annual crop, regenerating) of tropical peatlands in Southeast Asia. Arithmetic mean (x̄) (standard deviation) and the number of samples (*n*) are provided. Four land use groups and three depth intervals were used to categorise the many variations of land use classification and depth sampling intervals used in the original papers

Land use	Depth (cm)	Bulk density ($g\ cm^{-3}$)		Particle density ($g\ cm^{-3}$)		Woody fraction ($g\ cm^{-3}$)	Fibre fraction ($g\ cm^{-3}$)	Amorphic fraction ($g\ cm^{-3}$)		Porosity (%)	Hydraulic conductivity ($m\ s^{-1}$)				
		$\bar{x}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*
Forest	0–40	0.17	654	0.97	NS	0.02	6	0.42	35	0.04	6	89.75	6	0.0002	9
		(0.13)						(0.31)				(0.35)		(0.00)	
	40–80	0.11	61			0.01	6	0.39	10	0.09	6	89.46	6	0.0007	NS
		(0.04)						(0.44)				(2.41)			
	> 80	0.11	929			0.01	9	0.35	10	0.09	9	82.76	144	0.0004	NS
		(0.02)						(0.45)				(10.47)			
Perennial	0–40	0.24	2649	1.16	80			0.25	9			76.49	72	0.0051	6
vegetation		(0.13)		(0.89)				(0.05)				(19.78)		(0.01)	
	40–80	0.23	22	0.09	NS			0.28	5			64.00	0	0.0005	NS
		(0.11)						(0.07)							
	> 80	0.14	1744	1.77	4			0.30	16			91.33	0	0.0005	NS
		(0.05)						(0.06)							
Annual crop	0–40	0.29	338			0.01	3	0.16	16	0.11	3	82.12	3		
		(0.09)						(0.08)				(8.18)			
	40–80	0.11	11			0.02	3	0.24	17	0.11	3	88.20	3		
		(0.04)						(0.13)							
	> 80	0.13	19			0.02	6	0.20	29	0.07	6	90.80	6		
		(0.07)						(0.12)							
Regenerating	0–40	0.23	853	1.16	NS	0.01	3	0.10	3	0.17	3	79.23	3	0.0000	60
		(0.15)						(0.11)				(6.63)		(0.00)	
	40–80	0.13	125			0.01	3	0.11	3	0.06	3	78.35	3	0.0004	NS
		(0.06)						(0.10)				(18.88)			
	> 80	0.10	614			0.01	6	0.14	6	0.08	6	90.05	6	0.0004	51
		(0.03)						(0.14)							

NS not stated

Table 3 Arithmetic mean ($\bar{x}$) (standard deviation) and the number of samples (n) of pH, electrical conductivity (EC), carbon content (C), nitrogen content (N), ammonium (NH_4^+) and nitrate (NO_3^-) from three depths at four land uses (forest, perennial vegetation, annual crop, regenerating) of tropical peatlands in Southeast Asia

Land use	Depth (cm)	pH		EC (mS cm^{-1})		C (%)		N (%)		NH_4^+ (ppm)		NO_3^- (ppm)	
		$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n
Forest	0–40	3.66 (0.54)	600	34.37 (101.55)	127	51.67 (9.58)	626	1.68 (2.62)	547	251.94 (286.68)	78	31.01 (27.81)	78
	40–80	3.60 (0.26)	28	0.17 (0.07)	16	51.93 (8.39)	70	1.14 (0.27)	74				
	> 80	3.55 (0.39)	442	0.24 (0.20)	317	48.71 (9.62)	629	0.91 (0.33)	182				
Perennial vegetation	0–40	3.63 (0.33)	813	61.65 (122.73)	85	46.16 (12.00)	787	1.58 (7.07)	649	27.39 (28.93)	77	84.15 (93.61)	77
	40–80	3.82 (0.32)	6	0.23 (0.09)	3	43.67 (9.34)	34	1.31 (0.82)	16				
	> 80	3.58 (0.20)	381	0.28	225	46.72 (5.20)	361	1.75 (1.08)	227				
Annual crop	0–40	3.95 (0.69)	354	0.20 (0.07)	14	47.09 (9.49)	352	1.33 (0.31)	352	158.26 (224.18)	21	147.99 (128.55)	21
	40–80	3.78 (0.31)	22	0.39 (0.51)	15	47.27 (13.84)	22	0.83 (0.23)	22				
	> 80	4.00 (0.62)	40	0.42 (0.58)	30	41.86 (18.27)	51	1.17 (0.98)	78				
Regenerating	0–40	3.83 (0.69)	323	33.33 (78.45)	45	52.86 (11.78)	188	1.51 (4.19)	343	73.66 (76.66)	65	27.09 (22.68)	65
	40–80	3.30	3			54.44 (9.77)	53	0.99 (0.36)	53				
	> 80	3.55 (0.56)	95			52.83 (6.01)	190	0.96 (0.34)	111				

the property (Tables 2, 3, 4 and 5); in general, more sampling was done of the surface layer than of the two deeper layers.

3.5 Meta-analysis

The differences in peat soil properties between land uses and depths were statistically assessed. Bulk density ($n = 8019$ where n is the total number of samples of this property in the literature), pH ($n = 3107$), P ($n = 1167$) and Ca ($n = 1054$) showed significant differences between land uses and depths. Fibre fraction ($n = 159$), K ($n = 1245$), Fe ($n = 1153$) and Zn levels ($n = 1157$) showed a significant difference between land uses only, while N content ($n = 2666$) was only significantly different between soil depths. Other physical and chemical properties such as hydraulic conductivity, porosity, woody fraction, amorphic fraction, EC, C, NH_4^+ and NO_3^-.

Clear differences were evident in soil bulk density between land uses at the surface level (0–40 cm), with the primary differences being between the forest sites, which had the lowest bulk density values, and the annual crop sites, with highest bulk density values (Fig. 4a). At annual crop sites, bulk density was found to be 40% higher at the surface level than in forest sites of the same depth. In perennial vegetation, bulk density was 66% higher at the 40-–80-cm depth than in the forest sites, while at the deeper peat layer (> 80 cm) it was lower than in the upper layers, in the range of 0.10–0.12 g cm^{-3}. Bulk density tended to be higher in drained peatlands than in forest sites. Unlike bulk density, fibre fraction was only significantly impacted by land use and not by soil depth. The highest fibre fraction was in the forest site (0.45 g cm^{-3}), which was about double of that in other sites and showed a highly significant difference from other land uses (Fig. 4b). The lowest fibre fraction was in the annual crop site (0.20 g cm^{-3}).

Mean pH varied (3.6–4.6) and was highest at the annual crop sites (Fig. 5a), that is, between 11 and 24% higher than at other sites of the same depth. At the surface and in the deepest layer of these sites, soil pH was significantly higher than at

Table 4 Arithmetic mean ($\bar{x}$) (standard deviation) and number of samples (*n*) of available nitrogen (available N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and aluminium (Al) from three depths at four land uses (forest, perennial vegetation, annual crop, regenerating) of tropical peatlands in Southeast Asia

Land use	Depth	available N (mg g^{-1})		P (mg g^{-1})		K (mg g^{-1})		Ca (mg g^{-1})		Mg (mg g^{-1})		Al (mg g^{-1})	
	(cm)	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*
Forest	0–40	1.14	2	0.36 (0.23)	213	0.32 (0.17)	243	0.41 (0.32)	216	0.57 (0.23)	216	0.41 (0.29)	11
	40–80			0.13 (0.07)	7	0.07 (0.03)	16	0.07 (0.02)	16	0.42 (0.41)	16	0.30 (0.43)	11
	> 80			0.03	9	0.06	9	0.08	9	0.29	9	0.87 (1.13)	14
Perennial vegetation	0–40	0.72	4	0.42 (0.38)	413	0.43 (0.31)	431	1.46 (0.92)	324	0.84 (0.45)	324	0.09	NS
	40–80			0.12	3	1.61 (2.01)	12	0.36 (0.24)	12	1.41 (0.66)	12	0.07	NS
	> 80												
Annual crop	0–40			0.31 (0.37)	303	0.39 (0.16)	303	2.63	303	0.69 (0.31)	303	0.03	3
	40–80			0.03	3	0.37	3	0.94 (0.78)	3	0.56	3	0.03	3
	> 80			0.06	6	0.38	6	0.82	6	0.45	6	0.04	6
Regenerating	0–40	0.64	6	0.29 (0.23)	201	0.45 (0.60)	213	2.79	156	0.61 (0.26)	156	0.16 (0.13)	3
	40–80			0.03	3	0.15	3	0.97 (2.29)	3	0.77	3	0.07 (0.01)	3
	> 80			0.02	6	0.17	6	0.12	6	0.15	6	0.04	6

Table 5 Arithmetic mean ($\bar{x}$) (standard deviation) and the number of samples (*n*) of copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), sulphur (S) and silicon (Si) from three depths at four land uses (forest, perennial vegetation, annual crop, regenerating) of tropical peatlands in Southeast Asia

Land use	Depth	Cu (mg g^{-1})		Zn (mg g^{-1})		Mn (mg g^{-1})		Fe (mg g^{-1})		S (mg g^{-1})		Si (mg g^{-1})	
	(cm)	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*	$\bar{X}$	*n*
Forest	0–40	3.17 (5.08)	180	1.64 (3.33)	184	2.83 (4.23)	166	0.71 (0.79)	184	1.45 (0.65)	51	0.04	6
	40–80	1.70) (6.22)	10	1.37 (2.36)	16	0.90 (1.27)	4	0.26 (0.31)	16	1.87 (1.61)	36	0.02	6
	> 80			0.00	9	0.00	3	0.58	9	1.92 (1.66)	69	0.02	9
Perennial	0–40	6.51 (10.18)	435	7.28 (9.24)	433	11.72 (20.25)	413	1.71 (2.15)	431	5.63	20		
	40–80	4.40 (6.22)	12	13.07 (18.48)	12	22.90	3	1.65 (2.76)	12	0.50	10		
	> 80												
Annual crop	0–40	0.01	300	0.01 (0.01)	303	0.04 (0.05)	303	1.43 (1.50)	303	0.90	3	0.03	3
	40–80			0.00	3	0.00	3	0.18	3	0.86	3	0.02	3
	> 80			0.00	6	0.01	6	0.45	6	0.90	6	0.03	6
Regenerating	0–40	5.03 (8.03)	181	3.80 (5.24)	182	9.05 (18.06)	180	0.97 (1.20)	180	(0.50)	54	0.17 (0.20)	5
	40–80			0.01	3	0.01	3	0.20 (0.26)	3	1.42 (0.91)	48	0.02	3
	> 80			0.00	6			0.07	6	2.05 (1.73)	81	0.02	6

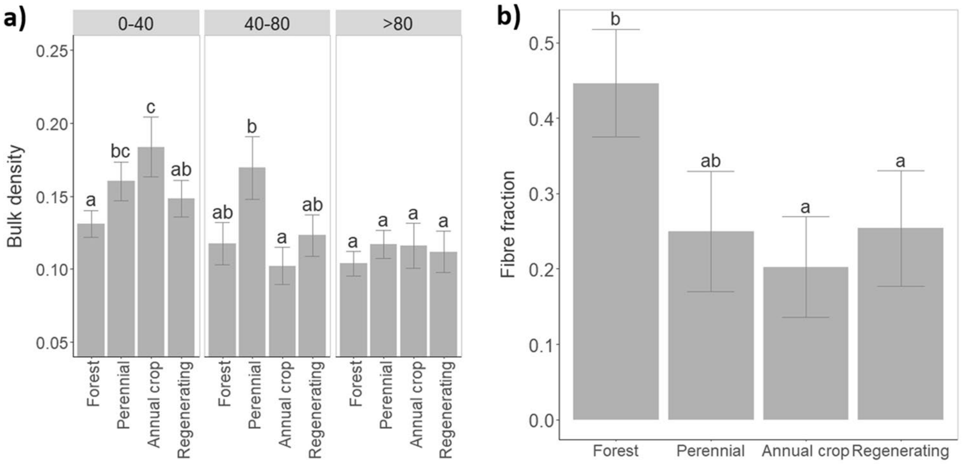


Fig. 4 Model estimated means of **a** bulk density (g cm^{-3}) and **b** fibre fraction (g cm^{-3}) across four land uses in Southeast Asian peatlands. Error bars represent standard errors, and letters represent groupings from post-hoc pairwise comparisons (using Tukey adjustment), where distinct letters within a panel indicate statistically distinct means

all other sites, except for surface soil in regenerating sites. At 40-–80-cm depth, soil pH value was not significantly different between land uses, sitting in the range of 3.7–4.1.

Carbon content in unmanaged or less managed peatlands (forest and regenerating sites) was slightly, but not significantly, higher than in intensively managed peatlands (perennial and annual crop sites); it was about 50% in unmanaged peatlands compared with about 46% in the two types of intensively managed peatlands. Carbon content showed no significant difference across land use and depth (Fig. 5b). Nitrogen content showed a significant difference across depths only (Fig. 5c): it

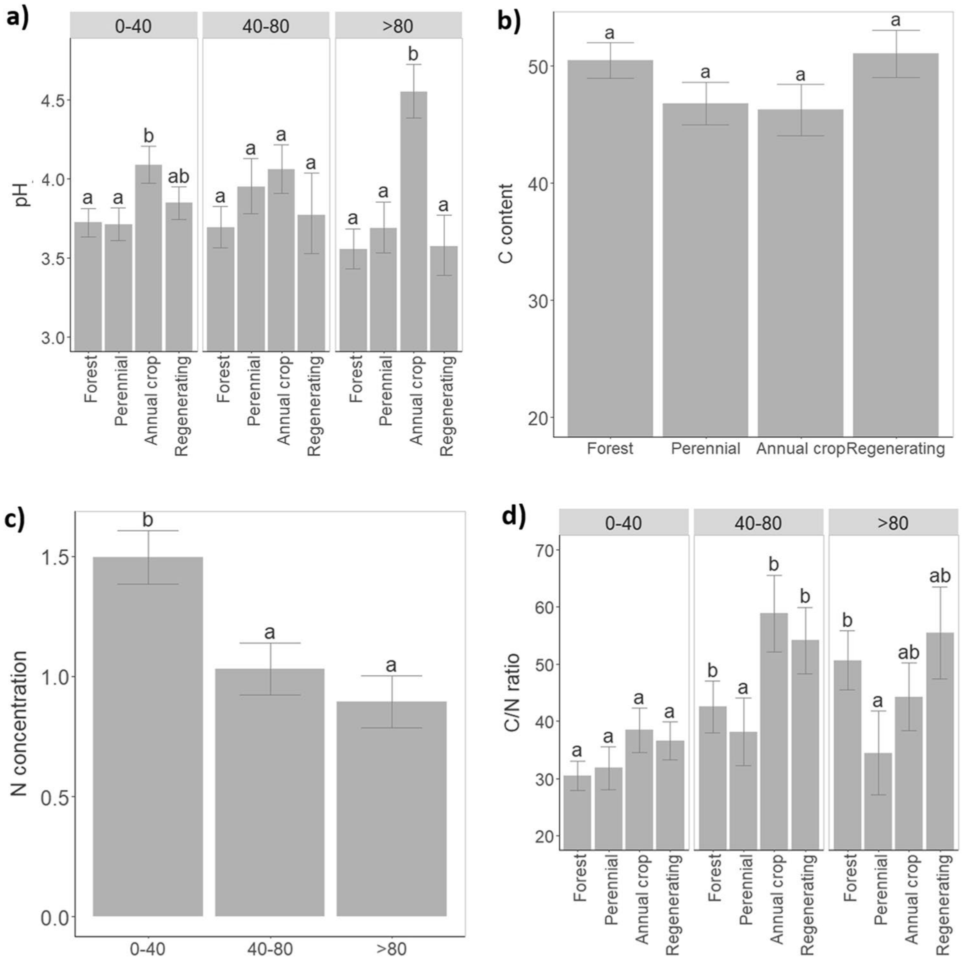


Fig. 5 Model estimated means of **a** pH, **b** carbon (C) content (%), **c** nitrogen (N) concentration (%) and **d** carbon to nitrogen (C:N) ratio across four land uses in Southeast Asian peatlands. Error bars represent standard errors, and letters represent groupings from post-hoc pairwise comparisons (using Tukey adjustment), where distinct letters within a panel indicate statistically distinct means

was generally high (1.5%) at the top layer of all land use types and tended to decrease to 1.03% at 40-–80-cm depth and 0.89% in the deeper layer (> 80-cm depth). Consequently, the C:N ratio was low at the top layer and increased with depth (Fig. 5d). The highest C:N ratio was at 40-–80-cm depth of the annual crop site (58.9), and the lowest was at the top layer of the forest site (30.5). The C:N ratio in the perennial vegetation was in the range 31.8–38.1 and showed no significant difference between depths.

Phosphorus concentration was generally high in the top soil layer in all land uses and decreased with depth (Fig. 6a). In the forest sites, P concentration was higher than all other land uses at all depths. Calcium concentration was highest in the annual crop sites and lowest in the forest sites at all depths (Fig. 6b). Calcium concentration also tended to decrease with depth for all land use regimes. The Ca concentration in the forest sites ranged from 0.1 to 0.3 mg g^{-1} and showed a significant difference to other land uses.

In contrast, potassium (K), iron (Fe) and zinc (Zn) concentrations varied significantly only with land use (Fig. 7). Potassium concentration was highest in the more intensively managed land (annual and perennial vegetation) than in the areas of unmanaged or less managed land uses (forest and regenerating sites) (Fig. 7a). In comparison, the lowest K and Zn concentrations were in the forest sites. In general, the highest Fe and Zn concentrations were in the perennial vegetation sites (1.69 mg g^{-1} and 0.45 mg g^{-1}, respectively) (Fig. 7b, c). The Fe concentration was about a third of that in the forest site (0.55 mg g^{-1}) and also showed significant differences to other land uses. In the annual crop sites, the Fe concentration was just slightly higher than in the regenerating sites, but with no significant difference between those two land uses.

4 Discussion

4.1 Current State of the Literature

This review documented the current literature in English language journals on tropical peat soil properties of Southeast Asia. It has provided insights into where, by whom, by what method and what kind of data have been published so that research gaps can be highlighted to set the agenda for future research. Southeast Asia's physical and chemical peat soil properties have been documented across a wide range of research foci and are receiving continued interest as part of assessing peat soil characteristics. Since 2012, more than two studies per annum have been consistently published in English language journals, with an increasing rate in the last three years (Fig. 1). Despite the greater number of studies on Southeast Asian peat soils, the published data are still limited for many soil properties and some locations. We recognise that studies on Southeast Asian peat soil have also been published in peer-reviewed journals in languages other than English and in a range of 'grey' literature such as reports and conference proceedings. We did not include those papers because they tend not to be consistently accessible using online search engines. Moreover, inclusion of non-English language journals and 'grey' literature is unlikely to dramatically change the general qualitative patterns of peat properties across land uses observed here.

Geographically, studies were concentrated in Central Kalimantan, Indonesia, and Selangor, Malaysia. Both regions contain large peatland areas, and researchers' attention was likely attracted by their history of peatland management. The failed Mega Rice Project (MRP), which aimed to convert 1 Mha of peatlands into agricultural land in the late 1990s in Central Kalimantan, permanently altered the natural landscape of the peatland area and increased fire risk in the dry season. This situation drew increased attention

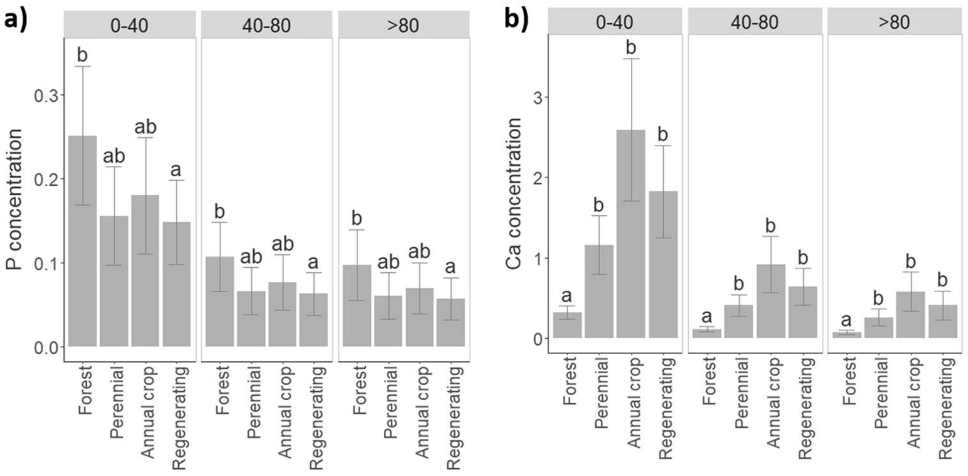


Fig. 6 Model estimated means of **a** phosphorus (P) concentration (m mg^{-1}) and **b** calcium (Ca) (m mg^{-1}) concentration across different land uses in Southeast Asian peatlands. Error bars represent standard errors, and letters represent groupings from post-hoc pairwise comparisons (using Tukey adjustment), where distinct letters within a panel indicate statistically distinct means

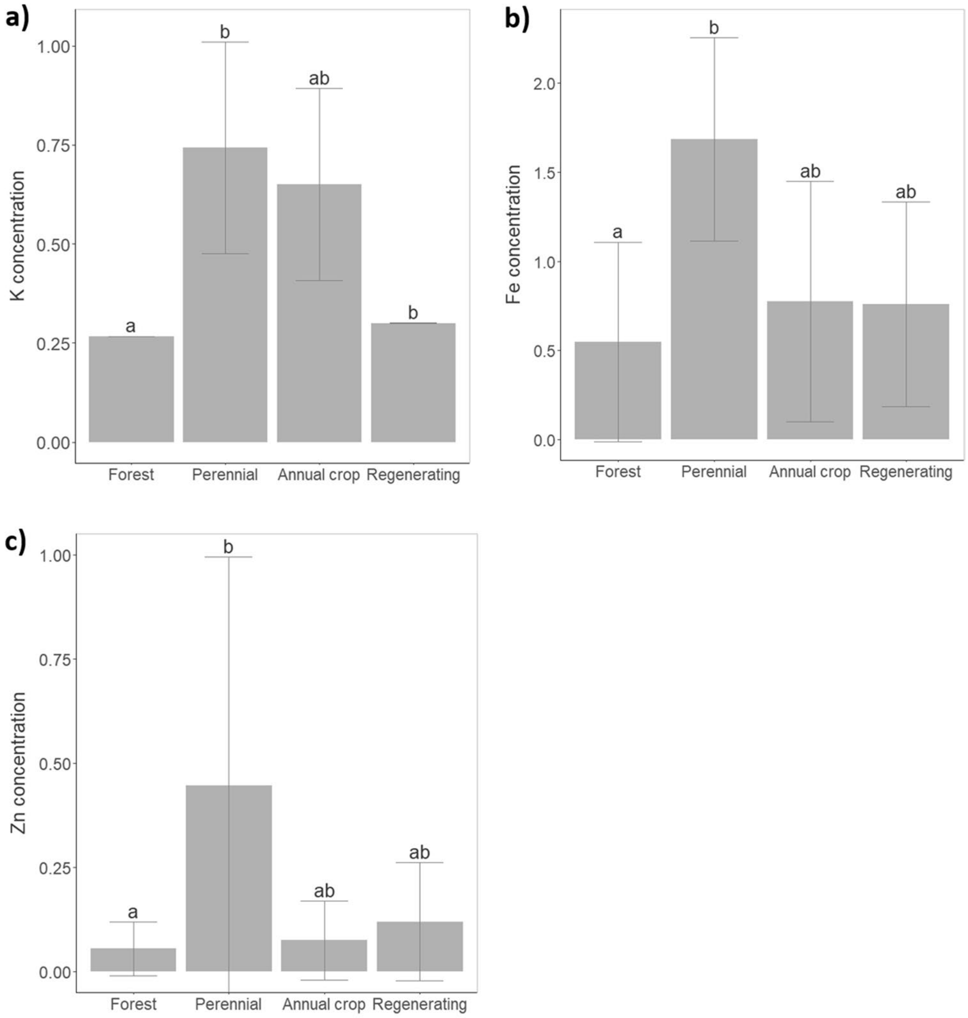


Fig. 7 Model estimated means of **a** potassium (K) concentration (mg g^{-1}), **b** iron (Fe) concentration (mg g^{-1}) and **c** zinc (Zn) concentration (mg g^{-1}) across different land uses in Southeast Asian peatlands. Error bars represent standard errors, and letters represent groupings from post-hoc pairwise comparisons (using Tukey adjustment), where distinct letters within a panel indicate statistically distinct means

from local and international organisations who wanted to contribute to peatland restoration in this area. Dohong et al. (2018) reports at least five large-scale restoration projects conducted in the ex-MRP project in the period 2003–2009 that were funded by collaborations of international organisations and involved many local NGOs on the ground. In this review, most data reported from Central Kalimantan were collected in the ex-MRP location and its surrounding area, with only six papers documenting peat properties from other parts of Central Kalimantan Province. Meanwhile, studies from Selangor were mostly conducted in two protected areas, the Raja Musa Forest Reserve and Sungai Karang Forest Reserve. Prior to gaining reserve status in 1990, those areas were state forests subject to uncontrolled deforestation (Tonks et al. 2017). Likely, recent studies in these protected areas aimed to support future better management of these protected forests.

There were few studies from provinces of Indonesia containing peatlands other than Central Kalimantan, and no studies from Papua or East Kalimantan. Until 2012, the number of oil palm plantations in the peatlands of Papua encompassed an area of 0.05 Mha (~2% of the Papua peatlands) (Afriyanti et al. 2016). About 43,500 Ha or 6.3% of total peatlands in East Kalimantan have been drained for oil palm plantations (Miettinen et al. 2012). However, alterations of natural peatlands in these two provinces seem to have received little attention from researchers in relation to soil properties. It is likely that the limited number of papers from provinces other than Central Kalimantan corresponds to the lack of peatland restoration projects conducted in those areas, especially projects funded by international organisations. Such historical happenstances that concentrate research attention in specific areas are liable to substantially bias our general understanding of peatland responses to land use change.

No papers were found about the peatlands of Vietnam or Myanmar. The few studies from Thailand and the Philippines focussed on yeast communities and plant diversity assessment (Aribal and Fernando 2019; Boonmak et al.

2020; Nasanit et al. 2020). The chemical peat properties provided in these papers were used to determine the relationship between land use and diversity of yeasts and plants. Another paper from Thailand characterised the soil moisture condition in a reclaimed peatland by monitoring the volumetric water content and groundwater level (Iiyama et al. 2012). As such, scientific understanding of tropical peat properties from countries other than Indonesia and Malaysia remains extremely limited.

To date, research on physical properties also remains limited, especially those related to hydrologic properties such as porosity, hydraulic conductivity and water retention. Bulk density is the only physical property of tropical peat soils reported in more than a handful of studies. Bulk density has been measured in many research areas, such as soil microbiology, peat subsidence, plant diversity, GHG emissions, peat and carbon accumulation and peat decomposition. It is likely included in more studies than other physical properties because, as an essential parameter in characterising peat soil, it is relatively easier to measure than other properties. Bulk density is also required to calculate soil carbon stocks (per unit area), which are estimated as the product of carbon concentration (% C), bulk density (g cm^{-3}) and soil volume (m^3) (Warren et al. 2012). Carbon stocks and fluxes have been the focus of growing research attention as the greenhouse gas emissions from peatlands, as well as their potential to act as carbon sinks, have gained international prominence in forums such as the COP talks and IPCC reports. Hydraulic conductivity data were reported in six papers from Selangor and Sarawak in Malaysia, West and Central Kalimantan Provinces in Indonesia, Brunei Darussalam and Thailand. No hydraulic conductivity data were reported from any of the other Indonesia islands with major peatland soils such as Sumatra and Papua. A few hydraulic conductivity studies conducted in tropical peatlands of Southeast Asia were reported by Dommain et al. (2010), but all of these were published in grey literature. Studies on hydraulic conductivity of Southeast Asia peatlands remain scarce, probably because the direct estimation of hydraulic conductivity in the field and the laboratory is time-consuming and costly. Moreover, measuring hydraulic properties of peat soil is methodologically challenging because the soft physical structure of peat soil can easily be changed by the measurement process, either in the field or the laboratory (Grover and Baldock 2013). Physical properties of peat soils urgently require further research attention, due to their critical role in the planning and monitoring of peatland restoration and hence fire prevention and greenhouse gas emission reduction.

Other than pH, C and N content, studies on the chemical properties of tropical peat are limited. Most of the papers that studied peat chemical properties only present those three properties in their analyses. Only Könönen et al. (2015), Funakawa et al. (1996) and Dhandapani et al. (2021) report a wide range of chemical properties in their research, including the levels of P, Ca, Mg, Fe, K, Mn, Zn and Cu. There is good coverage of C and N content and pH as this review includes studies focused on GHG emissions and carbon accumulation assessments, which require C content as a key variable. Moreover, pH and C:N ratios are also widely used as important indicators for peatland degradation (Anshari et al. 2010; Leifeld et al. 2020), which is demonstrated by high pH and low C:N ratios. However, evidence for such trends can be inconsistent due to external factors. For example, managed peatlands are typically characterised by relatively high soil pH to allow suitable conditions for plant growth. However, establishing drainage canals may destroy peat layers over pyrite (FeS_2)-containing sediment, resulting in oxidation of the pyrite causing acidification and leading to extremely low pH values (Anda et al. 2009; Haraguchi 2007). The C:N ratio indicates the degree of decomposition of peat material, as more decomposed peat has a lower C:N ratio and vice versa (Krüger et al. 2015). A more quantitative approach to characterising peat chemistry and predicting the extent of the decomposition of *sphagnum* peat has been widely applied, using solid-state ^{13}C nuclear magnetic resonance (NMR) spectroscopy (Baldock et al. 1997; Grover and Baldock 2010, 2012; Hammond et al. 1985; Normand et al. 2017; Preston et al. 1987; Rodriguez et al. 2021). This approach may be usefully applied to tropical peatlands to understand and monitor the decomposition process in tropical peats following land use changes.

4.2 Responses of Peat Soil Properties to Land Use Changes

Our review provides an important assessment of tropical peat soil characteristics under different land uses and depths. In general, some peat properties responded to land use or depth. Bulk density, pH, P and Ca showed significant differences between land uses and depths. Fibre fraction, K, Fe and Zn levels showed a significant difference between land uses only, while N differed significantly only between soil depths. The most distinctly different means of bulk density occurred at the surface layer (0–40 cm), and these were generally higher than those at the lower depths. High bulk density in drained sites and at the surface layers is linked to the water table and occurs where the position of the water table tends to be below the surface throughout the year. Sinclair et al. (2019) classified three factors contributing to changes of bulk density in degraded tropical peatlands: (1) changes of hydrological condition due to drainage, causing shrinkage, compaction and consolidation of peat material, (2) changes of vegetation structure due to deforestation, causing peat shrinkage and changes to plant root characteristics, thus changing the soil structure and (3) changes in fire regimes, causing loss of upper peat strata and increasing particle density. Our results also revealed that all 22 papers comparing bulk density between different land uses reported higher values in the drained peat than for the forest sites (Table 6).

Fibre fraction is a physical property that can be used to determine the degree of peat decomposition (Baillie 2001; Kurnain 2019). The higher the fibre content, the lower the degree of peat decomposition and vice versa (Kurnain 2019). The lowest fibre fraction, found at the annual crop sites, indicated a high degree of peat decomposition. In their natural condition, peatlands are inundated throughout most of the year due to poor drainage. In order to make them suitable for crops, canal schemes are constructed to drain excess water (Wignyosukarto 2013). As the annual crop sites are intensively drained and managed, the decomposition process becomes more rapid, decreasing the soil's fibre content and increasing its bulk density (Fig. 4).

Intact and undisturbed tropical peat soils are characterised by high acidity. Our quantitative analysis shows higher pH in the annual crop sites compared with other land uses at all depths. High pH in agricultural land may be due to soil amelioration, as lime and chicken manure are known to be ameliorants that effectively increase soil pH (Saputra and Sari 2021). In addition, farmers in Indonesia have traditionally used fire as a cheap tool for land preparation, increasing the soil pH by burning plant debris before planting. The ash from burning is believed to function as an ameliorant to improve peat pH. However, as this ash is easily leached it is unlikely to increase fertility in the long term (Armanto 2019; Sulaeman et al. 2021).

In general, the C content at the forest sites was slightly higher than at the drained sites, indicating a high organic matter supply from the vegetation. However, there were no clear trends of C concentrations in relation to the studied land uses and depths. Thirteen papers reported higher concentrations of C at the forest sites, and ten papers reported higher C concentrations at the managed sites. Itoh et al. (2017), Könönen et al. (2015) and Könönen et al. (2018) reported an increase in C content with increasing depth. Conversely, Lupascu et al. (2020) and Funakawa et al. (1996) found that C content decreased with depth. A recent study conducted in West Kalimantan, Indonesia also suggested that soil C content was not affected by depth in both forested and managed sites (Novita et al. 2021). The C content of tropical peatlands can be influenced by the degree of peat decomposition and the occurrence of burnt materials (Lampela et al. 2014). The variability of C content is probably affected by variation in the degree of decomposition due to differences in hydrological conditions and land management. Furthermore, the occurrence of burnt material in peat may vary depending on the fire frequency and fire characteristics (surface or deep peat fire). Presence of charcoal up to 250-cm depth has been observed reflect past occurrence of fires (Hapsari et al. 2018, 2017), which may contribute to high C content in the deep peats. The high C content values found in managed peat may derive from a more intensive process of fire and deep ploughing for land preparation in cultivated peatlands (Inubushi et al. 2003).

The highest N, P and K concentrations were at the surface layer, where most of the litter deposition and organic matter decomposition occurs in the natural tropical peatland (Könönen et al. 2015). High concentrations of N, P and K in managed peatlands are likely due to fertiliser application (Armanto 2019), which may contribute to lowering C:N ratios in the top surface layer. With regards to land use, lower C:N ratios occurred in the perennial vegetation sites as intensive management in oil palm and timber plantations requires high fertiliser input and thus increases N content. Additionally, intensive drainage applied to support productivity exposed peat to aerobic conditions, causing a loss of carbon. The high concentrations of Ca, Fe and Zn in the managed peatlands were likely due to the addition of ash derived from peat fires (Könönen et al. 2015; Kurnain 2019; Takakai et al. 2006).

4.3 Limitation of the Data

Our meta-analysis highlights a number of limitations to our ability to compare peat properties between land uses or depths that will be useful in guiding future research directions. The first limitation is the difference in methods of sampling and laboratory assessments between studies, which complicates the capacity to directly compare properties. An example is the variability in sampling equipment and laboratory measurement used to quantify bulk density and carbon content. Previous research on methods of bulk density measurement showed overestimates when measured with a small cylindrical ring compared to a big cylindrical ring (≥ 100 cm^3) or a rectangular box (Al-Shammary et al. 2018; Lestariningsih et al. 2013; Walter et al. 2016). Similarly, different methods used to quantify soil organic carbon of tropical peatlands also resulted in different outcomes (Farmer et al. 2014; Paramananthan et al. 2018). However, selecting peat properties by sampling method for collection or laboratory analyses can be complicated. Thus, we included all peat properties entered into the database in the meta-analysis. The development of standardised methods for physical and chemical peat soil analysis, agreed at international level, will be essential in monitoring the effects of land use change in future sustainable development and restoration of tropical peatlands. For example, a big cylinder ring (250 cm^3 volume) which provides a low variation of bulk density values (Walter et al. 2016) may be considered for the international standard size for direct measurement of shallow peat soil sampling. However, factors such as sampling timing and challenges in samples transport from the field should be taken into account in the justification of the best and internationally agreed apparatus.

The second limitation is the paucity of samples. Other than for bulk density, C and N content and pH, the limited number of samples made it difficult to properly assess differences in each property between land uses or depths and to draw clear conclusions, as a statistical significance could not always be reliably assessed. While our results suggest consistent differences in peat properties between land uses (as indicated by bulk density, pH and N, which are properties that have been subject to greater research effort), less studied peat properties showed less consistent trends. For example, hydraulic conductivity showed no significant difference between land uses and depths, likely due to limited data across the full range of these criteria. However, in the only study that compared hydraulic conductivity across different land use types, Kurnain (2019) suggested a strong effect of interaction of depth at forested sites and a strong relationship with von Post degree of decomposition. Thus, there is a need for more research on less studied peat soil properties to better understand the physical and chemical characteristics of tropical peat soil. The third limitation is the lack of data for monitoring changes over time. Currently, most (70%) of the studies were conducted in two or more land uses and compared intact and drained peatlands without sampling prior to drainage. There is a need for more research monitoring changes in peat soil properties over time to thoroughly understand the effects of land use changes on peat soil properties. As change in peat soil properties is affected by many factors, we cannot be 100% confident that the differences in peat soil properties between land uses can be interpreted as reflections of change that occurred as a result of drainage and land use changes.

5 Conclusion and Future Directions

Despite the increasing number of studies on Southeast Asian peatland physical and chemical properties, only bulk density, pH, C and N content are widely reported, and studies on other properties remain limited. Only research published in peer reviewed English language academic journals was included in this review, so the database it produced is authoritative but not exhaustive. However, we did find distinct differences in bulk density and pH between less managed and intensively managed peatlands; bulk density and pH were both higher in intensively managed peatlands (ranging from 0.10 to 0.18 g cm^{-3} and from 3.6 to 4.6 respectively). There is a great opportunity for more research on the nutrients of peat soil and hydraulic properties (such as hydraulic conductivity and porosity) of tropical peatlands. Geographically, the studies we assessed were concentrated in a specific area (Central Kalimantan, Indonesia and Selangor, Malaysia), which can substantially bias our general understanding of peat soil physical and chemical properties. Therefore, research on less-studied geographical regions also needs more attention as soil properties are site specific and differ between sites within the same climate. Finally, there is an urgent need for internationally agreed methods for sampling and laboratory analysis of the physical and chemical properties of tropical peat soils, to enable comparison between studies as well as to enable monitoring of sustainable development and peatland restoration efforts.

Appendix

Table 6 Details of 66 papers assessing tropical peat properties of Southeast Asia

Authors (years)	Journal	Location	Peat properties
Brunei Darussalam			
Gandois et al. (2013)	Biogeochemistry	Belait	C, N, S
Gandois et al. (2014)	Geochimica et Cosmochimica Acta	Belait	C, N
Jaafar et al. (2016)	Malaysian Journal of Science	Belait	pH, N, P, K, Ca, Mg, EC
Lupascu et al. (2020)	Global Change Biology	Belait	BD, pH, EC, C, N, S
Suhip et al. (2020)	Engineering Geology	Badas	BD, hydraulic conductivity
Tripathi et al. (2016)	Frontiers in Microbiology	Belait	pH, N
Indonesia			
Agus et al. (2019)	International Journal of Environmental Science and Technology	Central Kalimantan	BD, pH, EC, C, N, available N, Cu, Zn
Ali et al. (2006)	Wetlands	Jambi	BD, pH
Anda et al. (2009)	Geoderma	Central Kalimantan	Fibre fraction, pH, EC, C, N, Al
Anshari et al. (2010)	Biogeosciences	West Kalimantan	BD, pH, C, N
Arai et al. (2014)	Soil Science and Plant Nutrition	Central Kalimantan	pH, C, N, NH_4^+, NO_3^-
Armanto (2019)	Journal of Ecological Engineering	South Sumatra	C, N, Al, Fe
Couwenberg and Hooijer (2013)	Mires and Peat	Jambi	BD
Farmer et al. (2014)	Geoderma	Jambi	BD, C
Gusmayanti et al. (2019)	Biodiversitas	West Kalimantan	BD, particle density, porosity, pH, C, N
Hadi et al. (2001)	Microbes and Environments	South Kalimantan	Hydraulic conductivity, pH, C, N, NH_4^+, NO_3^-
Hergoualc'h et al. (2017)	Biogeochemistry	Central Kalimantan	BD, pH, C, N
Hikmatullah et al. (2013)	International Research Journal of Agricultural Science and Soil Science	Central Kalimantan and South Kalimantan	BD, fibre fraction, pH, EC, C, N
Hikmatullah and Sukarman (2014)	Journal of Tropical Soils	Central Kalimantan. South Kalimantan, Jambi, Riau	BD, fibre fraction, pH, C, N
Hooijer et al. (2012)	Biogeosciences	Riau	BD
Husnain et al. (2014)	Mitigation and Adaptation Strategies for Global Change	Riau	C, N, P, K, Cu, Zn, Mn, Fe
Inubushi et al. (2003)	Chemosphere	South Kalimantan	pH, EC, C, N, NH_4^+, NO_3^-
Ishikura et al. (2016)	Soil Science and Plant Nutrition	Central Kalimantan	BD, pH, C, N, NH_4^+, NO_3^-
Itoh et al. (2017)	Science of the Total Environment	Central Kalimantan	BD, C, N
Jauhiainen et al. (2012)	Biogeosciences	Riau	BD
Khasanah and Noordwijk (2019)	Mitigation and Adaptation Strategies for Global Change	Jambi	BD, C
Konecny et al. (2016)	Global Change Biology	Central Kalimantan	BD
Könönen et al. (2015)	Mires and Peat	Central Kalimantan	BD, woody fraction, fibre fraction, amorphic fraction, porosity, pH, C, N, P, K, Ca, Mg, Mn, Zn, Al, Fe, S, Si
Könönen et al. (2018)	Soil Biology and Biochemistry	Central Kalimantan	BD, pH, C, N, NH_4^+, NO_3^-
Kool et al. (2006)	Geoderma	Central Kalimantan	BD, pH, EC
Kurnain (2019)	International Agrophysics	Central Kalimantan	BD, fibre fraction, porosity, water retention
Kurnianto et al. (2019)	Mitigation and Adaptation Strategies for Global Change	West Kalimantan	BD, hydraulic conductivity

Table 6 (continued)

Authors (years)	Journal	Location	Peat properties
Lampela et al. (2014)	Plant and Soil	Central Kalimantan	BD, fibre fraction, C, N, P, K, Ca, Mg
Miyamoto et al. (2009)	Nutrient Cycling in Agroecosystems	Riau	BD, K, Ca, Mg, Cu, Zn, Fe
Murdiyarso et al. (2019)	Mitigation and Adaptation Strategies for Global Change	Central Kalimantan	Hydraulic conductivity
Nurulita et al. (2015)	International Journal of Agricultural Sustainability	Riau	BD, pH, C, N
Nurulita et al. (2016)	Agriculture, Ecosystems and Environment	Riau	BD, pH, C, N, NH_4^+, NO_3^-
Page et al. (2004)	Journal of Quaternary Science	Central Kalimantan	BD, pH, NH_4^+, NO_3^-
Sazawa et al. (2018)	ACS Earth and Space Chemistry	Central Kalimantan	BD, C
Shimada et al. (2001)	Biogeochemistry	Central Kalimantan	BD, porosity, C
Sinclair et al. (2019)	Science of the Total Environment	Central Kalimantan	BD
Takakai et al. (2006)	Soil Science and Plant Nutrition	Central Kalimantan	BD, porosity, pH, C, N, NH_4^+, NO_3^-
Wakhid et al. (2017)	Science of the Total Environment	Central Kalimantan	BD, C, N, S
Malaysia			
Abat et al. (2012)	Geoderma	Sarawak	BD, pH, C, N, Cu, Zn
Cooper et al. (2019)	Geoderma	North Selangor	pH, C
Cooper et al. (2020)	Nature Communications	North Selangor	BD, pH
Dhandapani et al. (2019a, b)	Agriculture, Ecosystems and Environment	North Selangor	BD, pH, C, N
Dhandapani et al. (2019a, b)	Science of the Total Environment	Trengganu and North Selangor	pH, C, N
Dhandapani et al. (2021)	Soil Use and Management	North Selangor	P, Ca, Mg, K, Fe, Mn, Zn, Cu
Funakawa et al. (1996)	Soil Science and Plant Nutrition	Sarawak	BD, EC, C, N, P, K, Mg, Ca, Na, Fe, Mn, Zn, Cu
Katimon and Melling (2007)	Jurnal Kejuruteraan (Journal of Engineering), UTM	Selangor	Hydraulic conductivity
Matysek et al. (2017)	Wetlands Ecology and Management	Selangor	BD
Melling et al. (2005)	Tellus, Series B: Chemical and Physical Meteorology	Sarawak	BD, pH, C, N, NH_4^+, $N0_3^-$
Murayama and Bakar (1996)	The Japan Agricultural Research Quarterly	Selangor	BD, particle density, pH, EC, C, N
Paramananthan et al. (2018)	Communications in Soil Scpage ience and Plant Analysis	Perak	C
Purwanto et al. (2002)	Soil Science and Plant Nutrition	Sarawak	BD
Sangok et al. (2020)	Catena	Sarawak	pH, C, N
Satrio et al. (2009)	American Journal of Environmental Sciences	Sarawak	BD, C, N, P
Sim et al. (2019)	Journal of Oil Palm Research	Sarawak	BD, pH, EC
Smith et al. (2018)	Global Biogeochemical Cycles	Pahang	BD, C, N
Tonks et al. (2017)	Geoderma	North Selangor	BD, porosity, pH, C, N
Yule et al. (2016)	Frontiers in Earth Science	North Selangor	pH, C, N, K
The Philippines			
Aribal and Fernando (2019)	Mires and Peat	Mindanao	pH, C, N, P, K
Thailand			
Boonmak et al. (2020)	Antonie van Leeuwenhoek	Surat Thani	pH, EC, N, P, K
Iiyama et al. (2012)	Soil Science and Plant Nutrition	Nakhon-Si-Thammarat	BD, hydraulic conductivity, particle density, C, water retention
Nasanit et al. (2020)	Mycological Progress	Surat Thani	pH, EC, N, P, K

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Declarations

Conflict of Interest The authors declare no competing interests.

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