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Liming and soil acidity management in tropical peatlands under oil palm: A review

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ABSTRACT

In Southeast Asia, vast tracts of tropical peatland have been converted to agricultural land, primarily for the establishment of oil palm plantations, due to anticipated significant economic benefits for the nations involved. Peat soils, on the other hand, have been considered a challenge for agricultural activities. One of the primary agronomic challenges in crop production on peat soil is its high acidity (pH 3.3–3.5) and low fertility. To address these constraints, liming has become a common agricultural practice to adjust soil pH. However, due to the substantial buffer capacity in peat soil, determining optimal lime rates for maximum productivity and cost-effectiveness is relatively challenging. Liming can enhance the physical, chemical, and biological characteristics of soil by reducing its acidity and mobilizing certain elements through direct and indirect mechanisms. Nevertheless, the effectiveness of lime in improving crop productivity is affected by various factors, including initial soil pH, peat heterogeneity, crop species, lime material type, and application method. Plants require a large amount of macronutrients to grow and thrive. In soil with high acidity, most macronutrients are less available to plants. Hence, this review aims to examine how liming helps manage soil acidity and improve soil conditions for oil palm growth on tropical peat soils.

1. INTRODUCTION

Over the last decade, oil palm (*Elaeis guineensis* Jacq.) has emerged as the predominant vegetable oil globally, with Southeast Asia (SEA) accounting for 90% of the world's consumption[1,2]. The oil palm (OP) is the primary source of consumable oil[3,4], with a prevailing global cultivation area exceeding 23 million hectares (MHa)[5]. As reported by the Malaysian Palm Oil Board (MPOB)[6], the total land area allocated for oil palm cultivation amounted to 5.61MHa in 2024, with Sarawak emerging as the predominant state for OP development, accounting for 1.62MHa or 28.9% of the total OP area in Malaysia. Peatland in Sarawak is often used to grow sago and oil palm[7]. Oil palm originated as an ornamental plant in Malaysia and has since evolved into a major industrial sector, producing 19.34 million tonnes of crude palm oil (CPO) and 16.70 tonnes per hectare of fresh fruit bunches (FFB)[6]. The average production of FFB in Sarawak in 2024 was 14.89 tonnes per hectare[6].

The predominant distribution of peatlands in Southeast Asia (SEA) is primarily located in Indonesia (84%, 21 MHa), followed by Malaysia (13%, 2–2.5 MHa), with the others found in Thailand, Vietnam, Brunei, and the

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Philippines[8]. Peat is characterised by the accumulation of decomposed organic matter in vast waterlogged basins under anaerobic conditions, where the accumulation rate of organic material is greater than its decomposition rate[9]. In Southeast Asia, extensive areas of tropical peatland have been converted into deforested areas and drained terrains, subsequently allocated for agricultural purposes. A part of this agricultural land is deemed suitable for OP cultivation due to its homogeneous soil qualities, reliable water availability, and even terrain, which will improve yield efficacy in agricultural production.

In general, fertile soil facilitates extensive root system development, providing robust anchorage while retaining ample supplies of water and essential nutrients for plant growth. However, tropical peat soil is regarded as problematic for agriculture, primarily because of its inherent characteristics, which present various challenges. Nutrient deficiency is particularly problematic in agricultural peatlands, as certain elements are essential for the crops growth[10]. The elevated acidity in peat soil exacerbates this issue, rendering certain vital nutrients inaccessible to plants. One of the primary agronomic challenges for crop production in peat soil is its high acidity (pH 3.3–3.5) and low fertility[11]. In comparison to mineral soils, acidity in peat soils is predominantly determined by the presence of organic acids, while the significance of mobile or hydrolysable aluminium (Al) is relatively lower. Soil pH plays a crucial role in nutrient availability, which directly affects plant growth and yield[12]. Some limitations in acidic soils include reduced base saturation, cation exchange capacity (CEC), organic matter content, soil nutrients, and increased toxicity levels. The low concentration of base cations inhibits essential nutrient uptake and leads to nutrient deficiencies[12,13]. These reduce the availability of vital nutrients for plants, thereby hindering their development and vitality.

In numerous countries, liming has become a widespread agricultural technique to reduce soil acidity. The improvement in soil pH, particularly induced by liming, has a direct impact on soil transformation processes and provides a variety of benefits to both soil and plant[14]. For instance, the increase in soil pH after liming application enhanced peat decomposition, stimulated microbial activity, and thus improved soil nutrient availability and solubility[15]. By reducing soil acidity and mobilizing certain components, liming can also enhance the physico-chemical and biological properties of soil[16]. Inappropriate liming rates, or overliming, can reduce soil exchangeable potassium even when liming has positive impacts on soil acidity[17].

Liming soil does have advantages; however it is expensive since it usually takes a lot of lime to raise the pH of peat soil. The substantial buffering capacity of peat soil, coupled with ample rainfall, presents a challenge in ascertaining the optimal lime application rates that strike a balance between productivity and cost-effectiveness. Despite extensive research on soil acidification and liming effects on nutrient availability, a significant knowledge gap regarding their broader impact on tropical peat soil properties remains. Addressing this gap is crucial in developing effective liming strategies that can optimize OP cultivation while ensuring cost-effectiveness and long-term soil sustainability. Hence, this review aims to examine the role of liming in managing soil acidity and improving soil conditions for OP growth on tropical peat soils.

2. TROPICAL PEATLANDS

Peatland is regarded as one of the most fragile wetland ecosystems worldwide. Peat soil is distinguished by a significant amount of organic matter that has experienced partial decomposition[18]. In Malaysia, a significant portion of lowlying peatlands was formed behind growing mangrove coasts. The presence of sulfides (S) in the mud and water slows down bacterial activity, allowing organic matter to build up over time, eventually forming peat. The formation of peatlands in SEA began in depressions that were located on marshy alluvial plains[19]. These depressions experienced a rapid accumulation of organic litter and debris at a rate of up to 4.5 millimetres per year (mm yr^{-1})[19]. The waterlogged and anaerobic conditions in these environments significantly slow the decomposition of biomass, further contributing to peat accumulation[20].

Typically, tropical peatlands create a “peat dome” by forming between two river systems or stream channels. One trait that contributes significantly to the formation of thick peat surface layers is the cohabitation of lowland tropical peatlands with swamp forests at their borders[20]. The high acidity of peat soil is caused by both the leaching of organic materials into the water and a lack of mineral components. According to Sangok et al.[21], vast tropical peatland areas are situated and formed within swamp forests found in low latitudes. These peatlands primarily are consisted of the remnants of rainforest trees, including branches, trunks, and plant litter, which have accumulated for thousands of years[22].

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2.1. Distribution of peatlands

It was reported that peatlands make up approximately 423 million hectares (Mha), accounting for about 2.84% of the global land area, with 38.4% found in Asia[23]. Notably, two-thirds of these peatlands are concentrated in Southeast Asia, with Indonesia having the largest coverage (20.7 Mha), followed by Malaysia (2.5 Mha)[23–25]. Sarawak has over 1.6 Mha of peatland, making up nearly 70% of Malaysia's total peatland area. These peatlands are extensively used for oil palm and sago cultivation[7,20,26]. In contrast, peatlands in Brunei, Myanmar, the Philippines, Thailand, and Vietnam collectively accounted for only about 1% of the region's total[27].

Approximately 13% of all peatlands globally are tropical[28]. The lowland areas of Africa, Southeast Asia, and Central and South America are home to most of these peatlands. Nonetheless, there are also some high-altitude peatlands found in Papua New Guinea, South America, and Africa's mountain ranges[27]. The area of peatlands remains uncertain despite several mapping studies of peatlands worldwide[28–31]. Table 1 shows the distribution of peatland and the estimated proportion of peatland area in SEA respectively. Tropical peatlands in Malaysia cover approximately 2.56 Mha, making up 7.5% of the country's total land area (Fig. 1 and Table 2).

Table 1. The estimated extent of peatland across Southeast Asian countries

Country	Country Area (Ha)	Total Peatland Area (Ha)
Indonesia	191,944,000	20,695,000
Malaysia	33,080,300	2,588,900
Myanmar	67,657,800	122,800
Brunei Darussalam	576,500	90,900
The Philippines	30,000,000	64,500
Thailand	51,312,000	63,800
Vietnam	33,121,200	53,300
Cambodia	18,103,500	4580
Laos	23,795,500	19,100
Singapore	72,860	50
Total	449,663,660	23,702,930

Source: Omar et al. (2022)[25]

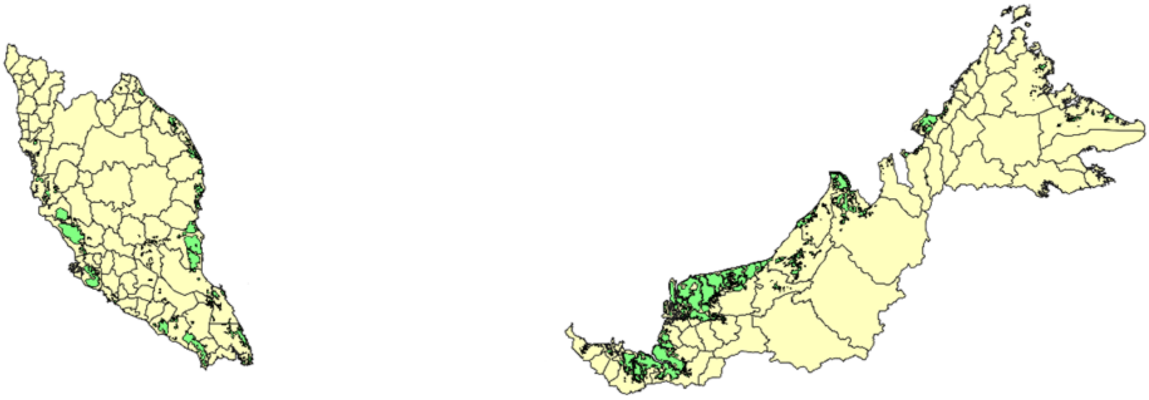

Fig. 1. The distribution of peatland in Malaysia.

Source: This map was re-digitized and modified from Xu et al.[23] using QGIS software (v3.10, https://qgis.org)

Table 2. Peatland distribution in Malaysia

State	[a]Land Area (ha)	[b]Peat soil in State (ha)	Percentage Peat (State) (%)	Percentage Peat (Country) (%)
Johor	1,916,600	187,151	9.76	7.31
Kelantan	1,504,000	7692	0.51	0.30
Negeri Sembilan	665,600	6220	0.93	0.24
Perak	2,097,600	75,124	3.58	2.93
Pahang	3,596,500	196,050	5.45	7.66
Sabah	7,390,400	200,600	2.71	7.83
Sarawak	12,445,000	1,645,585	13.22	64.27
Selangor	795,100	173,198	21.78	6.76
Terengganu	1,305,200	68,338	5.24	2.67
Putrajaya	10,429	383	3.67	0.01
Total Land Area	33,062,100	2,560,341	7.74	100.00

Source: Kato (2021)[26] and [a]Data of 2017 from Department of Statistics, Malaysia; [b]Department of Environment (2019)[32]

2.2. Tropical peatlands and peat swamp forests of Sarawak: Characteristics, ecological importance, and land-use changes

Ombrogenous characteristics of Sarawak's peatland were first described by Anderson[33,34]. The peat swamp forest (PSF) in Sarawak typically features a high-water table and high soil moisture throughout the year due to its closed canopy ecosystem, and highly humid, damp, and shaded forest settings[35,36]. The peat soils here vary in colour, ranging from reddish brown to very dark brown, depending on the stage of decomposition. Moreover, Anderson[19] identified six "phasic communities" (PC) in a tropical peat dome, which are characterised by variations in vegetation types, diversity, and morphology, contributing to the distinct characteristics of tropical PSF (Table 3).

Table 3. An overview of Anderson's phasic communities within the concentric forest associations of the coastal basin peat swamp in Borneo

Phasic Community	Main Tree Species Association	No. of Species	Stems (ha^{-1})	Canopy and Structure of Forest
Mixed Peat Swamp Forest (PC1)	*Gonystylus - Dactylocladus - Neoscortechina*	129	630	Located at peat swamp margins, the structure and physiognomy are similar to lowland dipterocarp evergreen rain forests on mineral soils.
Alan Batu Forest (PC2)	*Shorea albida – Gonystylus - Stemonurus*	136	642	Mixed, uneven, with prominent emergents. Dense middle/lower storeys. *Stenomurus umbellatus* is the indicator species.
Alan Bunga Forest (PC3)	*Shorea albida Consociation*	41	506	Middle storey commonly absent; moderately dense understory; *Pandanus andersonii* forms dense thickets in the shrub layer; climbers and epiphytes are uncommon.
Padang Alan (PC4)	*Shorea albida - Litsea-Parastemon*	45	711	Canopy is even and mostly unbroken, marked by a pole-like structure. Indicator species include small prostrate shrubs (*Euthemis minor* and *Ficus deltoiea* var. *motleyana*). Herbs, ferns, epiphytes, and climbers are rare or absent.
Padang Selunsor Forest (PC5)	*Tristania-Parastemon-Palaquium*	19	1280	Typically found in peat swamps' central dome; narrow transitional fore; the layer between PC4 and PC6 is rare; dense, even, closed canopy at 15 – 20 m with a high density (850 - 1,250 stems ha^{-1}) of small-sized trees.
Padang Keruntum Forest (PC6)	*Combretocarpus-Dactylocladus*	6	-	Stunted, xeromorphic trees. with pneumataphor. Pitcher plants (*Nepenthes* spp.) and epiphytic vegetation are the indicator species.

Source: Anderson (1964)[19]

The pristine tropical PSF of Sarawak is unique due to the six types of PC identified by Anderson[19,34], each distinctly transitioning from the forest margin to its centre. Each community has its unique features in terms of the species' richness and structures, shaped by the topo-morphology of the peatlands and the fertility of the peat soils, which are heavily influenced by the hydrological conditions[20]. In water-logged conditions, the peat decomposition rate is less than the production rate, leading to carbon accumulation over time. The last two phasic communities (PC5 and PC6) occur at the centre of highly developed swamps.

In Sarawak, more than one million hectares (Mha) of peatland have been converted into OP plantations[37]. The expansion of OP plantations has increasingly encroached onto marginal lands, particularly tropical peatlands, due to growing land scarcity. High-quality mineral soils are often occupied by existing agricultural developments, settlements, or conservation areas. As a result, peatlands, despite being ecologically fragile and carbon-rich, have become the next frontier for oil palm cultivation[29]. This shift raises significant environmental and ecological concerns, as peatlands are ecologically fragile and carbon-rich ecosystems. This response examines the environmental implications of this trend, focusing on greenhouse gas (GHGs) emissions, soil degradation, microbial community changes, and potential mitigation strategies.

The conversion of tropical peatlands to OP plantations has significant implications for GHG emissions. Peatlands, when intact, act as critical carbon sinks, storing large amounts of carbon in their soils. Peatland drainage for conversion to OP plantations encourages aerobic decomposition of peat carbon, resulting in substantial carbon dioxide (CO_2) emissions[38,39]. The drainage lowers the water table, exposing the peat to oxygen and increasing microbial decomposition, which releases stored carbon into the atmosphere[38]. For instance, a study in Sarawak, Malaysia, reported CO_2 fluxes ranging from 4.27 to 4.4 g CO_2–C m^{-2} d^{-1} from drainage ditches in OP plantations[40]. Similarly, another study in Indonesia found that CO_2 emissions from OP plantations on peatlands could contribute up to 0.74% of global annual emissions[41]. In Southeast Asia, the conversion of peat swamp forests to OP plantations has been estimated to contribute between 16.6% and 27.9% of the region's total GHG emissions[41]. Additionally, the production of nitrous oxide (N_2O) from oil palm plantations further exacerbates GHG emissions, with N_2O emissions reaching levels significantly higher than those from natural forests[41,42]. The emission of GHGs from oil palm plantations is not static, as it varies over time. For instance, methane (CH_4) emissions decrease following land-use changes, while N_2O emissions increase[42]. The temporal dynamics of these emissions are influenced by factors such as groundwater table levels, humification, and the carbon-to-nitrogen (C:N) ratio in the soil[42]. Understanding these dynamics is crucial for developing strategies to mitigate GHG emissions from oil palm plantations.

The conversion of peatlands to OP plantations leads to significant changes in soil physico-chemical properties, which can degrade soil health and reduce its carbon storage capacity[43,44]. The OP plantations often require intensive fertilization and liming to maintain soil fertility. This practice can alter the exchangeable cation content, increasing levels of calcium and potassium in the soil[6,44]. However, prolonged monocropping can deplete nitrogen stores, as evidenced by lower carbon-to-nitrogen (C:N) ratios in cultivated peat soils compared to forest peat[6]. Drainage for OP cultivation reduces soil moisture, particularly in surface layers, leading to increased bulk density and reduced porosity. This change can impede water infiltration and root growth, further degrading soil health[6].

The microbial community in peatlands plays a critical role in governing ecosystem functions, including carbon cycling and greenhouse gas emissions. Land-use changes associated with oil palm plantations significantly alter microbial community structure. Studies using phospholipid fatty acid (PLFA) profiling showed distinct microbial community structures under different land-use types, including forest, drained, burned, and oil palm plantation peatlands. Bacterial dominance is observed across all land-use types, with Gram-positive bacteria being most abundant in the surface layers, except in burnt peatlands[45]. Microbial communities vary consistently in depth, with a characteristic shift at approximately one meter. This shift is likely due to the changes in oxygen availability, moisture, and organic matter composition. Gram-negative bacteria replace Gram-positive bacteria in deeper layers, reflecting adaptations to anaerobic conditions[45].

The conversion of natural habitats, such as forests and peatlands, into OP plantations has led to significant biodiversity loss. Intact peatlands support unique and diverse flora and fauna, many of which are endemic to these ecosystems. Drainage and land conversion disrupt habitats, leading to population declines and the extirpation of sensitive species[46]. In Southeast Asia, where OP plantations are most prevalent, the clearance of PSF has resulted in the decline of forest-dwelling species. For instance, in Peninsular Malaysia, this land-use change has resulted in a 12.1% decline in biodiversity, equivalent to the loss of 46 species[47]. Similarly, in Sumatra, biodiversity declined by 3.4%, representing 16 species lost[47]. These losses are attributed to the fragmentation of habitat and the destruction of ecosystems that are critical for the survival of many species.

The expansion of OP plantations onto tropical peatlands in Sarawak raises significant environmental and ecological concerns. While the conversion of peatlands to agricultural land provides economic benefits, it comes at the cost of increased greenhouse gas emissions, soil degradation, and biodiversity loss. Mitigation strategies, such as intercropping and community-based rehabilitation, offer promising solutions to reduce the environmental impact of OP cultivation.

However, further research and policy reforms are needed to ensure the long-term sustainability of these practices and the conservation of tropical peatlands.

2.3. Chemical properties of tropical peat soil

Tropical peat soils are unique ecosystems that play a critical role in supporting oil palm cultivation, which is a major agricultural activity in Southeast Asia. However, their inherently challenging chemical properties such as high acidity, low nutrient availability, and poor structural stability, present significant constraints to crop productivity. In regions like Sarawak, where land scarcity has driven OP expansion into peat-dominated landscapes[20], understanding the chemical dynamics of these soils has become increasingly important.

Tropical peat soils are characterised by their high organic matter content, which is a result of the incomplete decomposition of plant material under anaerobic conditions[27,48]. This high organic matter contributes to the soil's water-holding capacity and nutrient retention, which are beneficial for oil palm growth[49,50]. Tropical peat soils are highly acidic, with pH values typically ranging from 3.0 to 4.5[11,51]. This acidity is due to the accumulation of organic acids from the decomposition of plant material under waterlogged conditions[52]. Such acidity restricts the availability of macronutrients such as phosphorus (P), calcium (Ca), and magnesium (Mg), while enhancing the solubility of potentially toxic metals like Al and iron (Fe)[53].

Potassium (K) is often the most yield-limiting nutrient in peat soils, particularly due to its high mobility and susceptibility to leaching. Studies have shown that K leaching is a major concern in tropical peat soils, such as those used for pineapple cultivation in Malaysia, where conventional fertilization practices fail to adequately quantify and manage K uptake and distribution[54]. Liming acidic soils can also reduce K leaching by altering the soil's cation dynamics, although this approach may not be as effective in peat soils as compared to mineral soils[55]. Application of water-soluble phosphate fertilisers such as triple superphosphate (TSP) has been shown to improve foliar P levels and reproductive development in oil palm[49].

According to Yang et al.[56], although tropical peat soils exhibit high cation exchange capacity (CEC) due to the organic colloidal structure, the base saturation is typically low, leading to insufficient availability of essential cations such as K^+, Ca^{2+}, and Mg^{2+}. Fertiliser response trials have demonstrated that regular application of base cations, particularly K and Mg, is essential for optimum yield performance[50]. Maintaining a base saturation level of at least 50% has been suggested for sustainable nutrient supply in peat-based systems[49]. The C:N ratio in tropical peat soils is typically high due to the dominance of C-rich organic matter. This ratio plays a critical role in microbial activity and nutrient cycling, with higher C:N ratios often leading to slower decomposition rates and reduced N availability for plants[42].

In conclusion, while tropical peat soils offer some advantages in terms of water retention and nutrient holding capacity, their chemical limitations pose significant challenges for oil palm cultivation. Key issues such as high acidity, low nutrient availability, poor base saturation, and nutrient imbalances must be addressed through well-designed and site-specific soil fertility programs.

Soil Acidity

Soil pH is a key indicator of soil reaction, which indicates alkaline or acidic. Neina[57] defined soil pH as the "master soil variable" because it impacts a multitude of biological, chemical, and physical properties of the soil, subsequently influencing plant growth and biomass production[12,58–62]. The quantity and accessibility of plant nutrients can differ depending on the soil pH level. Some plant nutrients are more accessible in acidic conditions, while others are more accessible in basic or alkaline conditions. Moreover, soil pH significantly influences the functions of soil microorganisms that are responsible for the decomposition of plant residues. Additionally, charges on soil organic matter and certain mineral surfaces can influence the CEC of the soil. However, it is important to highlight that the pH range of cultivated peat is relatively higher, as indicated in Table 7, which may be attributed to the application of fertilisers.

Soil acidification naturally happens during the process of soil formation. However, the shift from natural ecosystems to intensive cropping methods can expedite this phenomenon[63,64]. Soils originating from acidic parent materials, inherently low in essential basic cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+, may undergo acidification. Similarly, the downward movement of these cations through the soil profile due to excessive rainfall can lead to the formation of acid soils. This scenario is prevalent in regions with high rainfall, where precipitation surpasses evaporation, causing the leaching of basic cations[64]. The generation of H^+ ions during C, N, and S cycling provides an additional contribution to

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soil acidification. The generated H^+ ions during C cycling can be formed in two ways: the dissolution of CO_2 to form carbonic acid (H_2CO_3) and the dissociation of carboxylic acids released by plants and microorganisms. Mineralization and oxidation of organic N and S are major contributors to the release of H^+ ions[65]. In addition, the use of commercial fertilisers, especially those with ammonia-based components, causes soil acidification.

Soil acidity in peat soils reduces nutrient availability, which is essential for oil palm growth. Key nutrients such as P, K and Ca become less available as soil pH decreases[66]. Additionally, high acidity increases the solubility of toxic elements like Al, which can interfere with root function and nutrient uptake[67]. The solubilization of Al^{3+} in acidic soils is particularly detrimental to oil palm roots. Al toxicity can alter root morphology, reduce water and nutrient uptake, and trigger oxidative stress in plants[68,69]. This results in stunted growth and reduced yields. Acidity-induced oxidative stress can damage cellular components, including DNA, proteins, and membranes, further impairing plant growth[69]. Oil palm plants exposed to high Al concentrations exhibit increased production of reactive oxygen species (ROS), which can lead to cellular damage if not mitigated by antioxidant defenses[70]. Soil acidity in tropical peat soils significantly impacts oil palm growth by reducing nutrient availability, impairing root development, and increasing oxidative stress. However, various management strategies, such as liming, organic amendments, water management, and balanced fertilization, can alleviate these effects.

2.4. Challenges of oil palm cultivation on tropical peat soil

The OP cultivation on tropical peat soils presents several agronomic challenges due to the unique properties of peat soils and the environmental conditions of tropical regions that influence growth and yield. The inherent characteristics of peat soils, including high acidity, deep water tables, and low nutrient availability, lead to nutrient leaching, making the soil unsuitable for cultivation in its natural state[71–74]. Additionally, the physical properties of swamp soils, such as soil texture, mineral and peat maturity, pyrite layer depth, solum depth, and fluctuating water table levels, further affect soil stability, moisture availability, and root development, presenting significant challenges for oil palm establishment and long-term productivity[72].

Beyond waterlogged conditions and nutrient deficiencies, peat soils pose additional agronomic challenges, including low bearing capacity and irreversible drying characteristics. Water table management is crucial in oil palm cultivation on peat soils, as it influences nutrient leaching and reduces oil palm growth[71–78]. Nutrient leaching losses are a persistent problem in oil palm cultivation on peat soils. These losses do not only reduce the efficiency of fertiliser application but also contribute to environmental pollution through the contamination of waterways[71,78]. However, maintaining this optimal water table depth is challenging due to rainfall variability and the need for frequent monitoring.

Furthermore, peat agriculture contributes to subsidence, which alters nutrient storage and cycling, necessitates fertiliser inputs, and intensifies greenhouse gas emissions[26]. Additionally, soil subsidence reduces the productivity of oil palm plantations and exposes deeper, more labile carbon layers to oxidation, further increasing greenhouse gas emissions.

Table 4. Physico-chemical properties of peat soil and its limitation to OP growth

Chemical properties	Limitation to OP	Reference
High moisture content and water-holding capacity	High buoyancy and high pore volume lead to low bulk density and low bearing capacity.	75,76
Low bulk density	Fewer nutrient per volume and not readily available. Leaching losses of applied fertilisers on peat. Tree crops with top-heavy structures, such as OP, often exhibit leaning and falling tendencies because of inadequate root anchorage in deep peat areas.	75,77
Peat acidity (<4.0)	Reduced nutrient availability and uptake by the plants, resulting in nutrient deficiencies and decreased productivity. Affects the activity of nitrifying microorganisms.	66,78,79
High organic matter content	Fire hazard when dry. The porous structure, low density and oxygen content up to 40% in peat enable combustion processes to occur in deposits with minimal air exposure.	80
Micronutrients and macronutrients deficiency	Nutrient status exerts a strong control on above and below-ground processes, including carbon dynamics and microbial activity. The need for fertiliser application.	81

While OP is known for its high tolerance and adaptability to various soil conditions, the specific qualities of peat impose significant limitations for crop growth and yield. The growth and yield of OP demand a substantial quantity of nutrients. Given the naturally low nutrient content of peat, the necessary nutrients will mainly be supplied through fertiliser inputs. Table 5 presents the physico-chemical properties of peat soils and their related agronomic problems.

3. INTRODUCTION TO OIL PALM (*Elaeis Guineensis*)

Palm oil, derived from the pulp of OP fruit, presently stands as Malaysia's primary agricultural commodity. The palm family (*Arecaceae*), previously known as *Palmae*, belongs to the order *Arecales* within monocotyledons. OP, characterised as a perennial crop, consistently yields economically viable quantities of fresh fruit bunches (FFB) over its entire 25-year economic lifespan. OP yields fluctuate based on the plantation's age and location, experiencing an initial increase during the first seven years, stabilization between 7 to 15 years, and gradually decrease leading to replacement at 25 to 30 years[82].

3.1. Evolution of the oil palm plantation industry in Malaysia

In 1907, Fauconnier planted OP seeds for oil production at the Tennamaram estate in Batang Berjuntai, Selangor, signifying the inception of the first commercial OP plantation. This event laid the foundation for the later growth of OP industry in Malaysia. Unbeknownst to Fauconnier, the industry would experience significant growth, resulting in plantations covering an expansive 5.61 MHa (Table 6)[6]. Sarawak has the largest OP planted area among the states, covering 1.62 Mha, making it the state with the highest OP cultivation in terms of land area[83].

Table 5. Malaysia's total oil palm planted area as of December 2024

State	Total	Percentage (%)
Johor	659,820	11.8
Kedah	85,526	1.5
Kelantan	163,906	2.9
Melaka	49,902	0.9
Negeri Sembilan	179,079	3.2
Pahang	739,427	13.2
Perak	351,427	6.3
Perlis	865	0.02
Pulau Pinang	7,748	0.1
Selangor	102,980	1.8
Terengganu	164,107	2.9
Peninsular Malaysia	2,504,786	44.6
Sabah	1,483,699	26.4
Sarawak	1,624,366	28.9
Sabah & Sarawak	3,108,066	55.4
Malaysia	5,612,852	100.0

Source: Malaysia Palm Oil Board (2024)[6]

Malaysia ranks as the second-largest producer and exporter of palm oil on a global scale. The agriculture sector has a major impact on the country's economy through exports, primarily from palm oil products and other agricultural commodities. Malaysia had successfully exported around 26.66 million tonnes of palm oil and palm-based products in the year 2024. The palm oil industry generated a total revenue of about RM109 billion[6], played a substantial role, contributing RM64.6 billion to the nation's overall gross domestic product (GDP). Currently ranked as the second-largest global producer of palm oil, Malaysia commands 23% of the world's palm oil production and accounts for 31% of global exports.

3.2. Botanical features of the oil palm: Morphology and characteristics

OP morphology pertains to the physical attributes and characteristics of the OP plant. A complete grasp of botanical features of the OP is significant for the implementation of effective agronomic management practices. This knowledge enables farmers and agricultural practitioners to make well-informed decisions when it comes to nurturing and cultivating OP plantations.

Three types of OPs can be distinguished based on the thickness of the shell, namely Dura, Pisifera, and Tenera (Fig. 2). In Malaysia, the commonly planted OP species is tenera, a hybrid between the Dura and Pisifera species, chosen for its favourable ratio of palm oil to palm kernel oil yields. Unlike Dura and Pisifera, Tenera has a thinner shell[84]. It also has a smaller kernel compared to Dura and contains higher oil. Dura has a thick shell, and when it is crossed with the sterile female Pisifera that has no shell, it produces the hybrid variety Tenera. This hybrid is distinguished by its thin shell and superior oil content[85–87]. Understanding the genetic origins and characteristics of these varieties is crucial in making educated decision in OP cultivation.

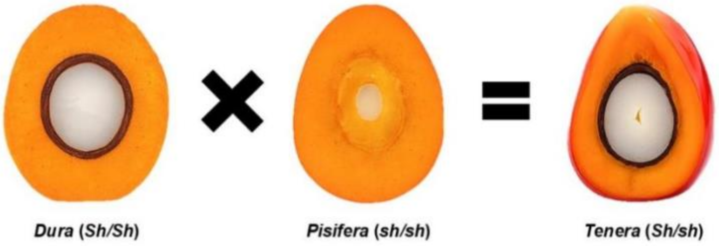

Fig. 2. Hybrid fruit forms of D × P and the monogenic inheritance of shell thickness gene

Source: Modified from Singh et al. (2015)[88]

The OP is a monoecious plant, meaning both male and female flowers are found on the same tree. The structure of the bunch consists of a peduncle, rachis, and rachillae, with approximately 30 to 60% of the flowers developing into fruits. The ratio of fruit to bunch typically falls within the range of 60 to 70%[82,89]. OP fruit production usually commences 2.5 to 3 years after planting and continues year-round. Each OP bunch weighs approximately 20 to 25 kg and consists of around 1000 to 3000 fruitlets. The fruitlets initially possess a dark purple hue, which transforms into orange red as they ripen[90]. The fruitlets consist of a hard kernel enclosed in a shell, with a fleshy mesocarp surrounding it.

The OP possesses an extensive and fibrous root system that extends from a substantial central bole (~ 0.8 metres in diameter) and delves 0.4 to 0.5 metres into the soil at the base of the trunk[91]. Most of the root mass is concentrated within the top 1 meter of the soil, while the roots that are responsible for nutrient absorption are predominantly found in the uppermost 0.5 metres of the soil[91]. The OP leaf is a crucial part of the plant that can be used to understand its nutrient status and diagnose any nutrient-related issues. The leaflets are formed through the process of dividing a complete leaf while the leaf axis is elongating. The annual leaf production of plantation palm increases to 30 to 40 at 2 to 4 years old and decreases to 20 to 25 per year after 8 years[92].

The mature OP stem, reaching heights of 25 to 30 metres, provides support for the leaves, acts as the vascular system for the transportation of nutrients and water, and serves as a storage site for carbohydrates and essential nutrients, particularly potassium[91,93]. Both young and mature tree trunks are adorned with fronds that can reach lengths up to 7 to 8 metres, lending them a rough appearance. In contrast, older trees display smoother trunks bearing scars from withered and fallen fronds. For economic reasons, usually after 25 years, OP is typically replanted with newer breeds when height exceeds approximately 10 metres[93].

This comprehensive exploration of OP morphology and characteristics underscores the intricate interplay of botanical features, providing a foundational understanding for practitioners in the cultivation and management of OP plantations.

3.3. Nutrient requirements of oil palm

OP requires adequate soil nutrients for optimum growth and development. Nutrient deficiency symptoms, poor growth, and declining yields can occur in OP plantations with low soil fertility and nutrient imbalance. The primary nutrients required by OP include N, P, K and Mg[94,95].

Table 7 presents a classification of soil nutrients based on varying ranges across different parametres. This classification serves as a practical reference guide for assessing soil fertility and guiding agricultural management decisions based on the observed nutrient levels in each category.

Various factors exert influence over the actual rates of fertiliser required for different nutrient statuses in the cultivation of OP. These factors encompass the specific nutrient needs, age of the palm, types of soil, terrain, moisture levels in the soil, and expected nutrient losses[96–98]. These considerations have an impact on both the nutrient requirements of the OP and the potential nutrient losses from the soil.

Determining the most suitable rates of fertiliser application is of utmost importance, taking into consideration these factors to ensure that the OP receives the essential nutrients for optimal growth and yield, while simultaneously minimizing losses and harm to the environment. Precise evaluation of soil nutrient levels and the implementation of management practices specifically tailored to the site enable farmers to optimize the application of fertiliser and enhance the efficiency of nutrient utilisation[99,100].

Furthermore, the selection of fertilisers, as well as the timing and frequency of application, play a significant role in influencing the availability and efficiency of nutrients. By embracing this approach, adverse environmental consequences can be diminished, thus contributing to an overall enhancement in the sustainability of OP cultivation.

Table 6. Classification of soil nutrient status for oil palm

Nutrient	Very low	Low	Moderate	High	Very high
pH	< 3.5	3.5-4.0	4.0-4.2	4.2-5.5	> 5.5
Organic C (%)	< 0.8	0.8-1.2	1.2-1.5	1.5-2.5	> 2.5
Total N (%)	< 0.08	0.08-0.12	0.12-0.15	0.15-0.25	> 0.25
Total P (µg g^{-1})	< 150	150-250	250-350	350-500	> 500
Available P (µg g^{-1})	< 10	10-25	25-40	40-60	> 60
Exchangeable K (cmol kg^{-1})	< 0.08	0.08-0.20	0.20-0.25	0.25-0.30	> 0.30
Exchangeable Mg (cmol kg^{-1})	< 0.08	0.08-0.20	0.20-0.25	0.25-0.30	> 0.30
CEC (cmol kg^{-1})	< 6	6-12	12-15	15-18	> 18

Source: Goh (2004)[101]

According to Goh[102], nutrient levels can be classified as follows:

- Very low: When nutrient levels are very low, nutrient deficiency symptoms are likely to appear, which can result in significantly reduced yields or crop failure. A definite response to fertiliser application is expected in such cases. It is recommended to increase the fertiliser rate to a corrective level to address the deficiency.
- Low: Nutrient deficiency symptoms may arise when nutrient levels are low. A fertiliser response is likely, and it is advisable to increase the fertiliser application to mitigate potential deficiencies.
- Moderate: At moderate nutrient levels, hidden hunger may occur, and plants may respond to additional fertiliser. It is suggested to either maintain the current fertiliser rate or slightly increase it to optimize growth and yield.
- High: When nutrient levels are high, no response to additional fertiliser input is expected. It is recommended to reduce the fertiliser rate. However, maintaining soil fertility should still be prioritized, especially if the grower has the means to do so.
- Very High: Very high nutrient levels may result in nutrient imbalances or induce deficiency symptoms in some cases. In such instances, fertiliser input is generally unnecessary, except when used to correct specific nutrient deficiencies or imbalances.

4. LIMING PRACTICES FOR SOIL IMPROVEMENT

To mitigate soil acidity, several approaches are employed, including the addition of chemical ameliorants[103–106] and/or organic materials[107,108], both of which provide liming effects. Additionally, the use of acid-tolerant cultivars[109] and improved agricultural practices[110] can help to alleviate the challenges posed by high acidity. Among the chemical ameliorants, finely-ground calcitic lime ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are commonly used for acidic soils, which are often referred to as the workhorse in acidic soils[111], with gypsum ($CaSO_4.2H_2O$) also being utilised. The reduction of soil acidity by lime occurs in two stages. Initially, Ca and Mg replace hydrogen ions on exchange sites, forming bicarbonate. Then, bicarbonate reacts with hydrogen ions to produce CO_2 and water, which, in turn, increases the soil pH. Lime application also increases the availability of exchangeable Ca and Mg in the soil[111].

In a recent incubation experiment conducted by Kanang et al.[112], lime application markedly increased the soil pH from 3.2 to 7.5, demonstrating the strong neutralizing effect of lime under highly acidic conditions. However, increasing lime rates beyond 6 t ha^{-1} did not further elevate pH, indicating a plateau response typical of peat soils due to their high buffering capacity and organic matter content. The study also showed that liming significantly affected nitrogen dynamics, enhanced total Ca concentration, and slightly increased total N, P, K, and Mg in the peat soil. These improvements suggest that lime application not only corrects soil acidity but also enhances nutrient availability and plant growth conditions. Therefore, combining lime with a balanced fertilization programme is crucial to maintain a continuous nutrient supply and sustain crop productivity in tropical peatlands.

Previous studies have also reported similar outcomes. Liming improves soil pH, nutrient uptake, and crop yield, while reducing the solubility of toxic metals such as Mn and Al[113–115]. Beyond chemical effects, lime contributes to better soil biological and structural health. It enhances nitrification and N mineralization[116], stimulates microbial activity and organic matter decomposition[117], and promotes earthworm colonization, which improves soil aggregation and porosity[118,119]. Collectively, these findings highlight lime as a key soil conditioner that restores soil chemical balance, improves nutrient cycling, and supports sustainable crop growth on tropical peat soils.

4.1. Lime requirement for peat soil

The lime requirement for peat soil in oil palm cultivation is a complex issue influenced by the unique properties of peat soils, such as high acidity and low nutrient availability. Recent studies in Sarawak found that the soil pH in tropical peatlands is very low, ranging from 3.3−3.5[11,120]. The uppermost layers of newly formed peat exhibit a notable deficiency in minerals, resulting in poor cation content and hence, extreme acidity[48]. Soil acidity also hampers important processes such as mineralization, nitrification, and N fixation[121].

Lime application is necessary for agricultural activities in peat soils due to their natural conditions. Lime requirement refers to the amount of liming material needed to raise soil pH to a specified level, thereby enhancing crop yields. However, determining the appropriate lime requirement for peat soils is challenging due to their distinct chemical characteristics and the potential for peat subsidence when lime is applied. The factors that can influence the effectiveness of lime application include original soil pH and peat heterogeneity[122–124]. Studies have demonstrated that lime application results in the highest soil pH compared to untreated control soils[122,123,125,126]. Acidic conditions can inhibit microorganism mineralization, which can limit the availability of major plant nutrients for uptake. Microorganisms involved in mineralization require a specific pH range in soils to operate effectively[127]. Soil with a pH below 5.5 is classified as infertile due to the toxic effects of Al, manganese (Mn) and hydrogen (H)[128]. This process uses the reduction of Al, Fe, Mn, and sulphate ($SO^{2-}{}_4$) hazardous compounds in soils contaminated with toxic elements, to improve soils that can support agricultural activities[129]. Simultaneously, the primary plant nutrients that are essential for growth are rendered less available under low soil pH. According to Ambak[125], the application of 8 tonnes per hectare of lime improved the number of fruits, dry weight of fruit and harvesting index maximally.

4.2. Liming and nutrient availability in acidic soils

Agricultural activities, including the use of ammonium (NH_4^+) and S fertilisers in the soil, plant nutrient uptake, decomposition of organic matter, acid rain, poor irrigation water systems, and land-use change, can decrease soil pH. Lime (either as calcitic or dolomitic limestone) is used to reduce soil acidity by reacting with H ions. It reacts slowly, so the soil pH changes gradually. Carbonate anions are formed from the lime and H ions, and the pH increases. The reaction is represented as $CO_3^{2-} + 2H^+ \rightarrow CO_2 + H_2O$. The addition of lime neutralizes soil acidity[130].

The soil pH plays a crucial role in nutrient availability, as different nutrients respond differently to different pH levels. Soil pH between 5.7 and 6.5 is considered the optimal range for plant growth, ensuring the availability of all plant nutrients[131]. However, the optimal pH for a specific crop may vary depending on its unique nutrient requirements and the limiting nutrient(s) under specific conditions[132]. Liming acid soil has profound effects, especially on soil pH, exchangeable Ca, extractable P, and effective CEC, and reduces exchangeable Al and Mn[17, 133]. The lime application increases P availability in soil by solubilizing soil organic matter and mineralizing organic P during dissolution[134]. Overliming, however, has the potential to decrease the accessibility of micronutrients such as Fe, Mn, Zn, Cu, and B, thus resulting in the occurrence of critical micronutrients deficiencies[111]. Therefore, due to the antagonistic effect of Ca and Mg on K uptake, overliming can lead to K deficiency in soils[135]. Hence, applying lime at an optimum rate is crucial to enhance nutrient availability and improve plant productivity.

5. CONCLUSION AND RECOMMENDATIONS

Liming has proven effective in improving the chemical, biological, and structural properties of peat soils. It increases soil pH, enhances nutrient availability (particularly Ca, Mg, K and P), and reduces the solubility of toxic elements. In addition, liming promotes microbial activity, stimulates nitrification and N mineralization, and improves soil aggregation through better biological activity and root development. However, excessive lime application can induce micronutrient deficiencies (Fe, Mn, Zn, Cu, and B) and disrupt nutrient balance due to the antagonistic effects among cations.

The overall findings highlight that liming is necessary to alleviate peat soil acidity and optimally increase beneficial nutrients for crop growth. Determining the optimal lime rate is crucial to avoid liming, which can be detrimental to the chemical and biological ecosystem of peat soil. A complementary fertiliser programme to overcome micronutrient deficiencies in peat soil is also recommended. Moreover, it is important to consider not only soil pH but also other factors, such as soil management practices and the ecosystem conditions within the plantation, particularly when evaluating soil nutrient status and plant nutrient uptake.

Key recommendations include implementing optimal liming practices based on site-specific soil conditions, adopting integrated soil management approaches that address both macro- and micro-nutrients needs, regularly monitoring soil conditions, and considering broader ecosystem conditions within the plantation.

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7. CONFLICT OF INTEREST

We hereby declare that there are no competing interests.

8. AUTHORS' CONTRIBUTIONS

Conceptualization: K.D Kanang, H. Mohidin
Data curation: K.D Kanang
Methodology: K.D Kanang
Visualization: K.D Kanang; H. Mohidin
Writing (original draft; review and editing): K.D Kanang, H. Mohidin
Validation: H. Mohidin
Supervision: H. Mohidin
Project administration: K.D Kanang

9. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT in order to proofread and improve readability and language quality. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

10. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

No data/Theory-based: Data sharing is not applicable to this article as no new datasets were generated or analysed during the current study.

11. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. The study is theory-based and complies with applicable academic and ethical standards.

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