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Soil Moisture Dynamics and Groundwater Quality under Oil Palm Cultivation in Tropical Peatlands

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Soil Moisture Dynamics and Groundwater Quality under Oil Palm Cultivation in Tropical Peatlands

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Oil palm plantation (OPP) establishment on peatland requires drainage, soil compaction as pre-requisite and fertilizer application for high oil palm yield. However, the effect of these activities on the environment is still understudied, particularly in OPP under tropical peatlands. Hence, to ensure sustainable oil palm production, this study evaluates soil moisture dynamics and groundwater quality under oil palm plantation on tropical peatland. A field-based comparative study was conducted at twelve sampling points (Q1-Q12) within an OPP planted on peat soil and grouped according to planting year, with an adjacent drained secondary forest (DSF) used as a control. Soil bulk density (BD), water table (WT), and soil moisture content (SMC) were measured at depths of 0–100 cm to evaluate the influence of compaction and drainage. Long-term groundwater quality data (2011–2017) were combined with post-replanting data (2021–2022) to assess changes in groundwater nutrients associated with plantation activities. Results showed that soil BD was lowest in the DSF (0.03–0.14 g cm^{-3}), suggesting the effect of high total C and N, and minimal soil compaction compared to OPP zones. Significant differences in SMC obtained via the Least Significant Difference (LSD) test were observed between OPP sites and the DSF at 10–40 cm depth ($p < 0.05$), demonstrating the influence of soil compaction. Across plantation areas, SMC increased with depth due to peat submergence below the WT. Groundwater monitoring indicated higher concentrations of K^+ and Cl^- in the OPP compared to the DSF, consistent with fertilizer leaching. Elevated groundwater pH and NO_3^- concentrations following replanting suggest reduced soil organic matter and adsorption capacity following land clearing and altered redox conditions. Correlation and regression analyses revealed that SMC was significantly related to groundwater electrical conductivity, PO_4^{3-}, Cl^-, K^+, and NH_4^+ concentrations. Overall, the findings indicate that SMC dynamics, regulated by soil compaction and drainage, play a key role in controlling nutrient transport from peat soils to groundwater. These results highlight the importance of integrated soil and water management strategies to support sustainable oil palm production on tropical peatlands.

Keywords: Water table, nutrient leaching, replanting, linear regression, oil palm sustainability

Dinamik Lembapan Tanah dan Kualiti Air Tanah dalam Penanaman Kelapa Sawit di Tanah Gambut Tropika

ABSTRAK

Penanaman kelapa sawit (OPP) di tanah gambut memerlukan sistem saliran, pemadatan tanah sebagai prasyarat serta aplikasi baja bagi mencapai hasil kelapa sawit yang tinggi. Walau bagaimanapun, kesan aktiviti-aktiviti ini terhadap alam sekitar masih kurang dikaji, khususnya bagi OPP di tanah gambut tropika. Oleh itu, bagi memastikan pengeluaran kelapa sawit yang mampan, kajian ini menilai dinamik kelembapan tanah dan kualiti air tanah di ladang kelapa sawit di tanah gambut tropika. Satu kajian perbandingan berasaskan lapangan telah dijalankan di dua belas titik pensampelan (Q1–Q12) dalam OPP yang ditanam di tanah gambut dan dikelaskan mengikut tahun penanaman, dengan hutan sekunder bersaliran (DSF) yang bersebelahan digunakan sebagai kawalan. Ketumpatan pukal tanah (BD), paras air tanah (WT) dan kandungan kelembapan tanah (SMC) diukur pada kedalaman 0–100 cm bagi menilai pengaruh pemadatan dan saliran. Data jangka panjang kualiti air tanah (2011–2017) digabungkan dengan data pasca-penanaman semula (2021–2022) bagi menilai perubahan nutrien air tanah yang berkaitan dengan aktiviti ladang. Hasil kajian menunjukkan bahawa BD tanah adalah paling rendah di DSF (0.03–0.14 g cm^{-3}), mencadangkan kesan kandungan karbon (C) dan nitrogen (N) dalam jumlah yang tinggi serta tahap pemadatan tanah yang minimum berbanding zon OPP. Perbezaan signifikan dalam SMC yang diperoleh melalui ujian signifikan LSD antara OPP dan DSF pada kedalaman 10–40 cm ($p < 0.05$), menunjukkan kesan pemadatan tanah. SMC meningkat dengan kedalaman tanah di OPP kerana tanah terendam di bawah paras air tanah. Pemantauan air tanah menunjukkan kepekatan K^+ dan Cl^- yang lebih tinggi di OPP berbanding DSF, selaras dengan proses larut resap baja. Peningkatan pH air tanah dan *kepekatan* NO_3^- *selepas penanaman semula menunjukkan pengurangan bahan organik tanah dan kapasiti penjerapan berikutan penebangan pokok dan tindak balas redoks. Analisis korelasi dan regresi menunjukkan bahawa SMC mempunyai hubungan yang signifikan dengan kekonduksian elektrik air tanah serta kepekatan* PO_4^{3-}, Cl^-, K^+ *dan* NH_4^+.*Secara keseluruhan, dapatan kajian menunjukkan bahawa dinamik SMC, yang dikawal oleh pemadatan tanah dan saliran, memainkan peranan penting dalam mengawal pengangkutan nutrien daripada tanah gambut ke air tanah. Hasil kajian ini menekankan kepentingan strategi pengurusan tanah dan air secara bersepadu bagi menyokong pengeluaran kelapa sawit yang mampan di tanah gambut tropika.*

Kata kunci: *Paras air tanah, larut lesap nutrien, penananam semula, regresi linear, kelestarian kelapa sawit*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

OPP	Oil Palm Plantation
BD	Bulk Density
DSF	Drained Secondary Forest
HP	Harvesting Path
PC	Palm Circle
PR	Planting Row
SMC	Soil Moisture Content

CHAPTER 1

INTRODUCTION

1.1 Study Background

Oil palm (*Elaeis guineensis*) is planted and grows in the humid tropics of Africa, Latin America and Asia. In Malaysia, peatlands cover large areas of land and a considerable portion has been developed for agriculture, including the establishment of oil palm plantations (OPP) on peat soils. The oil palm tree has become the best choice as an agricultural crop in Malaysia due to its capability to yield high amounts and good quality of vegetable oil in a small-cultivated area, as the country has limited agricultural land and needs to preserve its tropical forests.

Anthropogenic activities such as soil compaction and drainage are required for oil palm establishment. Land use plays a key role in controlling spatial and temporal variations in soil moisture by influencing infiltration rates and evapotranspiration. Numerous studies have examined the impacts of anthropogenic activities on soil physicochemical properties, particularly soil moisture content (SMC). Despite this, research examining the relationship between oil palm cultivation and soil water use remains limited.

Water availability strongly influences oil palm growth and yield, with rainfall serving as the primary water source and periodic water limitations occurring under certain conditions. In peat soils, drainage and compaction alter soil–water dynamic which could influence oil palm performance. Therefore, sustainable oil palm cultivation on tropical peatlands requires effective soil and water management practices. Nonetheless, information on the spatial and temporal distribution of soil moisture in tropical peatlands, especially under OPP, remains scarce.

In addition, OPP management involves replanting and the application of mineral fertilizers to achieve optimum yields. Poorly managed replanting and fertilization practices may contribute to water quality degradation. While previous studies have documented the effects of oil palm cultivation on groundwater quality, evidence on the long-term impacts of OPP on groundwater quality remains limited.

1.2 Problem Statement

Despite widespread oil palm cultivation on peatlands, there is limited understanding of how long-term OPP management affects soil moisture dynamics and groundwater quality. The combined effects of soil compaction, drainage for water table (WT) management, and fertilization on nutrient leaching remain poorly understood. Additionally, replanting cycles may exacerbate nutrient losses and alter soil-water interactions, yet research on these long-term impacts is scarce. This knowledge gap hinders the development of effective management strategies that balance high productivity with peatland conservation and groundwater protection. Thus, this study aims to evaluate the effects of the long-term establishment of oil palm on the parameters mentioned above, including soil moisture content, nutrient leaching, and groundwater quality. The outcome of this research will guide plantation management and relevant authorities in managing and monitoring sustainable oil palm activities, especially regarding peat soil moisture and groundwater quality. Specifically, the research questions are as follows:

i. How do soil compaction and drainage affect soil moisture content up to 100 cm soil depth in OPP compared to DSF?
ii. How do replanting and long-term fertilizer applications influence groundwater quality?

iii. What is the statistical correlation between soil moisture content and groundwater quality?

1.3 Research Hypothesis

The research hypotheses of this study are as follows:

i. Soil compaction and drainage for water table management in the OPP increases soil bulk density and reduces soil moisture content up to 100 cm soil depth compared to the drained secondary forest.

ii. Oil palm tree replanting and long-term fertilizer application increase groundwater nutrient concentration due to soil nutrient leaching, which deteriorates groundwater quality.

iii. The optimum level of soil moisture content for oil palm trees (30–75%) enhances nutrient leaching into groundwater, thereby affecting groundwater quality.

1.4 Objectives

The objectives of the research study are:

i. To determine soil moisture content up to 100 cm soil depth between OPP and DSF under drainage conditions and after soil compaction.

ii. To quantify groundwater quality parameters between OPP and DSF after replanting and fertilizer applications.

iii. To analyse the statistical correlation between soil moisture content and groundwater quality.

1.5 Research Significance

Currently, research on SMC distribution is limited, particularly at deeper soil layers critical for oil palm tree growth. Most existing studies focus only on the surface layer and rely heavily on satellite-derived data, which does not adequately represent moisture conditions below the surface. Furthermore, the influence of key factors such as soil compaction and water table fluctuations on SMC, especially up to a depth of 100 cm, critical for oil palm trees, remains underexplored. Comparative data with drained secondary forests (DSF) are also scarce. To address these gaps, this study utilizes in-situ soil moisture probes to measure SMC up to 100 cm depth, enabling a more accurate assessment of subsurface moisture dynamics. The effects of soil compaction and drainage (water table management) on SMC within OPP were evaluated with the data from DSF, as the control study.

In addition, there is a lack of long-term research on groundwater nutrient dynamics under established OPP, particularly in tropical peatland ecosystems. Understanding these dynamics is crucial to identify trends, capture seasonal variation and fully assess the impacts of agricultural practices that may not be immediately apparent. This study narrows this gap by analysing over seven years of groundwater nutrient data, comparing conditions between OPP and DSF sites, by considering the effect of replanting and fertilizer application.

Lastly, critical knowledge gaps remain in understanding solute transport in peat soils. Specifically, there is limited quantitative research on how SMC dynamics influence nutrient leaching and transport to groundwater. To address this, the study applies Pearson correlation and linear regression analysis to evaluate the relationship between SMC and groundwater nutrient concentrations. Based on statistically significant correlations, linear regression predictive models are constructed to support water quality monitoring.

1.6 Study Scope

The study was conducted under tropical peatland in an OPP ecosystem and a drained secondary forest. Peat soil and peat groundwater samples were collected from the oil palm plantation sampling points and drained secondary forest for laboratory analysis. Environmental data obtained such as rainfall and water table were all under tropical peatland conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Oil Palm

Oil palm (*Elaeis guineensis*) is a tropical, perennial crop mainly cultivated for its vegetable oil and is composed of palm oil and kernel oil. Palm oil is derived from the mesocarp, whereas kernel oil is derived from the endosperm or kernel (Goh et al., 2017). Oil palm thrives in humid tropics as an equatorial crop and demands high temperatures in which the best mean temperature range is 24ºC – 28 ºC. At high elevations or geographical limit of about 15°N oil palm may be growing with a minimum temperature of less than 20 ºC for part of the year (Corley and Tinker, 2003). Well-drained soil, with high organic matter content and adequate water-holding capacity is the most suitable for oil palm cultivation (Behera et al., 2022). Oil palm is also one of the most rapidly expanding equatorial food and biofuel crops in the world and the increasing demand for vegetable oil will remain the main driver of oil palm sector development (Schrier-Uijl et al., 2013; Lesage et al., 2021). Vegetable oils produced from oil palm are used for the production of foods, oleochemicals, medicinal and health products, household products, and industrial products. About 16% of world palm oil is converted to biodiesel (Goh et al., 2017).

Palm oil production is mostly concentrated in Southeast Asia, especially in Indonesia and Malaysia (Xu et al., 2020; Zhao et al., 2024). Malaysia is the second largest producer of world palm oil with a share of 23.3% of the total production (Malaysian Palm Oil Council, 2024). The development of oil palm plantations in Malaysia is not new as oil palm has been successfully planted on peat soils for two generations (planting cycles), moving into the third. In the state of Sarawak, peatland has been developed progressively since the 1990's due to the limited suitable arable land, where drainage and mechanical compaction have become prerequisites. In Peninsular Malaysia, oil palm plantations are largely concentrated in coastal and low-lying areas that are biophysically for oil palm production. However, the continued rise in global palm oil demand is expected to intensify pressure on remaining tropical forests, further limiting the availability of arable land, particularly in Sarawak. Consequently, peatland has become an increasingly important resource for supporting agricultural expansion, rural development, and the state's economic growth (Melling et al., 2008; Sangok et al., 2017; Shevade & Loboda, 2019).

Beyond Southeast Asia, future oil palm expansion is also anticipated in countries such as Brazil, Nigeria, Colombia, Ivory Coast, the Democratic Republic of Congo, and Ghana (Zhao et al., 2024). Given these global trends, assessing the environmental impacts of oil palm cultivation is crucial for conserving ecosystems and ensuring the long-term sustainability of oil palm production.

2.1.1 Soil and Water Management Under Oil Palm Plantation

Good soil management is essential for continuous and successful oil palm cultivation on the same piece of land for nearly a century or into the fourth generation of cropping. The main purposes of soil management are to maintain and improve soil fertility and productivity for sustainable crop growth and high yields. The basic principles for soil conditions conducive to crop productivity such as good anchorage for crops, sufficient soil volume for rooting activity and supply of adequate essential nutrients and water throughout each and every crop cycle (Goh et al., 2016). OPP establishment involves land clearing, road and drainage network construction, oil palm nursery, planting and management of immature and mature trees until replanting (Corley & Tinker, 2003). In selecting planting sites, those that have high site yield potential, require less input and have fewer problems in crop recovery are preferred (Goh et al., 2017). Land clearing for oil palm cultivation by mechanical methods such as chainsaws and bulldozers starts after site selection, and the felled vegetations are burnt or allowed to rot. The general layout of an oil palm plantation is dependent on the topography, drainage, palm oil mill and the distance to transport fresh fruit bunch (FFB) to the nearest road (Corley & Tinker, 2003). After land clearing and field planting of oil palm, leguminous cover crops are established quickly to improve soil fertility and organic matter; suppress weeds; conserve soils and water; and enhance soil physical properties such as infiltration rate (Goh et al., 2017).

Water management is crucial for oil palm cultivation because excess or deficit of water can cause stress to the oil palm, which is highly detrimental to crop yields (Afandi et al., 2017). For example, effective water management on peat land for oil palm cultivation needs to be emphasized for optimum and sustainable oil palm productivity and peat conservation (Ginting et al., 2016). In oil palm plantations, the main objective of water management is to retain the optimum water table, drain out excess water as well as avoid prolonged flooding periods, and avoid irreversible drying of peat surfaces. To construct efficient drainage systems, hydrology information and moisture characteristics of peat are important (Othman et al., 2010). Good prediction of prevailing soil water deficit is important in oil palm irrigation (Bakoume et al., 2013).

Water table control is important for effective water management. For example, a drainage system for water table management is needed to convert water-logged peat swamps suitable for agriculture and land use (Ritzema, 2007). In addition, soil compaction is one of the most important keys for water management to sustain peat moisture (Melling & Chaddy, 2016). For instance, Loso et al., (2021) concluded that drainage treatment could increase the soil moisture content in an oil palm plantation.

However, previous studies found that water table management in peatlands directly affects soil and water nutrient availability. Drainage and water table fluctuation could influence soil moisture which could also influence soil chemical properties. For example, a study by Marwanto et al., (2018) conducted analyses for soil solution from oil palm plantations in Indonesia has concluded that water table movement in the oil palm plantation controls the fluctuations of soil solutions chemical compositions. High pH and ion concentrations would be influenced by enhanced microbial activity due to the water supply from the risen water table. Another example is the designated soil column study by Kassim et al. (2019) which assessed the dynamics of soil nutrients under a fluctuating water table and found that water table fluctuations allow the gradual release of soil exchangeable cations K, Ca, Mg and Na. Water table fluctuations cause continuous shifting of aerobic and anaerobic conditions which could lead to soil biogeochemical changes that could affect the cycling of nutrients in the peat soil system.

2.1.2 Oil Palm Plantation Ecosystem Function

Ecosystem functions include physical, chemical, and biological processes like carbon and nutrient cycling, climate regulation, water functions, and providing wildlife habitats. Oil palm plantations act as ecosystem units (Figure 2.1), consisting of a mill and palm stands at various development stages, from land clearing to economic maturity (Anderson, 2008). Key elements include plant production (P), total respiration (R), and material balances involving fuels, greenhouse gases, nutrients, and water including particulate organic matter (POM) and dissolved organic matter (DOM). These balances indicate sustainability and environmental impact. The ecosystem's function can be assessed through inputs and outputs of water (leachates, suspended solids), nutrients (nitrogen fixation, fertilizers), gases (CO_2, NOx, CH_4, smoke aerosols), materials (inputs of fossil fuels, pesticides) and outputs of palm oil and biomass. Sustainable management practices, such as the recycling of materials within the plantation boundary, help maintain balance within the ecosystem.

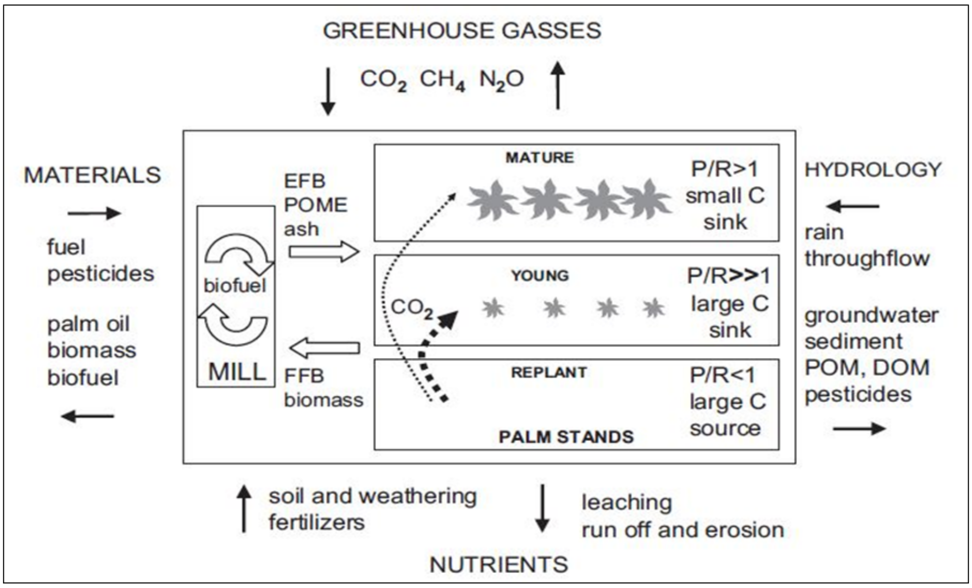


Figure 2.1: Adopted from Anderson, 2008

Soil-available nutrients or fertilizer nutrients that are not taken up by palm or adsorbed onto soil particles are dissolved and lost through surface run-off, volatilization, denitrification and leaching. In oil palm plantations, the greatest potential for nutrient losses is expected after land clearing when the soil surface is exposed to erosion and uncontrolled surface run-off losses. Besides, nutrient losses are greater in steep topography and little soil conservation measures result in erosion and uncontrolled surface wash. Thus, proper assessment must consider the temporal and spatial aspects of the potential of nutrient losses (Goh et al., 2003).

For peat soil, leaching losses of applied fertilizers are expected to be high due to the very high porosity (Melling et al., 2008). Arable cropping systems in the tropics have a high nutrient input-to-output ratio as a large proportion of biomass is harvested and soil disturbance from tillage results in higher nutrient leaching (Anderson, 2008). Leaching losses occur when nutrients are dissolved into drainage water as it percolates through the soil profile. Soil pore size, rainfall intensity, initial soil water content, amount and timing of fertilizer application affect nutrient losses by leaching. In older palms, leaching losses are generally larger probably because larger amounts of fertilizer have been applied (Goh et al., 2003).

2.2 Introduction to Peatlands

Peatlands are terrestrial wetland ecosystems in which waterlogged conditions prevent plant material from fully decomposing. As a result, the production of organic matter exceeds its decomposition, which results in a net accumulation of peat (International Peatland Society, 2024), forming a soil matrix that slows down water movement across the peatland basin (Loisel & Gallego-Sala, 2022). Peatlands are also carbon-rich ecosystems that store and sequester more carbon than any other type of terrestrial ecosystem, which exceeds even the global above-ground carbon stock of forest ecosystems (International Peatland Society, 2024). Peat formation is strongly influenced by climatic conditions and topography. In northern latitudes or high altitudes, the temperature may be high enough for plant growth but too low for vigorous microbial activity. Significant areas of peatlands are found in tropical and subtropical latitudes where high plant productivity combines with slow decomposition as a result of high rainfall and humidity (Parish et al., 2008).

Drained peatlands make up about 16% of the world's peatlands or 0.5% of the Earth's terrestrial surface (International Peatland Society, 2024). Peat drainage leads to peat oxidation such as intensified soil decomposition due to dry, aerobic conditions that promote microbial activity and carbon dioxide (CO_2) emissions (Loisel & Gallego-Sala, 2022). Over time, peatland drainage also results in soil compaction and subsidence, making it difficult to restore proper hydrology without water table management (International Peatland Society, 2024). As important carbon sinks, peatlands degradation mainly due to the lowering of the water table, has an adverse effect on the carbon cycle and largely burdens the atmosphere (Omar et al., 2022).

The majority of the world's peatlands occur in boreal and temperate parts of the Northern Hemisphere, especially, Europe, North America and Russia where they have formed under high precipitation-low temperature climatic regimes (Figure 2.2). In the humid tropics, regional environmental and topographic conditions enable peat to form under conditions of high precipitation and high temperature in Southeast Asia, mainland East Asia, the Caribbean, Central America, South America, Africa, parts of Australasia and a few Pacific Islands. Most tropical peatlands are located at low altitudes where rain forest vegetation grows on a thick layer of organic matter although some are found in upland or mountainous areas where peat can exceed 30 m. The largest area of tropical peatland is in Southeast Asia (International Peatland Society, 2024). According to Melling (2016), Malaysia has approximately 2.6 Mha of peatlands, of which about 70 % (approximately 1.6 Mha) are in Sarawak (Figure 2.3). The topo-morphology of tropical peatland is strongly influenced by the hydrological conditions, which then determine the vegetation structure, species composition, and peat type. However, to date, tropical peatland in Malaysia is still a largely unknown ecosystem and one of the understudied environments in the world.

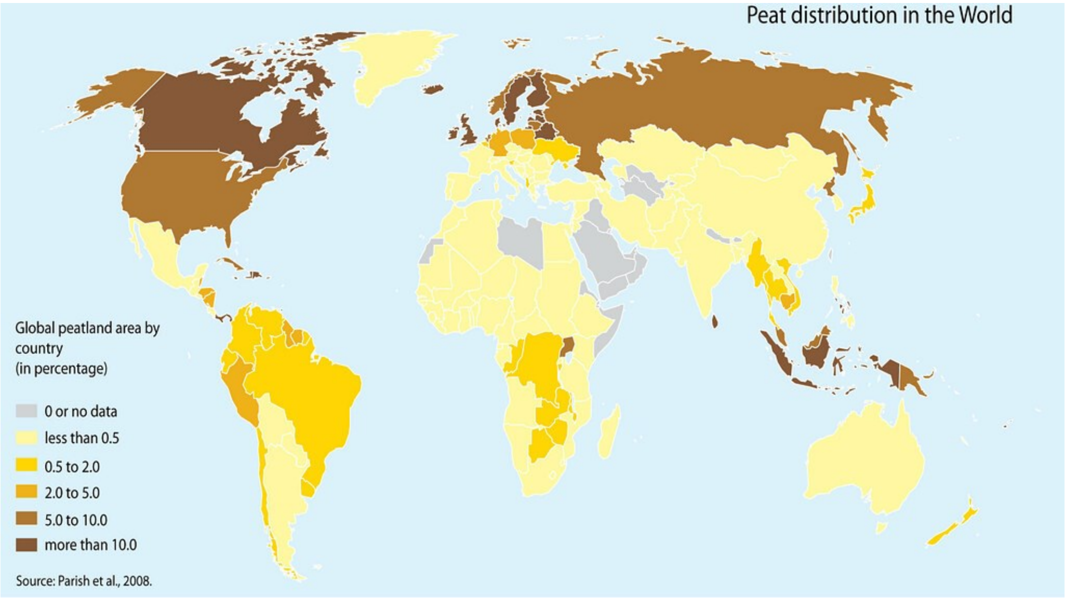


Figure 2.2: Global peatland distribution (Parish et al., 2008)

Figure 2.3: Peatland distribution in Malaysia (Melling, 2016)

2.2.1 Peatland Hydrology

Precipitation that falls on the land surface enters several pathways of the hydrologic cycle (Figure 2.4). Rain infiltrates the ground by seeping into porous surface soil. Below the land surface, soil pores contain both air and water within the vadose zone. Soil moisture, or vadose water, refers to the water stored in this zone and absorbed by the rootlets of growing plants. As plants use this water, they release it to the atmosphere through transpiration. Under certain conditions, water flows laterally within the vadose zone and migrates back to the land surface, where it evaporates. When soil moisture exceeds field capacity, gravity pulls the excess water downward through a process known as gravity drainage (Fetter, 1994).

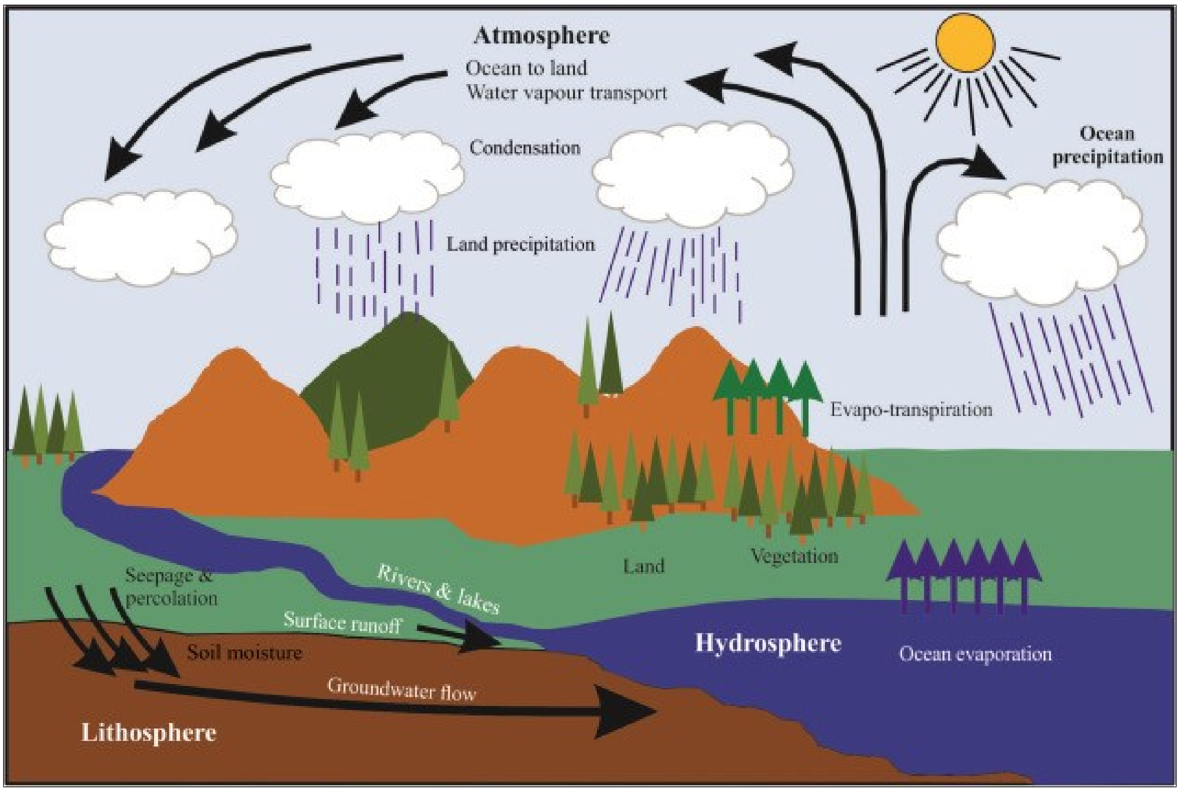


Figure 2.4: The hydrological cycle (Singh, A. A., & Singh, A. K, 2021)

Groundwater (Figure 2.4) occurs at varying depths below the Earth’s surface and plays a crucial role in sustaining human populations and aquatic ecosystems (Sen, 2014; Kellner et al., 2015). Brady and Weil (2004) explain that as drainage water moves downward and exits the soil, it eventually reaches a zone in which water completely fills the soil pores. This saturated zone overlies an impervious soil horizon or a layer of impermeable rock or clay. The upper surface of the saturated zone defines the water table, while the water stored within the saturated zone constitutes groundwater (Fetter, 1994).

On the other hand, surface water is stored in ponds, lakes, rivers, and streams. Surface-water hydrology focuses on drainage basins, which are land areas where water flows toward a specific discharge point, defined by topographic boundaries. In groundwater hydrology, a groundwater basin refers to the subsurface volume where water flows toward a discharge zone, outlined by groundwater divides. Surface water and groundwater basins may not coincide, but their water budgets must account for both. Hydrologic inputs include precipitation, surface-water inflow (streams, overland flow), groundwater inflow, and water imported via pipes or canals, while hydrologic outputs include evapotranspiration, surface water evaporation, surface runoff, groundwater outflow, and water exported through canals. Water movement through the hydrologic cycle, powered by solar energy via heat transfer, is crucial for Earth's heat balance. The hydrologic equation quantifies this process, based on the law of mass conservation may be expressed as (Fetter, 1994):

$$\text{Inflow} = \text{Outflow} \pm \text{Changes in Storage} \qquad \text{Equation 2.1}$$

In tropical peatlands of Southeast Asia, especially regions with maritime continent boundaries, water is mainly supplied by rain (Figure 2.5). Sea water evaporation brings water in cloud form to the land, and the rain produced contains extremely low amounts of nutrients. The sea and rivers supply nutrients and clay respectively by tidal effects, although the effects are insignificant. The nutrient supply in the dome of tropical peatland is very limited over the long term as the water supply in the dome-type peatland depends on only rainfall. Due to CO_2 solubilization, the rain is acidic with a pH value of 5.6. The low-pH rain leaches nutrients such as Na^+ and K^+ quickly. This nutrient balance pattern is the main reason for peat dome formation (Osaki et al., 2021). In addition, plant material in tropical peatlands accumulates under waterlogged conditions and develops into a dense organic soil layer (Apers et al., 2021).

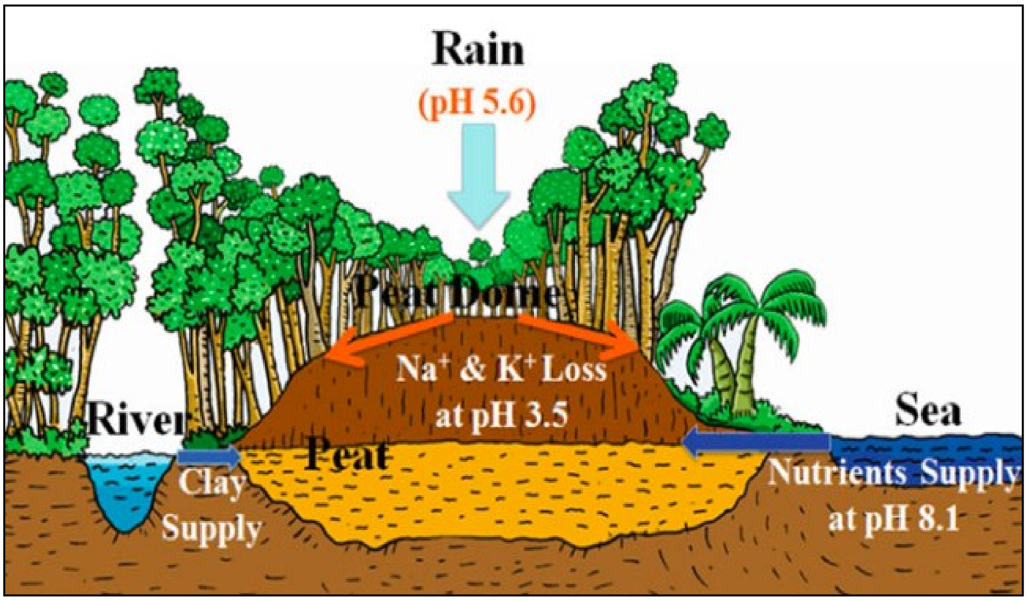


Figure 2.5: Water and nutrient supply system for the peatland (Osaki et al., 2021)

In the formation and functioning of peat swamp ecosystems, hydrology is an important factor, which depends on the climate, topographic conditions, natural subsoil and drainage base. In a peat swamp, the general water balance can be expressed as follows (Ritzema, 2007):

$$P = E + Q + \Delta S \qquad \text{Equation 2.2}$$

where:

P = total rainfall (m)

E = total evapotranspiration (m)

Q = total discharge (m)

ΔS = change in storage (m)

The WT in peat swamps rises with rainfall and falls as a result of evapotranspiration and the outflow of excess water. The fluctuation of WT in a peat swamp depends mainly on rainfall due to fairly constant evaporation and groundwater outflow. Nevertheless, the self-regulating hydrology of tropical peatlands could be disturbed by factors such as artificial drainage, land use change and climate change (Apers et al., 2021).

Hydrology is the dominant factor affecting the formation and functioning of peatland ecosystems by influencing nutrients flow. Knowledge of the topo-hydrological characteristics of the peatlands is notably important for understanding the physical and chemical properties of the peat. An understanding of the variability of peat properties in tropical peatlands is critically needed to formulate the strategies for conservation and sustainable management of tropical peatlands (Melling, 2016).

2.2.2 Soil and Nutrient Solute Transport

Most elements in soil are readily available in their exchangeable or soluble forms. (Caron & Riviere, 2002). However, soil nutrients may be lost by leaching and volatilization or taken up by the crop. Figure 2.6 depicts the nutrient transfer centred on the water-soluble form and involves processes assessed by biological and chemical indicators (Parent & Khiari., 2002). The amounts of nutrients removed are controlled by soil moisture, temperature, organic matter content, acidity, aeration, depth to impermeable layer, patterns and seasonality of rainfall, and microbial interactions. Anthropogenic activities such as soil management, crop selection and fertilizers also contribute to soil nutrient loss (Parent & Khiari., 2002).

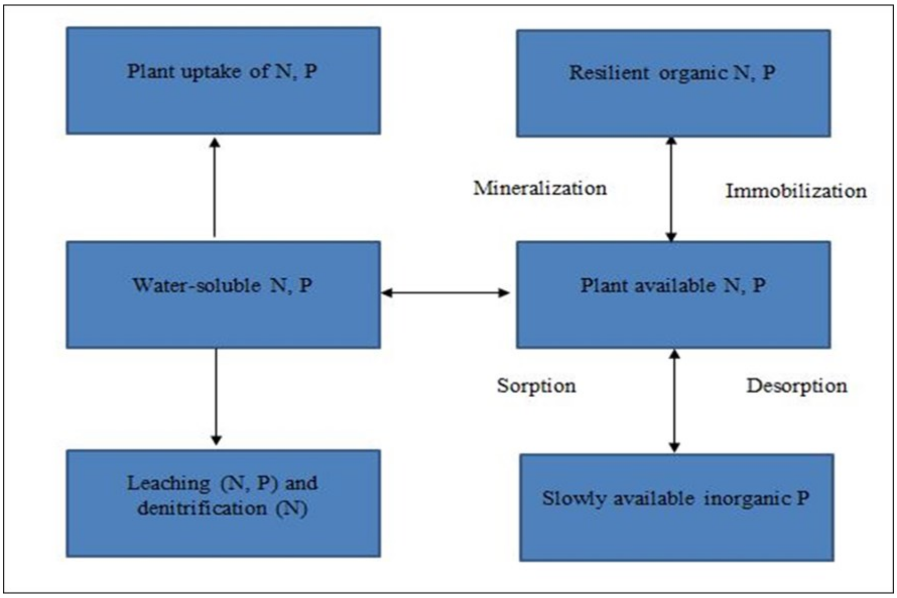


Figure 2.6: Nutrient transfer model (Parent & Khiari, 2003)

Infiltrating water dissolves additional solutes such as decomposed organic matter, fertilizers, and pesticides. As this soil water, or soil solution, moves through the soil, it carries solutes with it. Some solutes are left behind when they are adsorbed by soil particles, absorbed by plants, or precipitated during evaporation, especially at the surface. Solutes move with the soil solution via two main processes: diffusion and hydrodynamic dispersion. Diffusion occurs due to random molecular motion, causing solutes to move from high to low-concentration areas. Hydrodynamic dispersion results from uneven flow speeds in soil pores during water movement. Factors like flow velocity, pore size, saturation, and concentration gradients affect the degree of mixing. When water flow is fast, hydrodynamic dispersion dominates, and diffusion becomes negligible. Conversely, when water is still, only diffusion occurs. These processes drive nutrient transfers to plant roots and the movement of salts and potentially harmful compounds. Various factors, including soil acidity, temperature, and oxidation-reduction potential, influence solute interactions within the soil (Hillel, 2007).

Peat soil has a dual-porosity structure with open, connected pores and isolated, dead-end pores which affect water flow, solute movement, and biogeochemical processes. Water and solutes primarily move through the connected pores, while solute migration slows in the dead-end pores due to diffusion. Reactive species are further affected by sorption and degradation. Slow diffusion between connected and isolated pores creates chemical gradients and uneven microbial habitats in peat soils. Understanding peat's physical structure is essential for studying its geochemical and microbial processes, which are becoming increasingly well-researched (Rezanezhad et al., 2016). Despite that, there is sparse information on reactive solute transport in peat (McCarter et al., 2018).

2.3 Soil Moisture

SMC stored in the unsaturated soil zone is a water source for the atmosphere through processes leading to evapotranspiration from land which includes plant transpiration and bare soil evaporation (Seneviratne et al., 2010). The varying amounts of water contained in a unit mass or volume of soil and the energy of the state of water in the soil are important factors affecting plants growth and all living organisms associated with the soil (Hillel, 2007). SMC influence soil mechanical properties such as soil strength, compactness and penetrability, also as well as the air content and gas diffusion in the soil thus affecting roots respiration, microorganisms' activity and the soil chemical state such as oxidation-reduction potential. The per-mass or per-volume fraction of water in the soil is expressed in terms of soil wetness (water content):

$$W_m = M_w / M_s \qquad \text{Equation 2.3}$$

$$v_w = V_w / V_t = V_w / (V_s + V_w + V_a) \qquad \text{Equation 2.4}$$

Wherein the mass wetness, W_m is the dimensionless ratio of water mass, M_w to dry soil mass, M_s; while v_w, the volume wetness, is the ratio of water volume, V_w to total (bulk) soil volume, V_t. The latter is equal to the sum of the volumes of solids (V_s), water (V_w), and air (V_a). Both W_m and v_w are usually multiplied by 100 and reported as percentages by volume or mass. The two expressions can be related to each other by means of the bulk density of the soil d_b, the ratio of the mass of solids to the total volume including pores, and the density of water d_w:

$$v_w = W_m \, (d_b / d_w) \qquad \text{Equation 2.5}$$

The conversion is relatively simple for non-swelling soils in which the bulk density is constant regardless of wetness, but it can be difficult in the case of swelling soils for which the bulk density is a function of the mass wetness.

Sufficient SMC is important to sustain high yields in oil palm plantations and accurate predictions for soil moisture deficit are needed to supply water to plants through irrigation when the rainfall is insufficient. Several factors could affect SMC such as soil bulk density, soil depth, water table, root depth, palm age and climate change (Othman et al., 2010; Noor et al., 2011; Dadap et al., 2019; Hermawan et al., 2021; Asano et al., 2023).

According to previous studies, SMC influences solute transport (Walter et al., 2007; Dong et al., 2018). Initial SMC plays a major role in determining the extent of the solute losses to runoff. A higher initial SMC caused greater solute concentration in runoff (Dong et al., 2018). Thus, soil moisture study, particularly for peat soil is important for peatland conservation and environmental sustainability.

2.3.1 Soil Moisture Measurement Method

SMC is usually determined in many agronomic, ecological and hydrological investigations. One of the methods for measurement of soil mass wetness is called a gravimetric method which involves removing a sample by augering it into the soil using a soil auger and then determining its moist and dry weights (Wilson et al., 2023; Melo et al., 2023). The moist weight is obtained by weighing and the dry weight is obtained after drying the sample in an oven, generally at 105 ºC for over 24 hours.

An alternative method to measure SMC is to embed a sensor, which generally contains a pair of electrodes embedded in a porous material, inserted into the soil profile to provide a continuous in situ sensing of soil moisture at various depths (Velde et al., 2023; Markovic et al., 2024), which is used for this study. The sensor containing electrical resistance blocks must be pre-calibrated against soil moisture content or suction (Hillel, 2007; Gao et al., 2018). The electromagnetic (EM) probes can provide real-time and continuous readings through automation, can be used remotely and unattended, do not require maintenance and licensing, and are relatively inexpensive. In addition, the EM probe utilized in this study provides reliable SMC measurements up to 100 cm soil depth (Dhakal et al., 2019), in contrast to many other sensors and satellite measurement that only measures SMC limited to the topsoil surface.

2.3.2 Drainage and Water Table Influence on Soil Moisture

In general, the drainage system for water management consists of an interconnected network of fields, collection and main drains, which is an integral part of peat development for oil palm planting. Soil information such as peat hydrology and moisture characteristics is important for the design of an efficient drainage system (Othman et al., 2010). The term drainage can also be used to denote the outflow of water from the soil and described as the artificial removal of excess water, or the set of management practices designed to prevent the occurrence of excess water. In particular, groundwater drainage is the removal of excess water from within the soil by lowering the water table, which is generally carried out by means of drains such as ditches and pipes into which groundwater flows due to the hydraulic pressure gradients existing in the soil. The drains direct excess water by gravity or by pumping to the drainage outlet, which may be a stream, a lake, or the sea (Hillel, 2007).

Drainage is a prerequisite to any peat agriculture development and is required to facilitate the respiration of plant roots in peatland reclaimed for agricultural use (Miyamoto et al., 2009). Oil palm cultivation requires drainage activities which influence the water table in the soil. For example, drainage ditches are constructed in oil palm plantations, so the water tables are lowered (Laiho et al., 2003; Melling et al., 2004). However, over-drainage reduces water holding capacity, irreversible peat drying, forest fire, moisture stress to crops and nutrient imbalance. Over drainage also caused peat desiccation, making it water repellent thus creating the properties of irreversible drying causing the dried sterile peat to become a poor medium for plant growth. Infiltration of water into the peat decreases, which increases the occurrence of surface runoff and flooding. The rate of water infiltration is reduced mainly due to the formation of organic crusting caused by irreversible drying properties (Melling et al., 2004). The rate of water movement through peat is also influenced by peat type, degree of composition and bulk density (Othman et al., 2010).

Peat soil contains many large pores that lose their water quickly when the groundwater level is slightly lowered (Wosten et al., 2008). In addition, peat soil moisture retention and hydraulic conductivity are also strongly influenced by peat formation of humic substances due to progressive peat oxidation (Wosten et al., 2008; Flores, 2014). Groundwater acts as a soil water source as well and has substantial effects in areas where the water table is near. Because of the groundwater effects, spatial variations in the groundwater table can create an additional spatial variability of soil moisture and surface water flux (Chen & Hu, 2004).

Sufficient soil moisture is important for soil quality conservation and high crop yield. Globally, many studies have been conducted to study the relationship between drainage, WT and soil moisture. For example, Rozemeijer et al. (2016) concluded that controlled drainage reduced drain discharge and increased groundwater storage in the field by elevating the outlet control level via adjustable weirs. Controlled drainage is also effective for the optimization of soil moisture conditions and reduces unnecessary losses of fresh water and nutrients. Vopravil et al. (2021) aimed to monitor the soil water regime of differently managed meadows (drained versus undrained) near the village of Zelezna in the Czech Republic and found that the volumetric water content of all studied soil depths from 2016-2019 was significantly different ($p < 0.05$). Another study by Oleszczuk et al. (2022) in a lowland area of Central Poland found that the relationship between soil moisture content and WT varied depending on land use type and climatic conditions.

In an oil palm ecosystem under tropical peatlands, a study by Winarna et al. (2015) found that WT affected actual soil moisture content at layers of 0-10 cm, especially during the dry month. It was observed that WT of 40-60 cm from peat soil surface could store the highest soil moisture content at soil 0-10 cm depth, retain higher soil moisture and avoid the upper layer from hydrophobicity. Deep WT (>80 cm) during the dry month cause the soil in the 0-10 cm layer, at the circle area and interrow area of oil palm to become hydrophobic. Adhi et al. (2020) found that peat soil water content on peatlands surface was greatly affected by WT fluctuations. Strong correlations were shown between WT and peat soil water content in the 10 cm layer of the oil palm plantations and secondary forests.

Tropical peatlands have been widely converted for oil palm plantation activities which require drainage for WT control that could alter peat soil properties and hydrological functions, particularly soil moisture. However, studies on the effect of these activities on soil properties, such as soil water dynamics are still limited. Hence, information on drainage effects, WT and soil water content are important in soil quality monitoring and land development. In view of this, the effect of drainage for WT management and soil compaction on soil moisture under oil palm plantations is evaluated.

2.3.3 Soil Compaction and Bulk Density Influence on Soil Moisture

Soil is compacted when the total air-filled porosity is so low as to restrict aeration (Hillel, 2007). Natural processes such as rain, plant roots, foot traffic and anthropogenic activity such as mechanical farms cause soil compaction (Nawaz et al., 2013). Properly compacted peat has excellent capillarity and water-holding capacity, improves oil palm anchorage, and supply of nutrients and supports more rapid growth and yields of oil palm (Mutert et al., 1999).

Soil compaction affects soil bulk density and soil porosity in which these soil physical parameters are determinants of the influence of the soil compaction on the chemical properties of the soil, soil fauna and diversity of plant growth (Nawaz et al., 2013). Following drainage, peatlands are mechanically compacted using heavy machinery (Busman et al., 2021). Mechanical compactions reduce soil porosity and enhance the capillary rise of water in the soil, keeping the soil moist. During compaction, tools of various designs are thrust into and through the soil. Several different effects may occur simultaneously as the soil is cut, compressed, sheared, lifted, displaced, and mixed. Soil also may be pushed ahead of the moving tool against the resistance of the static soil body and is thus also compacted. Consequently, the pressures acting on any volume element of soil in the field are seldom isotropic, which is equal in all directions. Any differences between the principal stresses in the horizontal, lateral and vertical axes necessarily give rise to shearing and compressive stresses. Simultaneous application of compression and shearing contributes significantly to soil compaction (Hillel, 2007).

Soil compaction increases the soil mass per volume, thus reducing the rate of fertilizer leaching. It also increases nutrient supply (more nutrient per unit peat volume) and helps to reduce early palm leaning due to better root anchorage (Melling et al., 2004; Melling et al., 2008). Plus, crops grow only if their roots are able to extract a sufficient amount of soil water to maintain transpiration from a soil environment that also provides an adequate supply of oxygen for respiration at the same time (Bohne, 2005). The bulk density of peat soil in the top layer of developed peatland was significantly higher than that in the undeveloped site as peat materials are commonly more decomposed and subsequently result in finer materials. The arrangement of fine materials into the intrinsic peat structure results in closer contact among particles and in turn, lower total pore space and higher bulk density (Kurnain et al., 2006). Besides, Yahya (2010) found that soil compaction significantly increased the oil palm yield with increased mean bulk density. Similar results were obtained by Zuraidah (2019), in which there was a positive relationship between the increased soil bulk density due to compaction with fresh fruit bunch (FFB) yield.

Bulk density is the most frequently used parameter to characterize the state of compactness of the soil layer (Hakansson et al., 2000). According to Blake (1965), soil bulk density, D_b is the ratio of the mass to the bulk or macroscopic volume of soil particles plus pore spaces in a sample and is needed for converting water percentage by weight to content by volume, for calculating porosity when the particle density is known, and for estimating the weight of a volume of soil too large to weigh conveniently. The bulk density varies with the structural condition of the soil, particularly that related to packing and thus, often used as a measure of soil structure. In most agricultural soils work, bulk density is expressed in grams per cubic centimetre (g cm^{-3}).

Soil compaction has a positive impact on soil water content. Mechanical compaction lowered soil porosity and enhanced the capillary rise of water in the soil, keeping the soil moist. Soil compaction could raise the potential energy of soil moisture by reducing the matric suction that absorbs some of the mechanical energy imparted to the soil. Plus, the change in matric potential of soil moisture is also influenced by the change in soil porosity and pore-size distribution (Hillel, 2007). According to Osaki et al. (2021), soil water-holding capacity is determined by the interaction of peat with water molecules by the physical van der Waals force and bulk density. A study by Adhi et al. (2020) revealed that oil palm cultivation activities on peatlands increase the peat bulk density, which in turn increases water capillarity and soil water content. Another study by Al-Esawi et al. (2021) on the effect of soil compaction on soil infiltration rate showed that soil bulk density for clay and loam soil surfaces increased with increasing compaction. High bulk density increases soil moisture content and is found to decrease soil CO_2 fluxes in cultivated peat, observed by comparisons of compacted and non-compacted peat in OPP, as well as OPP versus primary secondary forest (PSF) (Melling & Chaddy, 2016). In addition, studies also shows that different land use affects soil bulk density (Table 2.1). The soil bulk density (g cm^{-3}) at different land use and soil depths (cm) are summarized in Table 2.1. For example, undisturbed peat swamp forests generally exhibit the lowest BD, ranging from 0.08 to 0.23 g cm^{-3} (Maryani et al., 2020; Vijayanathan et al., 2021; Crnobrna et al., 2022; Busman et al., 2023). In contrast, burned peatlands and mixed plantations report BD values between 0.17 and 0.20 g cm^{-3} (Maryani et al., 2020), while coconut plantations show a slightly lower but comparable range of 0.10–0.18 g cm^{-3} (Putri et al., 2024). Factors such as decomposition of organic matter and reduced soil pore space due to land burning affect soil BD. The widest and highest BD range is observed in mixed-crop systems (0.12–0.85 g cm^{-3}), indicating the effect of agricultural disturbances (Vijayanathan et al.,2021).

Table 2.1: Summary of soil bulk density (g cm^{-3}) at different land use and soil depth (cm)

No.	References	Land Use	Soil Depth (cm)	Soil Bulk Density (g cm^{-3})
1	Maryani et al., 2020	Primary peat swamp forest	20 40	0.10-0.13 0.10-0.11
		Burned peatland fire	20-40	0.17-0.19
		Mixed Plantation	20-40	0.17-0.20
2	Vijayanathan et al., 2021	Forest swamp	0-20	0.17-0.23
		Mixed crops	0-175	0.12 – 0.85
3	Crnobrna et al., 2022	Peatland Forest	100-150	0.08-0.19
4	Busman et al., 2023	Peat Swamp Forest	0-25	0.10-0.14
5	Putri et al., 2024	Coconut Plantation (planted on peat soils)	0-70	0.10-0.18

2.3.4 Climate Impact on Soil Moisture

In the unsaturated soil zone, soil moisture changes because of precipitation recharge and water exchange with both the atmosphere and groundwater (Chen & Hu, 2004). Hence, to study the climatic effects of oil palm performance, it is important to carry out precise measurements of rainfall, and monitoring of soil moisture and as well as soil water holding capacity. As a rain-fed crop, water stress is one of the major limiting factors in oil palm growth and productivity (Noor et al., 2011). In the dry season, groundwater levels fall far below the soil surface, resulting in soil moisture contents of the surface peat and its vegetation to decreasing, creating huge amounts of dry fuel that are a fire hazard (Wosten et al., 2008). For successful oil palm water management on peat, information on rainfall distribution is crucial as long-term rainfall records would serve as a guideline for actions to be taken before the onset of both dry and wet seasons such as preparation for water retention, irrigation and better anticipation of flooding and its control (Melling et al., 2008). Reliable long-term rainfall records provide a basis for decision-making at the estate level such as the selection of the most favourable times for land preparation and planting (Goh et al., 2011). However, in Malaysia, climatic parameters are insufficient for reliable estimates of water deficit and data are limited to rainfall and rain days (Bakoume et al., 2013; Shashikant et al., 2021).

2.4 Groundwater Quality

Groundwater quality comprises the physical, chemical and biological qualities of groundwater. Naturally, ground water contains mineral ions which slowly dissolve from soil particles, sediments, and rocks as the water travels along soil surfaces in the pores or fractures of the unsaturated zone and the aquifer. Natural groundwater consists of cations such as sodium, calcium, magnesium, potassium, iron, and anions such as sulphate, chloride, and nitrate. In most cases, trace constituents such as phosphate, copper, zinc and manganese occur in such low concentrations that they are not a threat to human health. Nevertheless, human activities can alter the natural composition of ground water through the disposal or dissemination of chemicals and microbial matter at the land surface and into soils (Harter, 2003).

Water quality assessment under oil palm cultivation remains an under-investigated topic (Comte et al.,2015) and to this date, the anthropogenic effect on tropical peatland’s groundwater quality (physical and chemical) has not been studied thoroughly. Studies on the water use characteristics of oil palms are still at an early stage and research on the impacts of oil palm cultivation is still scattered without a clear overview (Roll et al., 2015; Dislich et al., 2017). In addition, information on the effect of fertilization on groundwater quality in OPP is still very limited (Ah Tung et al., 2009). Moreover, the chemical composition of soil water depends on soil texture, soil aeration, type and fertilizers amount and precipitation intensity (Morkunas et al., 2005), and studies on water and solute transport in soils require information on soil physical properties (Taufik et al., 2019). In addition, critical knowledge gaps remain in understanding solute transport in peat soils (McCarter et al., 2018). Other than affecting water quality, nutrient leaching under oil palm cultivated peatlands impacts soil quality and fertility, which hinders efficient nutrient adsorption by crops and causes nutrient deficiencies (Sham et al., 2024).

2.4.1 Effect of Forest Conversion and Replanting on Groundwater Quality

Natural forests contribute to maintaining surface water quality in particular, and without anthropogenic activities, natural forests would have no significant adverse impacts on water quality (Camara et al., 2019). However, many forested areas around the world have been and continue to be cleared for expanding agriculture (Noteboom, 2020). In a review study by Camara et al. (2019), 82% indicated agricultural land use while 77% indicated forest land use as a major source of water pollution in Malaysia. Correlation analysis results showed that agricultural and forest-related activities affected water quality more as reflected in their significant positive correlation with physical and chemical indicators of water quality, in comparison to urban development activities. Land clearing can lead to increased salinity problems in a catchment, the export of sediments and the decomposition of organic matter in streams which could lead to acidity problems in the catchment such as low pH, increased total acidity and mobilization of dissolved heavy metals.

Oil palm has a 25-year commercial lifespan (normally with an average height exceeding about 10m) before it must be replanted, due to reduced productivity and difficulty of harvesting (Corley & Tinker., 2003). An OPP may be replanted with the same crop; for example, the oldest plantations in Malaysia have been through 3 or more cycles (Corley & Tinker., 2003; Corley & Tinker, 2015). Older palms especially those that are more than 30 years old need replanting due to economic rationale (Ismail & Mamat., 2002). In Malaysia, older palms especially those that are more than 30 years old need replanting due to economic rationale (Ismail & Mamat., 2002). The delay in replanting will result in the accumulation of old and unproductive palms and higher production cost as a result of the lower yield of old and ageing palms (Wahid & Simeh., 2010). Loss of the complex vegetation structure of oil palm plantations during the replanting process will likely have impacts on the ecosystem at a local and landscape- scale (Ashton-Butt et al., 2019). Oil palm plantations are a major agricultural land use in Southeast Asia. In the coming decades, large areas of mature oil palm will be cleared and replanted. To inform more sustainable long-term production in this globally important crop, it is crucial to understand how replanting impacts ecosystem functions and services (Woodham et al., 2019).

According to Goh et al. (2013), the soil surface is exposed to erosion and uncontrolled surface run-off after land clearing, contributing to the probably greatest potential for nutrient losses. For example, pruning of fronds and trunks during plantation development could release large amounts of nutrients such as potassium (K). Sparse ground vegetation, steep topography, soil erosion and uncontrolled surface wash also contribute to high nutrient losses. Besides, palm trunks represent a large pool of nutrients N and K, which are usually windrowed and left to decay in the field (Kee, 2004).

By the time of oil palm replanting, a considerable pool of nutrients has been sequestered in soils, in which much of the soil nutrients are lost through leaching, denitrification, and surface run-off (Anderson, 2008). In addition, the conversion of forest into an OPP is expected to cause changes in the whole land ecosystem which will directly affect the hydrological cycle (Afandi et al., 2017). The loss of the complex vegetation structure of OPP during the replanting process will likely have impacts on the ecosystem (Ashton-Butt et al., 2019). Replanting and forest conversion to oil palm have affected soil quality and caused biodiversity loss (Sahat et al., 2016; Ashton-Butt et al., 2019). Malaysia, as one of the world's largest producers of palm oil has prioritized replanting of trees to boost productivity and without expanding land use (Malaysian Palm Oil Council, 2025). Besides, the Malaysian government has also provided replanting incentives to oil palm smallholders to maintain or boost the country's palm oil production (News Straits Times, 2025). However, there remains a knowledge gap regarding how current replanting practices influence the soil and groundwater quality, particularly for the tropical peatland ecosystem.

Anderson (2008) concluded that nutrient management practice in oil palm plantations is assumed to have a low environmental impact, particularly on portable water supplies. However, the accessible records for leaching and groundwater quality to support the assumption are still limited. In addition to that, there is no chronological study that has been conducted to compare the amounts of nutrient leached under natural forest and oil palm plantations established on the same site neither after forest clearing nor between forested and oil palm catchments with similar climatic and soil conditions (Comte et al., 2012). As oil palm trees are a long-term cultivated crop with replanting stages (e.g. from the first establishment to fourth generation planting), therefore it is important to study and quantify the effect of forest conversion and replanting on nutrient leaching into groundwater, as nutrients released into groundwater could affect groundwater quality in the long term.

2.4.2 Fertilizer Effect on Groundwater Quality

Mineral fertilizers applied for oil palm cultivation include urea, either rock phosphate (RP), muriate of potash (MOP) for potassium (K) input, either kieserite or dolomite as magnesium (Mg) fertilizers, and high-grade fertilizer borate (HGFB) (Comte et al., 2015). For example, urea [$(NH_2)_2CO$] is an organic, highly water-soluble nitrogen fertilizer with nitrogen (N), phosphorus (P) and potassium (K) ratio of 46:0:0. NPK are essential macronutrients that critically influence the yield formation of storage root crops (Zhao et al., 2025). In soil, urea undergoes enzymatic hydrolysis to form ammonium carbamate compound, which is then converted into ammonia and carbon dioxide:

$$NH_2CONH_2 + H_2O \rightleftharpoons NH_2COONH_4 \rightarrow NH_3 + CO_2 \qquad \text{Equation 2.6}$$

NH_4^+ ions may be formed by conversion of NH_3. Hydrolysis of urea could increase the pH of the soil. The rise in pH can influence both soil integrity and plant nutrient availability. In peat soils, a short-term pH increase may reduce acidity and enhance nutrient retention by increasing cation exchange capacity, but if excessive, it may also promote NH_3 volatilization, reducing nitrogen-use efficiency and potentially stressing young palms sensitive to alkaline conditions (Peng et al., 2020; Choo et al., 2020; Krishnan et al., 2023).

On the other hand, RP (P_2O_5), is a stable fertilizer, insoluble in water and contains 20% - 40% P2O5 or 8.6% -17.2% P (Nadarajan & Sukumaran, 2021). In the OPP system, RP contributes to long-term P supply, improves root development during early palm growth, and helps maintain soil structural stability by reducing nutrient depletion and minimizing leaching losses typical in organic soils. Because RP is a slow-release, it remains in the soil for extended periods, making it suitable for young palms with sustained P requirements.

In young plantings, both potassium (K) and magnesium (Mg) are required, as these nutrients play critical roles in vegetative growth and early yield development (Prabowo et al., 2023). K is most supplied as MOP, which represents the principal source of K in OPP and has been widely reported to accelerate early bearing and improve fresh fruit bunch formation (Behera et al., 2022). Mg deficiency may occur on certain soils and is often accentuated by N and K applications. Where Mg deficiency is present, Mg is typically supplied as kieserite or dolomite, with the choice depending on soil acidity and liming requirements (Sidhu et al.,2014; Guan et al., 2020). In addition to macronutrients, micronutrients such as boron (B) are essential for oil palm growth, particularly in peat and sandy soils, and are commonly supplied as high-grade fertiliser borate (HGFB) to prevent B deficiency and support plant development (Prasetiyanto et al., 2024).

Fertilization is the most sensitive cause of groundwater contamination (Marouane et al., 2014). Previous studies have shown that groundwater nutrients and trace metal elements are associated with agricultural activities such as fertilization (Hashim et al., 2019; Islam et al., 2021; Harun et al., 2021). In oil palm plantations, fertilizer application is carried out periodically both on new and productive plants. Oil palm plantation is estimated to contribute to groundwater contamination not only from the use of pesticides but also from fertilization (Goh et al., 2003).

The use of fertilizers in the soil contributes to the accumulation of nutrients that could reach high concentration levels and be carried by rain into water bodies such as rivers and groundwater. Water pollution caused by nutrients, particularly, nitrate has increased due to the increased use of chemical fertilizers at high concentrations (Mateo et al., 2010). Water pollution caused by a high rate of fertilizers also affects aquatic ecosystems close to plantations (Sheil et al., 2009). Fertilizer nutrients that are not taken up by the palm or adsorbed onto soil particles are dissolved and lost through surface runoff, volatilization, denitrification or leaching. Adsorbed nutrients may also be lost in eroded soil and sediments (Goh et al., 2003). According to Harun et al. (2019), nitrates, phosphates and potassium derived from NPK fertilizers and manure applications at the oil palm plantations were the general substances in the groundwater samples from agricultural areas and have a great discharge into surface water through leaching, runoff and sedimentation. These substances accumulate in surface water and then infiltrate into the groundwater, contributing to the increasing electrical conductivity and deteriorating the quality of groundwater. For example, phosphate, PO_4 can be derived from residual fertilization, that if a small total phosphate value indicates that fertilizing using phosphate does not affect the state of water during monitoring (Sari et al., 2019). Potassium, K^+ leaches easily in peat soil and does not form compounds. At low pH, peat soil has extremely low cation absorption capacity in such a way that all nutrients, especially K^+ leach immediately through desorption mechanisms, even if fertilizer is applied (Osaki et al., 2021).

High fertilizer input is necessary to sustain high yields in oil palm agroecosystems, but it may endanger neighbouring aquatic ecosystems when excess nutrients are transported to waterways (Comte et al., 2015). However, information on the effect of fertilization activities on groundwater quality in oil palm plantations is still very limited (Ah Tung et al., 2009). In view of this, the long-term effect of fertilizer application on groundwater quality under an oil palm plantation in this study is evaluated.

2.4.3 Drainage Influence on Groundwater Nutrients

Agricultural activities require drainage for water table control and optimising soil water content to ensure high crop yield. Drainage could also reduce unnecessary losses of fresh water and nutrients (Rozemeijer et al., 2016). However, drainage and water table fluctuation could affect groundwater nutrients. Conventional drainage contains high sediment concentrations and fertilizer constituents such as organic nitrogen and phosphorus which could threaten aquatic ecosystems in surface waters (Evans et al., 1989; Rozemeijer et al., 2016). Rising water level increases nutrients concentration in groundwater due to agriculture-related activities such as fertilizer application and irrigation flow (Rajmohan & Elango, 2005).

2.4.4 Soil Moisture and Groundwater Parameters Correlation

In peat soils, precipitation and irrigation drive vertical percolation through highly porous organic structures, where preferential flow pathways develop and enhance solute transport to groundwater via dissolution and leaching processes. (Cheng et al., 2021). Some soil pollutants can be mobilized (solubilized in soil moisture) or others are immobilized on soil particles (adsorbed on the surface of minerals and organic fractions or chemically fixed, as precipitated or co-precipitated) in solid compounds, depending on the physical and chemical properties of the soil. The polluted soil can affect human health either by direct contact with the soil, by inhaling vaporized soil pollutants, or as a result of pollutants infiltration into the aquifers and groundwater for human consumption (Gavrilescu, 2021). Despite that, soils could regulate water quality by filtering out pollutants and regulating sediments (Adams et al., 2020). For peat soils, the resulting dual porosity nature affects water flow and solute migration, which influence reactive transport processes and biogeochemical function (Rezanezhad et al., 2016). Soil moisture could influence soil nutrient transport and chemical properties. However, the study on the correlation between soil moisture and water chemical parameters is still scarce, especially under tropical peatlands. Understanding the hydraulic properties of organic soils is essential for water quality management in cultivated agricultural lands and also for making predictions about the amount of solute that is exported from organic soils (Grenon et al., 2021). According to Gregory et al. (2022), soil and water interaction during subsurface flow can have impacts on water quality, thus it is fundamental to understand where and how certain soil water chemical processes occur within a catchment. Therefore, the correlations between soil moisture and selected groundwater chemical parameters are evaluated in this study.

2.5 Statistical Analysis

2.5.1 Least Significant Difference (LSD)

In this study, analysis of variance (ANOVA), followed by the Least Significant Difference (LSD) test, was used to analyse the differences in SMC between sampling points and soil depths ranging from 0 cm to 100 cm. Soil data were categorised into four (4) groups according to the OPP transplanting year: Q1–Q4 (2000), Q5–Q8 (2001), Q9–Q12 (2003), and drained secondary forest, DSF serves as a control of the study. During data analysis, two independent variables (factors) were considered: transplanting year and soil depths, while SMC was treated as the dependent variable. Following statistically significant ANOVA results, the LSD test was applied to identify pairwise differences between the predefined treatment levels. The LSD test has been widely used in previous studies investigating soil moisture and bulk density. For example, Ghaur and Ahmadi (2015) employed the LSD test to evaluate significant differences in soil BD under different soil moisture treatments and soil sampling depths. Al-Esawi et al. (2021) used LSD to determine significant differences in soil infiltration rates under varying soil compaction frequencies. More recently, Das et al.

(2024) applied the LSD test to evaluate significant differences in residual NH_3–N and NH_4–N concentrations in soil subjected to various soil compaction treatments, soil types, and soil treatments.

2.5.2 Pearson Correlation

A Pearson correlation matrix (two-tailed test, with significance levels at $p < 0.01$ and $p < 0.05$) was computed to assess the relationships between soil moisture content (SMC) and groundwater chemical parameters in this study. Mean SMC values from each group (Q1–Q4, Q5–Q8, Q9–Q12, and DSF) were correlated with the corresponding mean groundwater chemical data. In this study, the Pearson correlation analysis is appropriate because both SMC and groundwater chemical parameters are continuous variables, and the analysis aims to quantify the strength and direction of linear relationships. Pearson correlation analysis has been widely applied in previous research involving soil and groundwater datasets. For instance, Azlan et al. (2012) reported a positive correlation between soil organic matter (SOM), total organic carbon (TOC) concentrations, soil classes, and seasonal patterns (wet and dry seasons). Similarly, Patel et al. (2012) applied Pearson correlation to examine the relationships among various groundwater chemical parameters across monsoon, post-monsoon, and pre-monsoon seasons. Malik et al. (2021) used Pearson correlation to investigate the dynamic relationships between groundwater levels, soil moisture, soil temperature, and surface temperature. In another study, Saalidong et al. (2022) employed Pearson correlation to analyse the relationships between water pH and other water quality parameters in both groundwater and surface water systems.

2.5.3 Linear Regression

A linear regression analysis was also adopted in this study to illustrate the correlation between soil moisture content, soil bulk density, and groundwater chemical parameters. A linear regression model was created using data with high correlation values of $r > 0.7$ and $r < -0.7$ (Kannan & Joseph, 2022) between soil moisture content and groundwater chemical parameters. The linear regression model could be used to predict groundwater chemical parameters (dependant variables) based on the soil moisture content in situ data as the independent variable or predictor. According to Qiu et al. (2003), regression models could describe the relationship of soil moisture and environmental attributes and has been used in several previous research for groundwater quality monitoring (Saikrishna et al., 2020; Dargahi et al., 2022; Fernandes et al., 2023). For example, a recent study by Workie et al. (2024) has developed linear regression equations for water quality parameter estimation from remote sensing data (surface reflectance values) and in situ data (water quality parameters).

CHAPTER 3

MATERIALS AND METHODS

3.1 Site Description

This study was conducted from October 2021 until March 2022 in an oil palm (*Elaeis guineensis*) plantation on tropical peatland in the southwestern region of Sibu, Sarawak, Malaysia, in northwestern Borneo (Figure 3.1a) and is located in the catchment area of the Rajang River, Malaysia. Sibu has an equatorial climate with constantly high temperatures and humidity as well as distinct wet and dry seasons (Anggat et al., 2024).

According to Anggat et al. (2024), the studied OPP is situated inland, approximately 90 km from the coast, within the Assan and Naman River sub-basins, both of which are tributaries of the Rajang River (Figures 3.1b-3.1c). These sub-basins have a combined catchment area of about 408.3 km², with the Assan and Naman sub-basins covering approximately 221.4 km² and 186.9 km², respectively. The total area planted with oil palm spans roughly 103.59 km², accounting for approximately 25.4% of the total catchment area (Figure 3.1b). As reported by Nishina et al. (2023), the study area was originally a mixed peat swamp on an ombrotrophic peat dome before being converted into an OPP. The peatlands in this region, where oil palm cultivation is predominant, have been partially drained and developed for plantation purposes (Gaveau et al., 2016).

The Rajang River and its tributaries are tidal, with water levels fluctuating between 6 and 12 m above Mean Sea Level (MSL). The Assan and Naman sub-basins are predominantly low-lying, with elevations below 20 m MSL (Figure 3.1d). The landscape of the OPP is largely flat (Chaddy et al., 2021), while higher elevations are found in Julau, along the hilly southern boundary of the basin. These hills serve as the source of the rivers, which flow northward to merge with the Rajang River. According to Nishina et al. (2023), the plantation's elevation ranges from -1 meter to 44 meters above sea level. Geologically, the hills in Julau are composed of sandstone (Figure 3.1e), forming a natural southern boundary for the sub-basins, while the Rajang River marks the northern boundary.

The OPP is characterized by abundant ground cover, including frond stacks, and is encircled by drainage ditches (Figure 3.2). The drainage system in the plantation consists of (1) field drains, (2) collection drains and (3) main drains. The distance between the field drain is around 29.44 m while the length of the main drain depends on the surrounding boundary areas. The details of the drainage system are summarised in Table 3.1. Groundwater and surface drain water predominantly originate from the hilly regions on the southern side of the oil palm plantation and drains toward the Rajang River (Figure 3.2).

The peat surface in the plantation area was compacted using heavy machinery prior to oil palm cultivation. According to data from the OPP management, the primary fertilizers used in the plantation include MOP and urea. Table 3.2 provides a summary of the fertilizer application rate (kg/palm), the frequency of application per year, and the release of fertilizer ions.

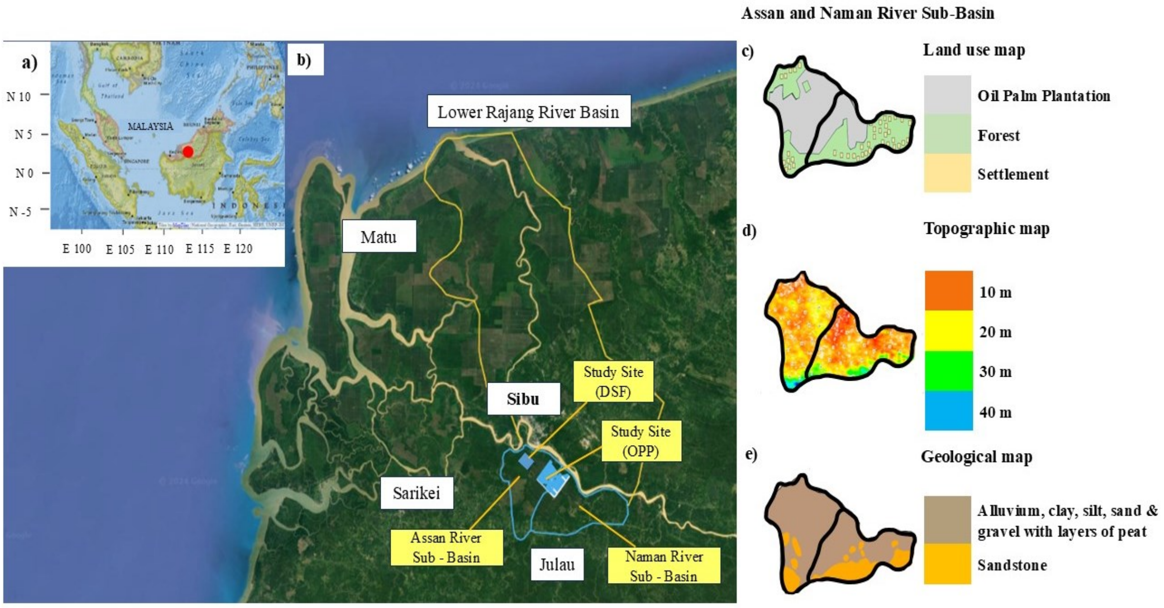


Figure 3.1a) Study site location, b) OPP and DSF location in the river basins, c) OPP land use map, d) OPP topography map, e) OPP geological map

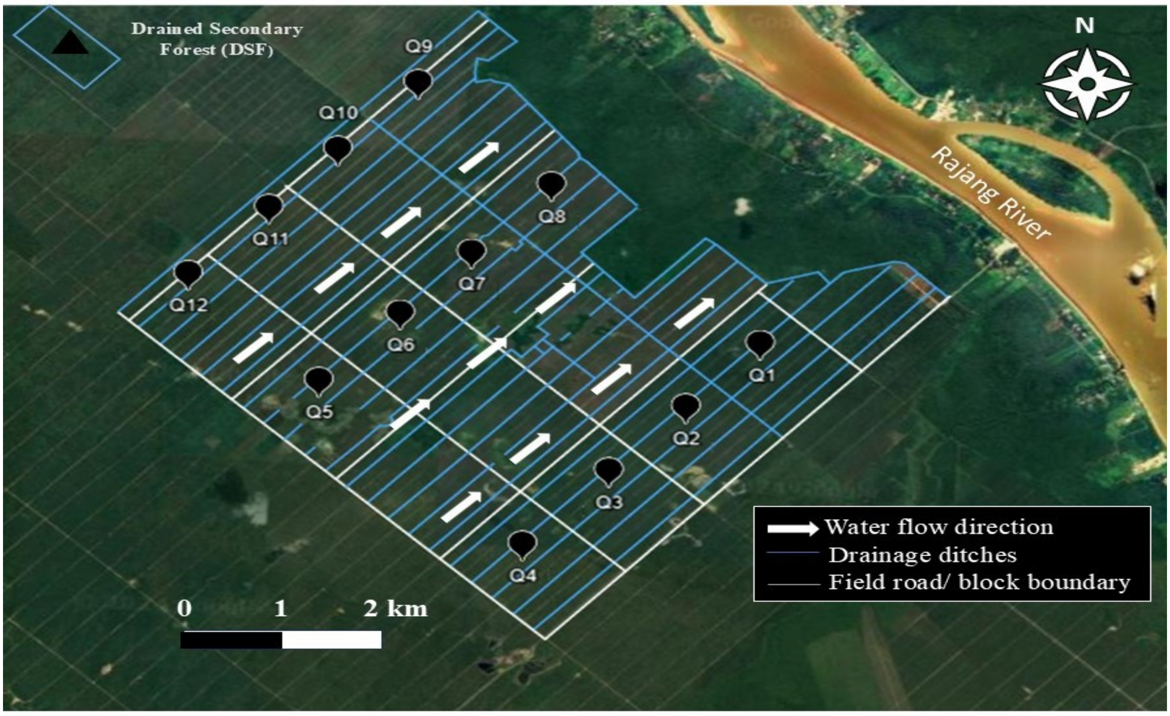


Figure 3.2: Location of the sampling points (Q1-Q12) and drained secondary forest (DSF) in the plantation

Table 3.1: Dimension of drainage system in the oil palm plantation

Drainage system	**Dimension**
Field drain	1.50 m (W) x 0.91 m (D) x 150 m (L)
Collection drain	2.50 m (W) x 1.22 m (D) x 1200 m (L)
Main drain	4.0 - 6.0 m (W) x 1.83 m (D) x 1500 m (L)

Table 3.2: Details of fertilizer applied in the oil palm plantation

Fertilizer Type*	**Chemical Composition**	**Fertilizer Rate* (kg/palm)**	**Frequency of Fertilizer Application (per year) ***	**Release Ions****
MOP	KCl	0.50 – 2.10	4 times	K^+, Cl^-
Urea	NH_2CONH_2	0.25 – 0.50	6 times	NO_3^-, H^+, NH_4^+

*Based on the fertilizer data obtained from the plantation management, **Islam and Mostafa (2021)

3.2 Determination of Sampling Points

Twelve sampling points (Q1– Q12) under tropical peatland with the same vegetation cover which is an OPP planted on peat soil were selected based on the oil palm initial transplanting year: Q1–Q4 (2000), Q5–Q8 (2001), and Q9–Q12 (2003) (Figure 3.2). Sampling points were also selected based on the availability of secondary data (groundwater chemical parameters and hydrological data before oil palm replanting). For the control study, a sampling point was selected in a drained secondary forest (DSF) located in the same oil palm plantation. Comprehensive details regarding the study site and the specific locations for sampling are presented in Table 3.3.

Table 3.3: Description of the study site and sampling points of the oil palm plantation sampling points (Q1-Q12) and DSF

Sampling point	Oil palm transplanting year (1st generation) *	Oil palm replanting year (2nd generation) *	GPS coordinate**
Q1	2000	2016	N: 2º 10’ 01.7” E: 111º 54’38.7”
Q2	2000	2018	N: 2º 09’35.1” E:111º 54’38.7”
Q3	2000	2018	N: 2º 09’03.8” E:111º 53’49.0”
Q4	2000	Nil	N: 2º 08’ 33.1” E:111º 52’22.6”
Q5	2001	Nil	N: 2º 09’ 39.2” E:111º 52’10.4”
Q6	2001	2020	N: 2º 10’ 09.0” E:111º 52’ 36.5”
Q7	2001	2020	N: 2º 10’ 36.0” E:111º 52’ 59.0”
Q8	2001	2021	N: 2º 11’ 05.5” E:111º 53’ 25.0”
Q9	2003	2020	N: 2º 11’ 56.4” E:111º 52’ 46.3”
Q10	2003	2020	N: 2º 11’ 22.6” E:111º 52’ 16.8”
Q11	2003	2021	N: 2º 10’ 50.7” E:111º 51’ 49.2”
Q12	2003	Land clearing in November 2021	N: 2º 10’ 22.8” E:111º 51’ 24.9”
DSF	Nil	Nil	N: 2º 11’ 50.0” E:111º 51’ 05”

*Based on the data obtained from the plantation management. **GPS data was measured via GPS device.

3.3 Materials

The materials used in this study are summarized in Table 3.4:

Table 3.4: Summary of materials

Scope	**Materials/ Equipment**
1. SMC Measurement	Soil Moisture Probe (PR2/6 Profile Probe, Delta T-Device, UK)
2. Soil Sampling	Peat Auger 0-100 cm (Eijkelkamp)
3. Water Table Measurement and Groundwater Sampling	1. Perforated polyvinyl chloride (PVC) pipe (for groundwater monitoring well) 2. Measuring tape 3. Polyethylene sample bottles
4. Laboratory Equipment	1. pH meter (Metrohm 827) 2. Electrical conductivity meter (Seven Compact S320, Mettler Toledo) 3. CN Analyser (Leco CN 828) 4. Thermogravimetric Analyser (Leco TGA 701) 5. Inductively Coupled Plasma Mass Spectrometry (Agilent 7700) 6. Ion Chromatography (Compact IC, Metrohm 867) 7. Laboratory Oven (Memmert)
5. Software	1. IBM SPSS Statistics 2. Microsoft Excel for Microsoft 365

To ensure consistency throughout the study, several parameters were kept constant, including the land use type (oil palm plantation) and drained secondary forest (as control), soil type (peat soil), sampling depths (0-100 cm) for soil and groundwater, sampling equipment, analytical methods, and laboratory instrumentation.

3.4 Soil Moisture Measurement and Soil Sampling

Soil sampling and soil moisture measurement were conducted only once in January 2022 (one-time sampling) throughout the study period. Soil moisture content, SMC (%) at 10, 20, 30, 40, 60, and 100 cm soil depth at each sampling point were measured using a soil moisture probe (PR2/6 Profile Probe, Delta T-Device, UK) with HH2 data recording meter (Figure 3.3). Adjacent to the points where SMC was monitored, undisturbed and composite soil samples were collected with a peat auger at 0-25, 25-50, 50-75, and 75-100 cm in 3 replicates representing different oil palm management zones: (1) planting row (2) harvesting path (3) palm circle. These zones were selected because they represent distinct micro-environments that differ in soil compaction, organic matter accumulation, fertilizer input, and root distribution (Lestariningsih & Hairiah, 2013; Wakhid et al.,2022). Investigating these zones allows for a better understanding of spatial variability and the influence of plantation management on soil properties. Soil samples were also collected in the DSF within the OPP as a control. All soil samples were brought to the laboratory for physicochemical analysis.

3.4.1 Field Calibration and Method Validation

For the soil moisture probe calibration, undisturbed soil samples (0-100 cm) were collected and analysed using the gravimetric method, in which samples were oven-dried at 105°C for 48 hours until a constant weight was reached. The SMC is calculated as the percentage of mass loss obtained via the gravimetric method (FAO, 2023), calculated as follows:

$$SMC\% = [(W_{wet} - W_{dry}) / W_{wet}] \text{ x } 100 \qquad \text{Equation 3.1}$$

SMC % = Soil Moisture Content Percentage

W_{wet} = Mass of wet soil (g)

W_{dry} = Mass of oven-dried soil (g)

The performance and accuracy of the soil moisture probe were evaluated using the RMSE equation based on a field calibration method (Markovic et al., 2024) as follows:

$$RMSE = (n^{-1} \sum_{i=1}^{n} (Si - Oi)^2 \qquad \text{Equation 3.2}$$

Where RMSE is the root mean square error, Si is the predicted value (PR2 Probe SMC), while Oi is the observed value (gravimetric SMC). The details of the method validation and SMC potential measurement errors are discussed further in Section 4.2.2.

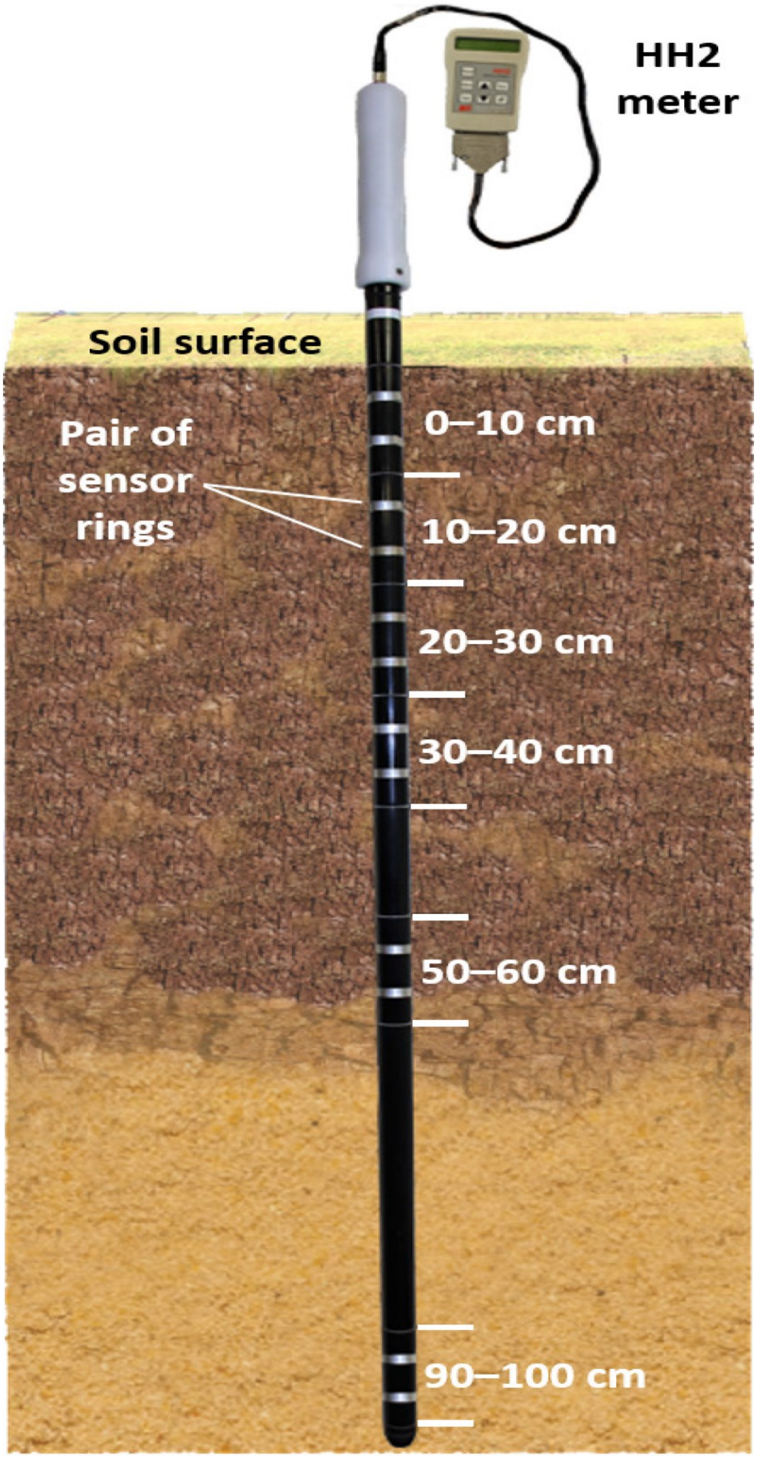


Figure 3.3: The soil moisture probe (PR2/6 Profile Probe, Delta T-Device, UK) with HH2 data recording meter (Dhakal et al., 2019)

3.5 Hydrological Monitoring and Groundwater Sampling

Hydrological monitoring and groundwater sampling was conducted from October 2021 until March 2022, while secondary data for the period of January 2011 until December 2017 were obtained. WT measurements and groundwater sampling were mostly conducted within one (1) day period in the first 2 weeks of every month, depending on the weather conditions such that groundwater WT measurements and groundwater sampling were not performed during rainfall to avoid inaccurate measurement. Manual WT measurements were conducted on a monthly basis via measuring tape in each monitoring well (perforated polyvinyl chloride (PVC) pipes (Figure 3.4) that were installed in 13 sampling points (Q1–Q12) and DSF. The pipe had a 0.15 m diameter with a perforated section along a 1.5 m length which was inserted into the ground with the remaining 0.5 m kept above the ground. A similar pipe installation setup for WT measurement was also used in other studies in tropical peatlands (Marwanto et al., 2018; Dom et al., 2021). The height from the top of the pipe until the water surface inside the pipe, (H1) and the height from the top of the pipe to the ground surface outside the pipe, (H2) were recorded to calculate the WT value at each monitoring well: WT (cm) = H1–H2. A total of four (4) sampling points (replication) were considered, and the standard error was determined. Shallow groundwater samples were collected from the same pipe (within a 1-m groundwater depth) immediately after WT measurements and stored in polyethylene sample bottles, transported to the laboratory for chemical analysis. Monthly rainfall data was measured with a tipping-bucket rain gauge (TE525; Campbell Scientific Inc.) positioned at the height of 1 m with installed sensors near the eddy covariance flux tower located in the plantation while monthly rainfall data set from the year 2011 until 2017 were acquired from Sg. Salim B meteorological station is located at an approximate distance of 7.4 km from the study site (Kiew et al., 2020).

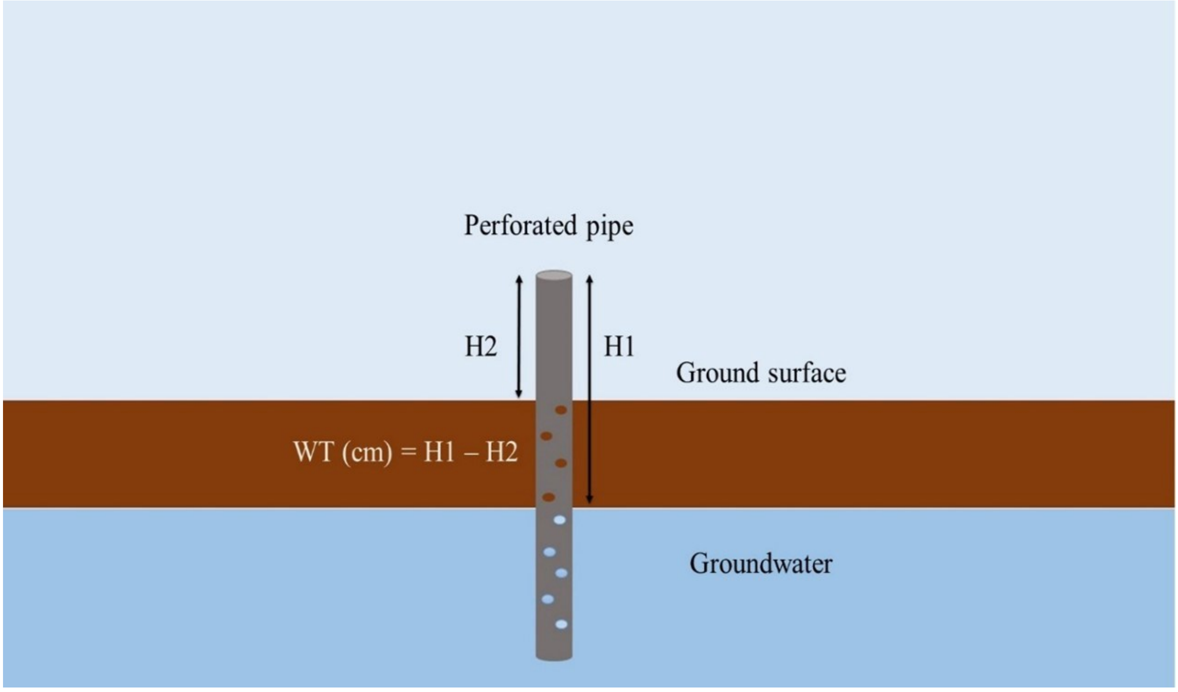


Figure 3.4: Schematic diagram of water table (WT) measurement in the monitoring well (Anggat et al., 2024)

3.6 Laboratory Analysis

3.6.1 Soil Physicochemical Parameters

Soil physicochemical parameters such as pH, electrical conductivity, moisture content (%), loss on ignition (LOI%), total carbon and nitrogen, and soluble ions (NO_3^-, NH_4^+, K^+, Ca^{2+}, Na^+, Cl^-, SO_4^-) were determined as summarized in Table 3.5. Soil bulk density, ρ *(g cm-*^{3}) is analysed using the gravimetric method. The samples were weighed and transferred to an aluminum container and oven-dried at 105 °C for 48 hours. Each dry soil sample was then weighed again, and oven-dried until its final constant weight was obtained.

The calculation of soil bulk density (*g* cm^{-3}) is calculated following Equation 3.3 below:

$$\rho_{bulk}\,(g\ cm^{-3}) = \frac{m_{dry\ soil}\ (g)}{soil\ sample\ volume\ (\,cm^3)} \qquad \text{Equation 3.3}$$

The soil sample volume (cm^3) is calculated using the internal volume formula ($V = \pi r^2 h$) of the cylindrical peat auger.

Table 3.5: Summary of soil physicochemical parameters and methodology

Parameter	**Methodology**
pH	MS 2457:2012 (soil-to-water ratio 1:2.5), pH meter (Metrohm 827)
Electrical Conductivity	MS 2458:2012 (soil-to-water ratio 1:5), Electrical Conductivity Meter (Seven Compact S320, Mettler Toledo)
Moisture Content & Loss on Ignition (LOI)	Thermogravimetric Analyser (Leco 701)
Total Carbon & Nitrogen	MS 13878:2014, CN Analyser (Leco CN 828)
Soluble Ions (NO_3^-, NH_4^+, K^+, Ca^{2+}, Na^+, Cl^-, PO_4^{2-})	Ion Chromatography (Compact IC, Metrohm 867)
Bulk Density	Gravimetric analysis, oven dry (Memmert Oven) at 105ºC based on FAO (2023) soil water content: gravimetric method

3.6.2 Groundwater Chemical Analysis

A total of 5 parameters (pH, electrical conductivity, total P, K, Ca, Mg, Fe, Mn, Cu, Zn, Na) and major ions (NO_3^-, NH_4^+, K^+, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, SO_4^-) were determined for groundwater quality analysis on monthly basis. The pH and electrical conductivity (EC) of water samples were measured in a laboratory using a pH Meter and an Electrical Conductivity meter. Before measurements, buffer solutions (pH 4 and 7) and calibration standard, 500 $\mu S\ cm^{-1}$ were utilised to calibrate the pH meter and electrical conductivity meter. For each sample, readings were recorded only once after stable readings were obtained. After pH and electrical conductivity measurements, all samples were filtered with Sartorius 293 filter paper, prior to other analyses. Samples were kept in polyethylene bottles and refrigerated at 4°C if analysis could not be carried out on the same day to maintain the freshness and integrity of the groundwater sample for analysis. Filtered groundwater samples were analysed for total elemental concentrations (P, K, Ca, Mg, Fe, Mn, Cu, Zn, B, and Na) using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) due to its high sensitivity and capability for simultaneous multi-element detection. All samples and calibration standards were prepared in an acid matrix of 1–2% (v/v) HNO_3 to ensure matrix matching and minimise analytical interference. Elemental quantification was performed using a multi-element calibration approach. A series of standard solutions with known concentrations was prepared from a certified multi-element standard and used to construct calibration curves. These calibration curves established the relationship between ICP-MS signal intensity and analyte concentration, enabling accurate quantification of elements in groundwater samples. Only calibration curves with acceptable linearity were used for analysis. Elements were quantified based on their most abundant and interference-free isotopes (^{31}P, ^{39}K, ^{24}Mg, ^{43}Ca, ^{55}Mn, ^{56}Fe, ^{63}Cu, ^{66}Zn, ^{11}B and ^{23}Na) selected to maximise sensitivity and analytical reliability. Internal standards were added to all samples and standards to correct for instrumental drift and matrix effects. On the other hand, Nitrate (NO_3^-), ammonium (NH_4^+) and major ions potassium (K^+), Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), sulphate (SO_4^-) concentration were determined via ion chromatography. The summary of the method for groundwater physicochemical parameters is as in Table 3.6:

Table 3.6: Summary of groundwater physicochemical parameters and methodology

Parameter	**Methodology**
pH	pH meter (Metrohm 827)
Electrical Conductivity	Electrical Conductivity Meter (Seven Compact S230, Mettler Toledo)
Total Elements (P, K, Ca, Mg, Fe, Mn, Cu, Zn, Na)	Inductively Coupled Plasma Mass Spectrometer (ICP-MS, Agilent 7700)
Soluble Ions (NO_3^-, NH_4^+, NO_2^-, K^+, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, SO_4^-)	Ion Chromatography (Compact IC, Metrohm 867)

3.6.3 Quality Control

Quality control procedures were implemented throughout laboratory analyses. All instruments were calibrated prior to use in accordance with manufacturer specifications. Laboratory analyses were conducted using standard methods, with the inclusion of blanks, duplicate samples, and reference standards where applicable. Data validation involved checking for consistency, precision, and potential outliers prior to statistical analysis to ensure reliability and accuracy of the dataset.

3.7 Statistical Analysis

One-way analysis of variance (ANOVA) was conducted for descriptive analysis of the variables studied, which are soil physicochemical parameters and groundwater chemical parameters. ANOVA was employed because the study involved comparisons of mean values among four independent groups of sampling points. ANOVA is appropriate for determining whether statistically significant differences exist among more than two group means. LSD test, Pearson correlation (2-tailed testing significant at $p < 0.01$ and $p < 0.05$) and linear regression analysis were performed to evaluate the relationships between the total monthly rainfall, WT and groundwater chemical parameters. An independent sample t-test (significant at $p < 0.05$) was conducted to test the significant difference between the WT and rainfall in the wet and dry seasons. The long-term groundwater chemical parameters and water table data were categorised into the wet seasons (November to March) and dry seasons (May to September) following the wet and dry seasons in Sarawak (Chaddy et al., 2021). Data cleaning was conducted by removing environmental parameters paired with missing values. Additionally, some missing water table values were replaced with water table data obtained via the automatic water table data logger installed in the monitoring well. These statistical analyses were conducted using IBM SPSS Statistics and Microsoft Excel for comprehensive data evaluation and interpretation.

3.8 Safety Protocol

All field and laboratory activities were conducted in accordance with safety guidelines to minimise risks to personnel and the environment. During field sampling, appropriate personal protective equipment (PPE), including safety boots, gloves, and protective clothing, was worn to reduce exposure to physical hazards and contaminated water or soil. Sampling was not carried out during heavy rainfall or extreme weather conditions to reduce the risk of injury and sample contamination. To minimise health risks, direct contact with peat soil and groundwater was avoided where possible. Hygiene practices such as hand washing and equipment cleaning were conducted after sampling.

For laboratory analysis, appropriate PPE, including laboratory coats, gloves, and safety goggles, was worn at all times during sample preparation and analysis. Chemical reagents were handled in compliance with safety data sheet (SDS) guidelines, and volatile or hazardous substances were managed using fume hoods where required. Laboratory equipment and instruments were operated with the guidance of trained personnel, following standard operating procedures (SOPs) to prevent accidents and equipment damage. Proper waste management practices were implemented, including the segregation and disposal of chemical waste according to the institutional and environmental regulations.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Meteorological and Hydrological Conditions

Figure 4.1 shows the monthly mean rainfall and mean WT data of the study area. January has recorded the highest monthly mean rainfall (372.2 ± 32.3 mm). The highest mean WT was also recorded in January for all sampling points with mean WT values of -50.9 ± 3.56 cm (Q1-Q4), -49.7 ± 1.94 cm (Q5-Q8) and -47.8 ± 3.52 cm (Q9-Q12) respectively, suggesting the effect of groundwater recharge due to high rainfall. July recorded the lowest monthly mean rainfall (133.6 ± 22.5 mm) throughout the study period. The lowest WT values were also obtained in July with mean WT values of -78.4 ± 2.59 cm and -85.4 ± 3.34 cm at Q1-Q4 and Q5-Q8 respectively. The low WT might be attributed to the low rainfall recorded in July, suggesting reduced precipitation, which leads to more WT drawdown (Carretero & Kruse, 2012; Corona et al., 2023). Furthermore, the evapotranspiration process or drainage could exacerbate the WT drawdown from the aquifer in the dry season (Jasechko et al., 2024; Yang et al., 2025). According to Chaddy et al. (2021), the wet and dry season in Sarawak occurs from November to March and from May to September and thus this explains the high and low mean WT in January and July, respectively. The descriptive statistics of the mean WT in the wet and dry seasons are summarized in Table 4.1. Based on observation, the mean WT for all the sampling points was lower in the dry season, in comparison to that of the wet season. A significant difference ($p < 0.05$) was found between the wet and dry seasons for the WT data based on the independent t-test results. According to Chaddy et al. (2021), the wet and dry season in

Sarawak occurs from November to March and from May to September and thus this also explains the high and low mean WT in January and July, respectively

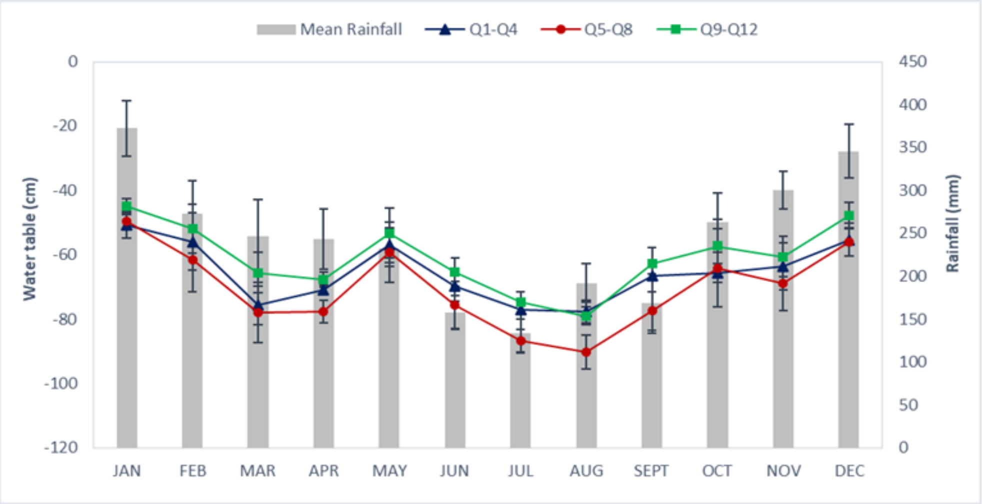


Figure 4.1: Monthly rainfall and WT variations at the study site throughout the study period January 2011 -December 2017 and October 2021-March 2022

Table 4.1: Mean water table, WT of the study site in the wet and dry seasons

WT (cm)	Q1-Q4 (Transplanting Year 2000)				Q5-Q8 (Transplanting Year 2001)				Q9-Q12 (Transplanting Year 2003)				Drained Secondary Forest (DSF)		
	Min**	Max**	Mean ± SE**	Independent sample t-test (p-value) *	Min**	Max**	Mean ± SE**	Independent sample t-test (p-value) *	Min**	Max**	Mean ± SE**	Independent sample t-test (p-value) *	Min**	Max**	Mean ± SE**
Wet season (Nov-Mar)	-89.2	-6.50	-55.9 ± 5.31	0.003	-104.65	-7.88	-57.7 ± 3.99	0.001	-90.80	-7.88	-52.6 ± 3.36	0.001	-59.1	-78.5	-68.5 ± 2.70
Dry season (May-Sept)	-89.9	-30.2	-69.2 ± 2.36		-104.28	-12.59	-77.3 ± 3.51		-85.33	-12.59	-66.5 ± 2.73		Nil	Nil	Nil

* The independent t-test is significant at $p < 0.05$ level between the wet and dry seasons.

** The negative (-) WT values indicate below ground surface reference.

4.2 Soil Chemical Properties

Based on Figure 4.2a, the mean soil pH in the study site ranges from 3.10 (75-100 cm) at DSF to 3.57 (25 – 50 cm) at Q5 -Q8. DSF soil is the most acidic with the lowest mean soil pH, and the highest mean soil pH was obtained at Q5-Q8 for each soil depth, respectively. The lower soil pH in DSF suggests the effect of organic acids produced from the decomposition of litter by microorganisms that entered the soil through leaching and gave rise to acidic substances, resulting in a decrease in soil pH and an increase in exchangeable H^+ and Al^{3+} (Zhang et al., 2020). Contrary to soil pH, mean soil electrical conductivity (Figure 4.2b) was recorded as the highest at DSF ranging from 135.8 μScm^{-1} (25-50 cm) to 186.1 μScm^{-1} (25-50 cm), which could be due to the accumulation of forest litter at the ground that increases soil nutrients (Kellner et al., 2015). Similarly, DSF also recorded the highest mean values for Total Nitrogen, TN % ranging from 1.42 % (25-50 cm) to 1.66 % (0-25 cm) (Figure 4.2c) and for Total Carbon, TC% ranging from 51.82 % (0 – 25 cm) to 54.51% (75-100 cm) (Figure 4.2d) indicating high organic matter supply from vegetation (Kunarso et al., 2022). Meanwhile, the lowest mean values for TN% (Figure 4.2c) and TC% (Figure 4.2d) were obtained at Q5-Q8 with values from 0.99% (0-25 cm) to 1.11% (25-50 cm), and 35.97% (0-25 cm) to 42.35% (75-100 cm) respectively. Plantations had significantly lower net primary production of aboveground biomass and litter than natural forests, in which these differences may result in lower C input into soil (Johnson & Curtis, 2001; Liao et al., 2012). The result is also consistent with previous studies that soil bulk density (BD) increased in OPP caused soil TC and TN concentrations to decrease or vice versa (Liao et al., 2012; Guillaume et al., 2016). The lowest C/N ratio was obtained at DSF (31.3) at 0-25 cm soil depth, while Q1-Q4 recorded the highest C/N ratio (43.7) at 75-100 cm (Figure 4.2e), which indicates a higher amount of soil N over soil C at DSF due to high organic matter decompositions. According to Marty et al. (2017) as cited by Guan et al. (2021), a high soil C/N ratio could slow down the decomposition rate of organic N by reducing soil microbial activities, while low C/N ratios could accelerate the processes, favourable to carbon accumulation. The lowest mean soil loss on ignition, LOI% (Figure 4.2f) which represents soil organic matter (Hoogsteen et al., 2018), was obtained at Q5-Q8 for each soil depth ranging from 93.78% (0-25 cm) to 95.62% (50-75 cm), while the highest mean soil LOI% was obtained at Q9-Q12, ranging from 98.44% (50-75cm) to 98.85% (25-50cm), (Figure 4.2f) could be attributed to the high WT that influence biogeochemical processes of soil organic matter by altering aerobic and anaerobic conditions, influencing C and N distributions (Guan et al., 2021; Ren et al., 2022). In addition, oil palm replanting could have increased the substantial amount of the above-ground oil palm residues, contributing to C and N mineralization in the soil (Khalid et al., 1999).

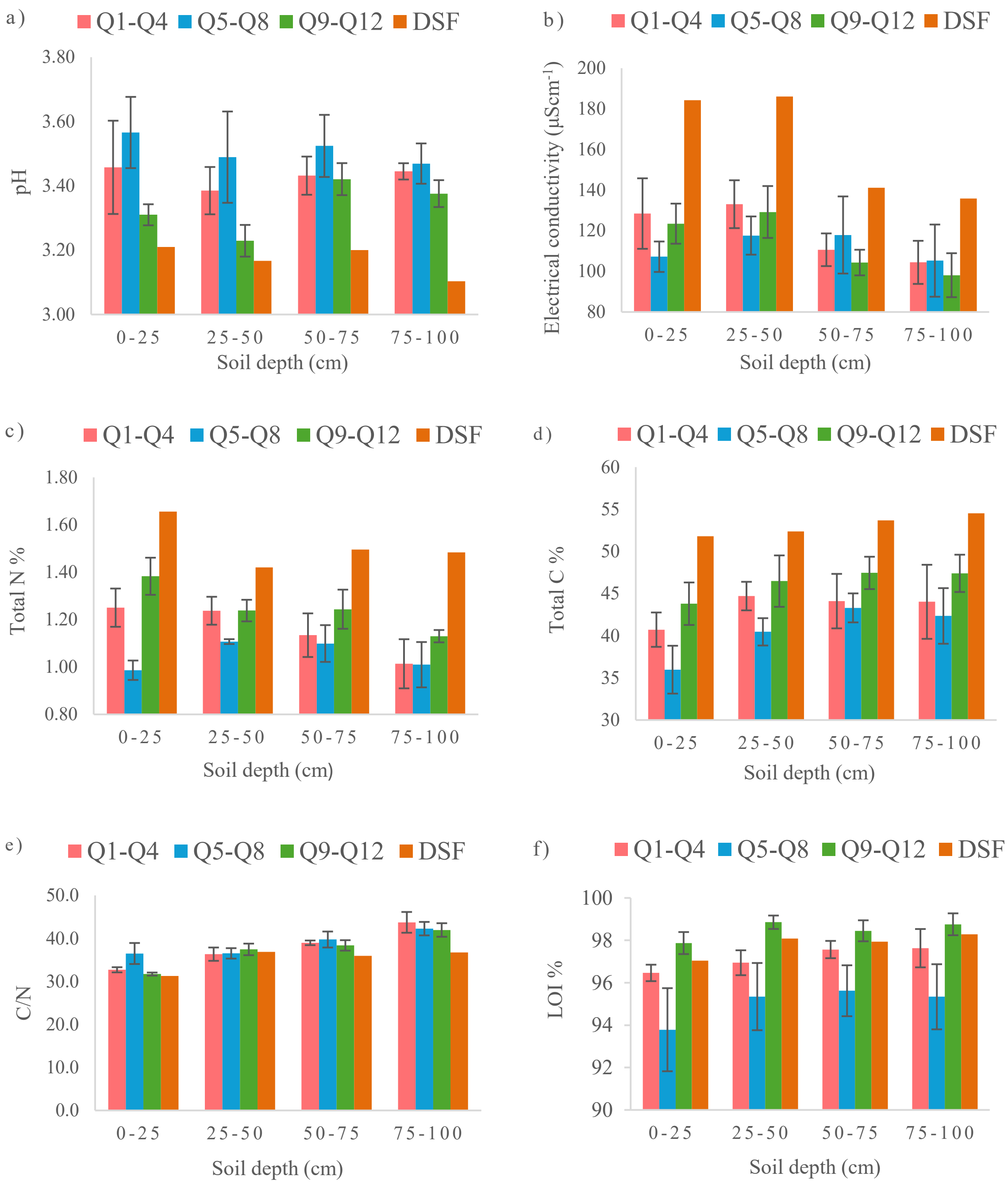


Figure 4.2: Summary of soil chemical parameters a) pH, b) electrical conductivity, c) total nitrogen, TN%, d) total carbon, TC%, e) C/N and f) loss on ignition, LOI%

Overall, DSF dominates the OPP with the highest concentrations of soluble NH_4^+ (122.06 mg L^{-1}) Figure 4.3a, K^+ (90.45 mg L^{-1}) Figure 4.3d and PO_4^{3-} (272.61 mg L^{-1}) Figure 4.3f, found at the top soil layer 0-25 cm, while the highest soluble Na^+ (126.17 mg L^{-1}) Figure 4.3b and Cl^- (145.24 mg L^{-1}) Figure 4.3e, was found at the bottom soil layer (75-100 cm). The accumulation of soluble nutrients in the DSF topsoil highlights the importance of the forest ecosystem in retaining peat soil nutrients, which is critical for maintaining peatland fertility and reducing nutrient losses to deeper layers and groundwater.

The high soluble ions found at the topsoil layer (0-25cm) at DSF suggest the effect of high TN and TC found at the topsoil layer (Figures 4.2c & 4.2d). Forest-derived organic matter inputs enhance nutrient cycling and cation retention, reinforcing the dominant role of TN in regulating soil ion availability. TN from forest litter or soil is highly correlated with soluble ions, which indicates the dominant role of TN in the soil ion content. The high TC at DSF can adsorb soil surface trace metal cations, reducing the mobility of these cations, leading to metal cation accumulation in the topsoil (Wang & Huang, 2001; Han et al., 2021). The natural nutrient retention mechanism reduces leaching risks and supports long-term soil fertility under forest conditions.

The conversion of forest to OPP could disturb the topsoil layer (Ramadhan et al., 2022), causing a lower amount of these ions in the OPP topsoil layer. High contents of C and N in peat soil have led to large hectares of peatland being developed for agricultural use (Muniandy et al., 2009), affecting the soil nutrient concentrations. Hence, agricultural development could alter nutrient distribution patterns, potentially increase nutrient losses and reduce peatland resilience over time.

However, Q5-Q8 recorded the highest soluble NH_4^+ (92.89 mg L^{-1}) Figure 4.3a, K^+ (98.45 mg L^{-1}) Figure 4.3d, and PO_4^{3-} (155.40 mg L^{-1}) Figure 4.3f at 75 -100 cm soil depth, suggesting the effect of the low TC% and TN% for ion absorptions, which results in the leaching of these ions down to the bottom soil layer . Thus, the downward movement of nutrients may increase nutrient loading to groundwater and drainage waters, posing risks to downstream water quality and long-term peatland sustainability.

In contrast, DSF recorded the lowest soluble Ca^{2+} (11.06 mg L^{-1}) found at 75-100cm soil depth, while the highest Ca^{2+} (31.31 mg L^{-1}) was found at Q1-Q4 (0-25 cm) Figure 4.3c. The high soluble Ca concentrations could originate from high Ca fertilizer amounts applied to mature oil palm trees at Q1-Q4, which were planted and replanted earlier than oil palm trees at Q5-Q8 and Q9-Q12. Moreover, high Ca content in soil can constrain K uptake by crops (Nguyen et al., 2017; Yadessa et al., 2019) and when facilitated by low pH can consequently increase the potential for soil K leaching from surface soil (Kassim et al., 2019), which explained the low concentrations of soluble K^{+} at Q1-Q4 (Figure 4.3d). This interaction highlights the importance of balanced nutrient management in oil palm plantations to reduce plant nutrient deficiencies and inefficient fertilizer use.

The highest Cl^{-} concentration (145.25 mg L^{-1}) at 75–100 cm depth obtained at DSF (Figure 4.3e) are likely caused by the evapotranspiration process influenced by the larger forest canopy and low soil BD due to lesser soil compaction, which decreases water capillary rise (Tarigan et al., 2020), consequently reducing Cl^{-} loss during evapotranspiration and solubilizing into the groundwater instead. Moreover, no KCl fertilizer was applied at DSF, which could increase the naturally present Cl^{-} concentrations in groundwater (Islam & Mostafa, 2021). From a peatland management perspective, this emphasizes the role of intact forest hydrology in regulating solute transport and minimizing surface nutrient losses.

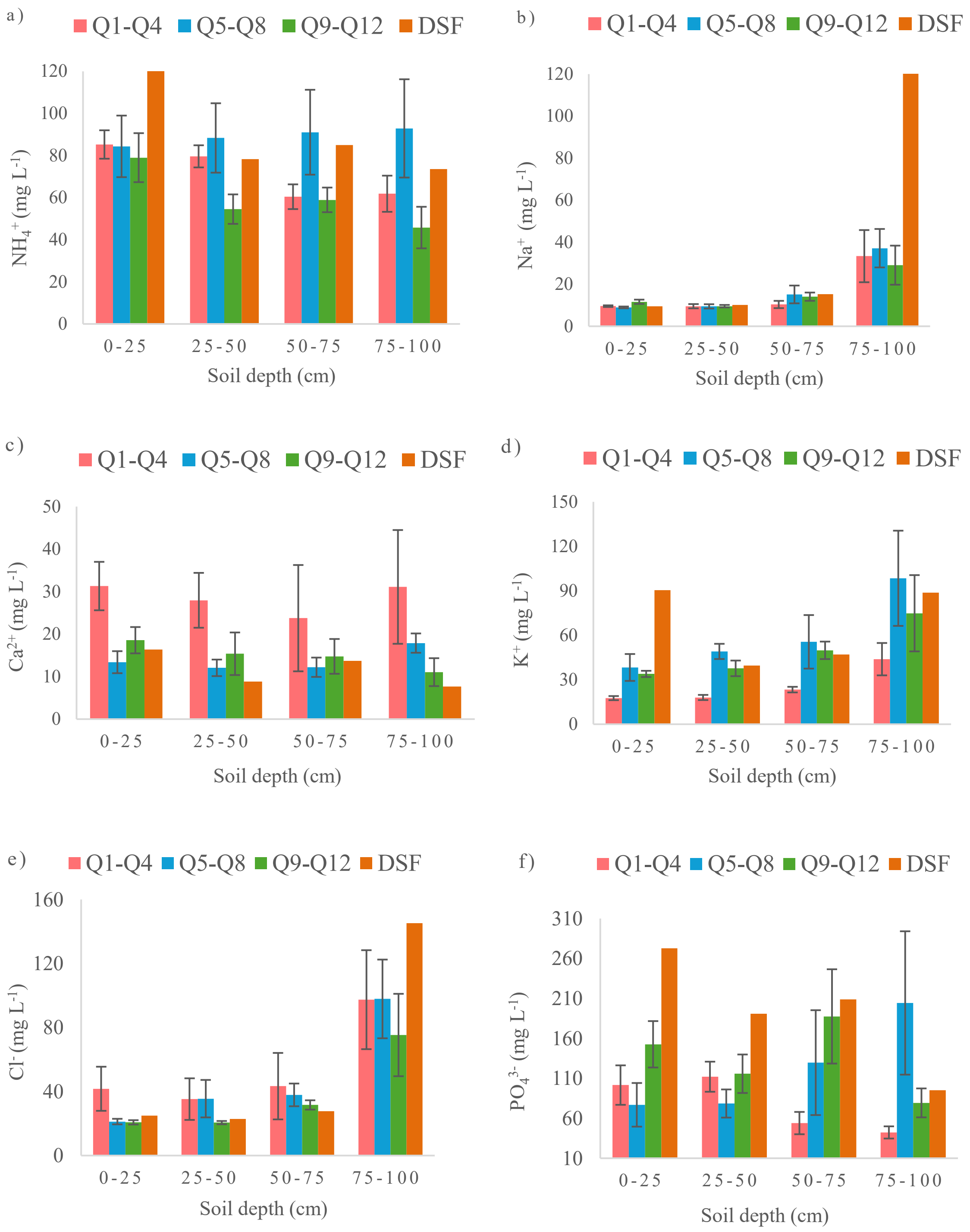


Figure 4.3: Summary of soil soluble ions concentrations a) NH$_4^+$, b) Na$^+$, c) Ca$^{2+,}$ d) K$^+$, e) Cl$^-$ and f) PO$_4^{3-}$

4.3 Objective 1: Effect of Drainage and Soil Compaction on SMC in OPP with comparison to DSF

4.3.1 Soil Moisture

Figure 4.4 summarises the mean SMC (%) value in the study site measured via the soil moisture probe PR2/6 Profile Probe, Delta T-Device at OPP a) planting row (PR), b) harvesting path (HP), c) palm circle (PC) and d) drained secondary forest (DSF). Mean SMC data obtained at DSF were repeated for LSD's significant test with mean SMC at respective oil palm plantation (OPP) management zones: PR, HP and PC.

The mean SMC in the OPP (Q1-Q4), (Q5-Q8) and (Q9-Q12) increases with soil depths (Figure 4.4). In the planting row zone (PR), the mean SMC values at Q1-Q4 at soil depths 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 50-60 cm and 90-100 cm were ranged from 39.5 ± 2.53 %, 53.1 ± 1.67 %, 58.0 ± 2.48 %, 59.1 ± 3.66 %, 73.5 ± 3.42 % to 98.4 ± 1.92 % (Figure 4.4a). At Q5-Q8, the mean SMC range was from 43.8 ± 2.44 %, 55.3 ± 1.05 %, 57.1 ± 2.52 %, 64.1 ± 2.98 %, 80.4 ± 1.53 % to 100.5 ± 0.96 % for the same sequence of layers. Meanwhile, the mean SMC values at Q9-Q12 ranged from 39.3 ± 2.47 % at 0-10 cm to 101.4 ± 0.84 % at 90-100 cm (Figure 4.4a). Overall, it was observed that the OPP (Q1-Q4), (Q5-Q8) and (Q9-Q12) exhibited higher SMC in between the 10 cm -100 cm soil layer, as compared to the DSF (Figure 4.4a). On the other hand, both HP and PC zones at Q9-Q12 show the widest SMC range, which are 42.5 ± 2.64 % to 99.2 ± 1.16 % in HP (Figure 4.4b) and 27.9 ± 3.30 % to 97.6 ± 1.21 % in PC (Figure 4.4c), respectively. The wide SMC range is likely associated with high organic matter supply at Q9-Q12, followed by the differences in soil compaction resulting from harvesting and plantation traffic activities. Soil moisture fluctuations can affect soil quality by altering peat structure, reducing soil bearing capacity, and influencing root aeration, which may lead to uneven root development, increased susceptibility to water stress or waterlogging, and crop performance.

In the harvesting path zone (HP), the lowest mean SMC was 42.5 ± 2.64 %, while the highest mean SMC was 99.2 ± 1.16 % both found at Q9-Q12 (Figure 4.4b). Similar to the HP zone, both the lowest mean SMC (27.9 ± 3.30 %) and highest mean SMC (97.6 ± 1.21 %) of the palm circle (PC) zone were also found at Q9-Q12 (Table 4.4).

The mean SMC % at DSF ranged from 33.1 ± 2.59 % to 97.9 ± 1.09 % at 10-20 cm and 60-100 cm respectively (Table 4.2 -Table 4.4). Contrary to the OPP sampling points, the mean SMC of the top 0-10cm soil layer at DSF (45.6 ±11.8 %) was higher than that of the second soil layer 10-20 cm (33.1 ± 2.59 %). The SMC at DSF only increased with depth starting from the 10 cm soil depth.

Overall, the OPP (Q1-Q4), (Q5-Q8), and (Q9-Q12) exhibited higher SMC in between the 10 cm- 100 cm soil layer, as compared to the DSF. Based on the LSD's significant test, the mean SMC of the OPP (Q1-Q4), (Q5-Q8) and (Q9-Q12) showed significant differences ($p < 0.05$) with DSF at 10-20 cm, 20-30 cm and 30-40 cm soil depths, both in the PR (Table 4.2) and HP zones (Table 4.3). No significant difference was found at the top 0-10 cm and bottom 60-100 cm soil layer between all the sampling points (Tables 4.2-4.4). Overall, the SMC range in the 0-60 cm soil depths at OPP falls within the optimal SMC range for oil palm trees, which is between 30 % to 75 % (Rawi et al., 2020).

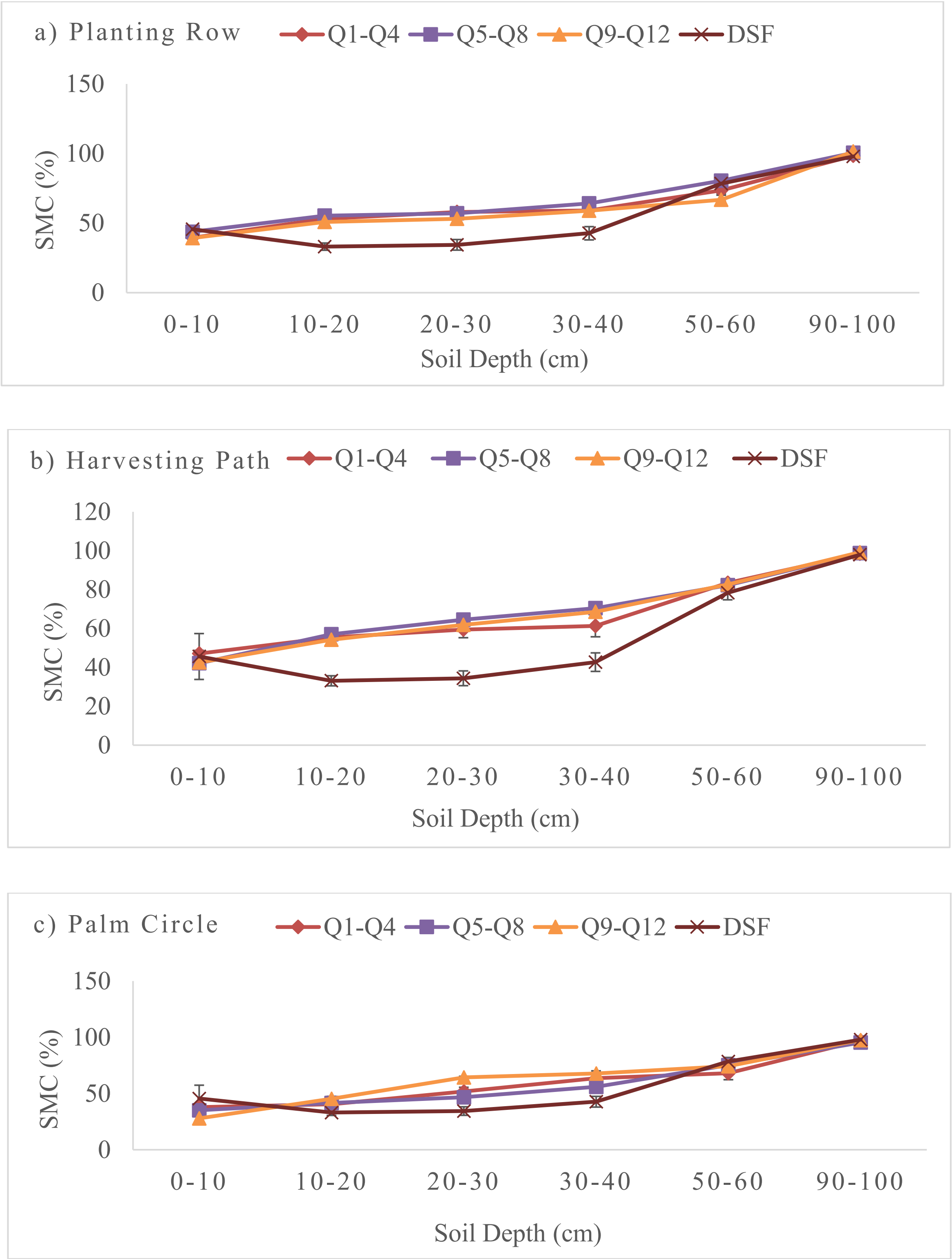


Figure 4.4: Mean SMC (%) at (a) planting row (PR) b) harvesting path (HP) and c) palm circle (PC) with comparison to DSF

Table 4.2: Summary of SMC (%) at (0-100) cm soil depths at planting row (PR)

Soil Depth (cm)	Q1-Q4 (n=20)	Q5-Q8(n=20)	Q9-Q12(n=20)	DSF (n=15)
0-10	39.5 ± 2.53	43.8 ± 2.44	39.3 ± 2.47	45.6 ±11.8
10-20	53.1 ± 1.67^{d}	55.3 ± 1.05^{d}	50.9 ± 1.53^{d}	33.1 ± 2.59^{abc}
20-30	58.0 ± 2.48^{d}	57.1 ± 2.52^{d}	53.1 ± 2.59^{d}	34.4 ± 3.80^{abc}
30-40	59.1 ± 3.66^{d}	64.1 ± 2.98^{d}	58.8 ± 2.98^{d}	42.7 ± 4.76^{abc}
50-60	73.5 ± 3.42	80.4 ± 1.53^{c}	66.7 ± 4.62^{bd}	78.4 ± 3.64^{c}
90-100	98.4 ± 1.92	100.5 ± 0.96	101.4 ± 0.84	97.9 ± 1.09
Mean	63.6 ± 1.70^{d}	67.3 ± 1.69^{cd}	59.1 ± 1.64^{bd}	50.6 ± 3.75^{abc}

Note: Statistically significant differences LSD test ($p<0.05$) between the respective sites and depths are indicated by superscript indices which denote the significantly different sites: a = Q1-Q4, b = Q5-Q8, c = Q9-Q12, d = DSF.

Table 4.3: Summary of SMC (%) at (0-100) cm soil depths at harvesting path (HP)

Soil Depth (cm)	Q1-Q4 (n=20)	Q5-Q8(n=20)	Q9-Q12(n=20)	DSF (n=15)
0-10	47.1 ± 1.66	42.1 ± 2.70	42.5 ± 2.64	45.6 ±11.8
10-20	55.4 ± 1.73^{d}	57.0 ± 0.79^{d}	54.2 ± 1.33^{d}	33.1 ± 2.59^{abc}
20-30	59.4 ± 4.14^{d}	64.5 ± 1.96^{d}	61.8 ± 2.41^{d}	34.4 ± 3.80^{abc}
30-40	61.3 ± 5.56^{d}	70.5 ± 2.08^{d}	68.6 ± 2.60^{d}	42.7 ± 4.76^{abc}
50-60	83.4 ± 1.05	82.2 ± 1.33	82.6 ± 1.34	78.4 ± 3.64
90-100	98.5 ±1.12	98.8 ± 1.07	99.2 ± 1.16	97.9 ± 1.09
Mean	66.9 ± 1.18^{c}	69.2 ± 0.87^{cd}	57.2 ± 2.35^{ab}	60.5 ± 5.14^{b}

Note: Statistically significant differences LSD test ($p<0.05$) between the respective sites and depths are indicated by superscript indices which denote the significantly different sites: a = Q1-Q4, b = Q5-Q8, c = Q9-Q12, d = DSF.

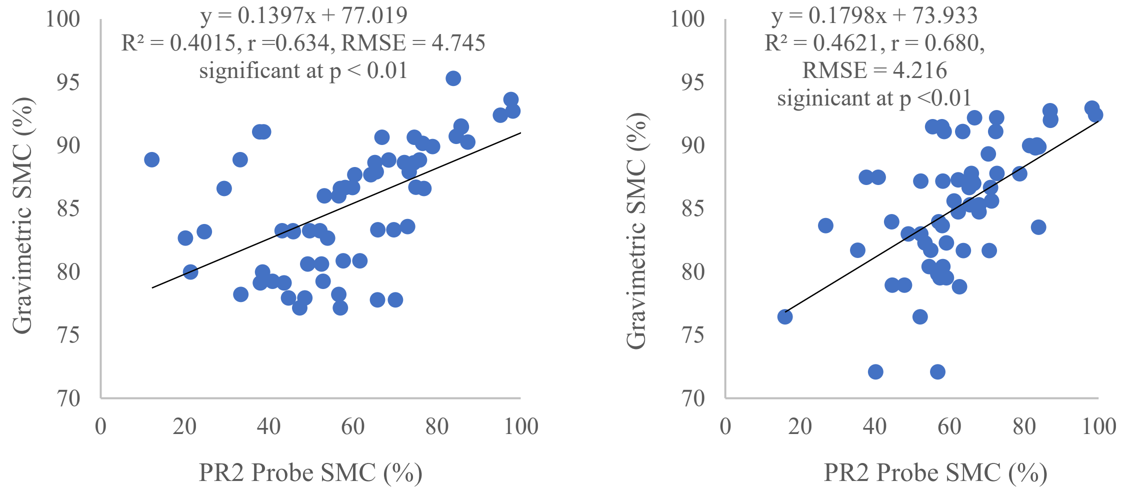
Table 4.4: Summary of SMC (%) at (0-100) cm soil depths at palm circle (PC)

Soil Depth (cm)	Q1-Q4 (n=20)	Q5-Q8(n=20)	Q9-Q12(n=20)	DSF (n=15)
0-10	37.9 ± 2.80	35.1 ± 2.84	27.9 ± 3.30^{d}	45.6 ±11.8^{c}
10-20	40.5 ± 3.23	41.6 ± 3.36	45.4 ± 2.09^{d}	33.1 ± 2.59^{c}
20-30	51.8 ± 3.74^{cd}	46.8 ± 3.62^{cd}	64.3 ± 0.98^{abd}	34.4 ± 3.80^{abc}
30-40	63.7 ± 2.15^{d}	55.9 ± 3.70^{cd}	67.8 ± 2.33^{bd}	42.7 ± 4.76^{abc}
50-60	68.1 ± 5.82	75.3 ± 2.81	74.3 ± 3.95	78.4 ± 3.64
90-100	97.1 ± 1.35	95.3 ± 2.55	97.6 ± 1.21	97.9 ± 1.09
Mean	61.7 ± 1.50^{bd}	67.9 ± 1.07^{acd}	61.9 ± 1.06^{bd}	54.9 ± 1.50^{acd}

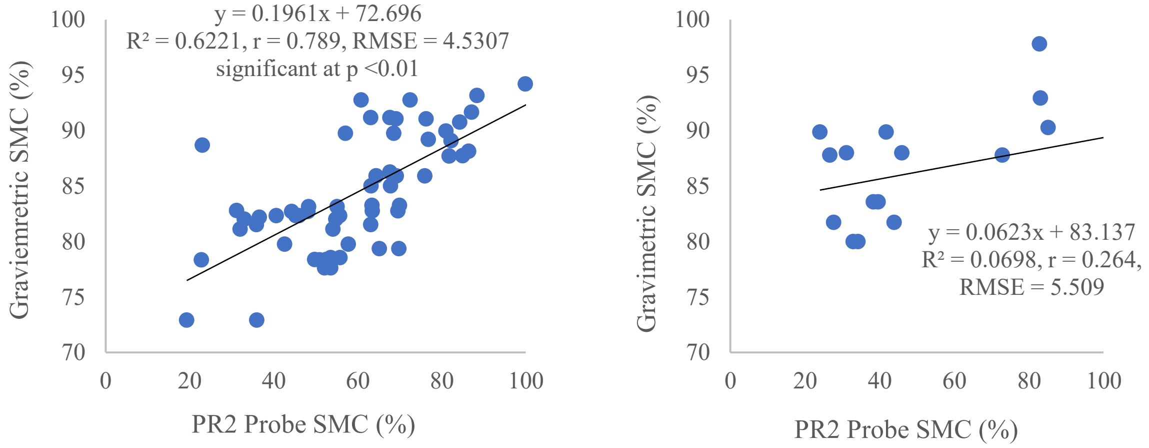
Note: Statistically significant differences LSD test ($p<0.05$) between the respective sites and depths are indicated by superscript indices which denote the significantly different sites: a = Q1-Q4, b = Q5-Q8, c = Q9-Q12, d = DSF.

4.3.2 Method Validation and Field Calibration for Soil Moisture Measurement

Linear regression equations between PR2 probe SMC (%) and gravimetric method SMC (%), which is used as a reference value, were obtained to validate the soil moisture measurement method using the PR2 probe in this study (Figure 4.5). The validation method has been used in previous soil moisture studies (Holzman et al., 2017; Dhakal et al., 2019), and the performance and accuracy of the PR2 probe were evaluated using the root mean square error (RMSE), based on the field calibration method (Markovic et al., 2024). The highest significant Pearson correlation is obtained at PC ($r = 0.789$, $p < 0.01$), followed by HP ($r = 0.680$, $p < 0.01$) and PR ($r= 0.634$, $p < 0.01$). The lowest Pearson correlation value ($r = 0.264$) is obtained at DSF, with an insignificant correlation. In contrast, the RMSE value obtained at DSF (RMSE = 5.509) is the highest as compared to PC (RMSE = 4.5307), HP (RMSE = 4.216), and PR (RMSE = 4.745). The higher correlations and lower RMSE in PC and HP zones might reflect more uniform soil conditions or management practices in the OPP zones, while the poor correlation in DSF could be due to greater natural variability or structural complexity in the forest soil (Liao et al., 2012; Rasheed et al., 2022). The peat soil in this study area has high organic matter content as reflected in the high soil loss on ignition (%) is > 93 % (Figure 4.3f). According to Holzman et al. (2017), high organic matter content could be the source of uncertainty in the measured soil moisture. Soil dielectric constant is affected by relative fractions of bound and free water in the soil, shape of the soil particles and the shape of the water inclusions around the particles (Hallikainen et al., 1985). The high soil organic matter content at DSF might interfere with dielectric readings of the moisture probe by altering soil water retention or introducing air gaps (Gulser & Demir, 2015). According to Tomer et al. (1999), BD variations could also have influences dielectric constant of the soil moisture sensor such that when BD is significantly high (> 1.7 g cm^{-3}), soil moisture sensor signal tends to overvalue soil moisture, while low BD (< 1.0 g cm-3) undervalues soil water content. This suggests the low SMC content found at the DSF as compared to the OPP at the 10-100 cm soil depth (Figures 4.4a-c, Tables 4.2a-c). Other than that, soil heterogeneity could also significantly affect the measured soil moisture by introducing variability in water content across a given area (Yetbarek et al.,2020). Precautionary steps, such as taking higher SMC readings frequency per sampling point, could reduce measurement error by obtaining the average SMC. Lastly, it is also important to avoid creating either air gaps or soil compaction around the access tube so that the soil would not shrink or swell as it is dried out or rewetted during the access tube installation and while measuring the SMC (Devices, 2008).


a) Planting Row (n =72)

b) Harvesting Path (n=72)

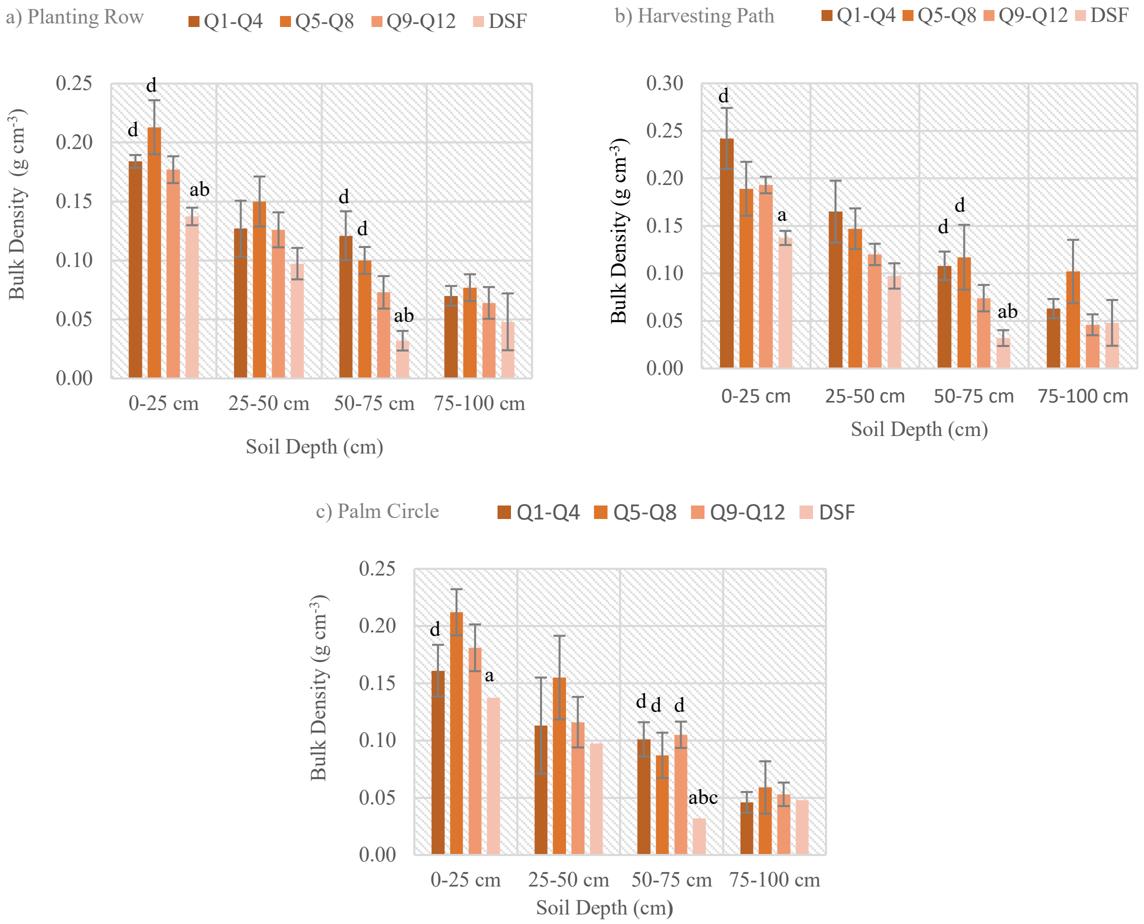

c) Palm circle (n=72)

d) Drained Secondary Forest (n=18)

Figure 4.5: Comparison between measured SMC (%) obtained via the PR2 Probe and reference SMC (%) obtained using the gravimetric method

4.3.3 Soil Bulk Density

Figure 4.6 summarizes the mean soil BD value in the study site at OPP, a) planting row (PR), b) harvesting path (HP), and c) palm circle (PC), with the comparisons to mean soil BD data at DSF, respectively. The degree of soil compaction was quantified and evaluated by using the soil BD value. Overall, the mean soil BD of all sampling points is in the range of (0.03 ± 0.01) g cm^{-3} at DSF to (0.24 ± 0.03) g cm^{-3} at HP (Figure 4.6b). DSF recorded the lowest soil BD in comparison to OPP at soil depths (0-25) cm, (25-50) cm and (50-75) cm of all the OPP management zones (Figures 4.6a-c). The lower soil BD at DSF suggests minimal mechanical disturbance (Shaheb et al., 2021) and higher organic matter content typical of peat soils (Bauer, 1974; Ekwue, 1990). In contrast, the higher BD at HP might reflect frequent trafficking or soil compaction from harvesting activities (Guillaume et al., 2016; Zuraidah, 2019). Results of LSD's test at $p<0.05$ shows that a significant difference in soil BD between OPP and DSF was only found at soil depths (0-25) cm and (50-75) cm. A significant trend was also observed at PC (50-75) cm soil depth in which the soil BD of all OPP sites is statistically significant in comparison to DSF respectively (Figure 4.6c). The result suggests the presence of oil palm roots at the 50-75 cm soil depth at PC could have influenced soil BD by modifying soil pore space (Lu et al., 2020; Fu et al., 2021).



Note: Statistically significant differences LSD test ($p<0.05$) between the respective sites and depths are indicated by letters which denote the significantly different sites: a = Q1-Q4, b = Q5-Q8, c = Q9-Q12, d = DSF.

Figure 4.6: Summary of mean soil BD value in the study site at OPP a) planting row (PR), b) harvesting path (HP) and c) palm circle (PC) with comparison to DSF respectively.

4.3.4 Correlation between Water Table and Soil Moisture

Figure 4.7 summarises the correlation of WT (cm) with SMC (%) at OPP management zones; a) planting row (PR), b) harvesting path (HP), c) palm circle (PC) and d) drained secondary forest (DSF). Weak correlations ($p < 0.05$) were found between mean WT and mean SMC (planting row, PR $R^2 = 0.2381$, harvesting path, HP $R^2 = 0.2467$, palm circle, PC $R^2 = 0.2534$, drained SF, DSF $R^2 = 0.0718$). Although weak correlations were observed, the positive correlations indicate that increased WT results in increased SMC and vice versa, similar to previous findings (Marwanto et al,2018; Adhi et al.,2020). The weakest WT and SMC correlation, with the highest RMSE value (8.264) found at DSF, could be attributed to the effect of high soil organic matter (Gulser & Demir, 2015) and low BD, which alters the dielectric readings of the soil moisture sensor (Tomer et al., 1999), as discussed previously.

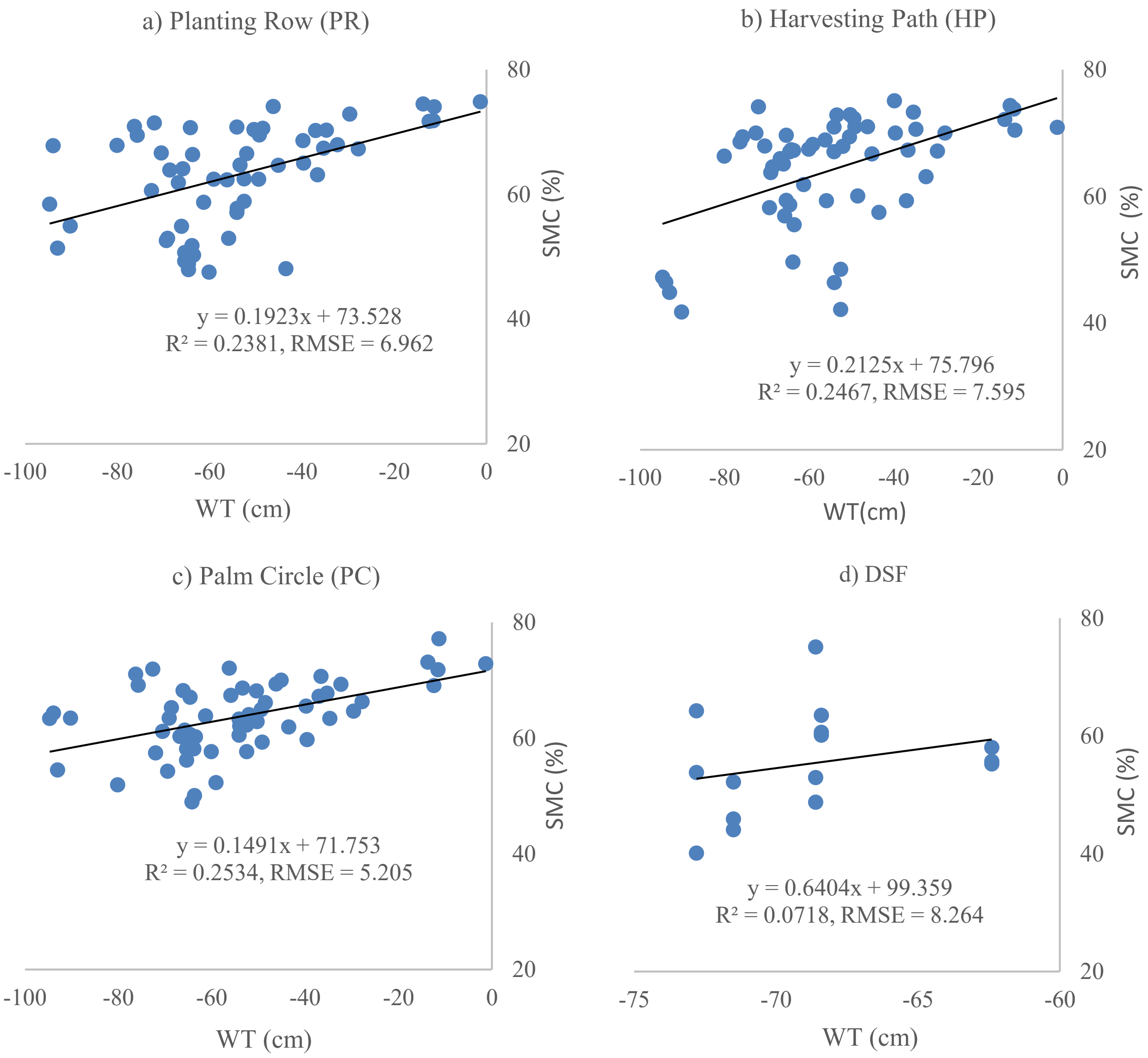


Figure 4.7: Linear regression of WT (cm) with SMC (%) at OPP management zones; a) planting row, b) harvesting path, c) palm circle and d) drained secondary forest (DSF)

4.3.5 Correlation between Soil Bulk Density and Soil Moisture

Figure 4.8 summarises the correlation between average soil BD (g cm^{-3}) with average SMC (%) at OPP management zones; a) planting row, b) harvesting path, c) palm circle and d) DSF. Weak correlations ($p < 0.05$) were found between soil BD and SMC (planting row $R^2 = 0.1672$, harvesting path $R^2 = 0.0913$, palm circle $R^2 = 0.1015$, DSF $R^2 = 0.2289$). The higher soil BD and SMC correlations, with the lowest RMSE value (3.574) obtained at DSF could be attributed to its lower BD and higher organic matter, potentially enhancing moisture retention (Word et al., 2021). Besides, the higher mean WT due to drainage obtained at OPP as compared to DSF, which could increase soil BD (Kunarso et al., 2022) might also influence the SMC readings (Chen & Hu, 2004; Guglielmo et al., 2021). In addition, low soil BD (< 1.0 g cm^{-3}) tends to undervalue the soil water content (Tomer et al., 1999) and thus alters the soil BD and SMC relationship.

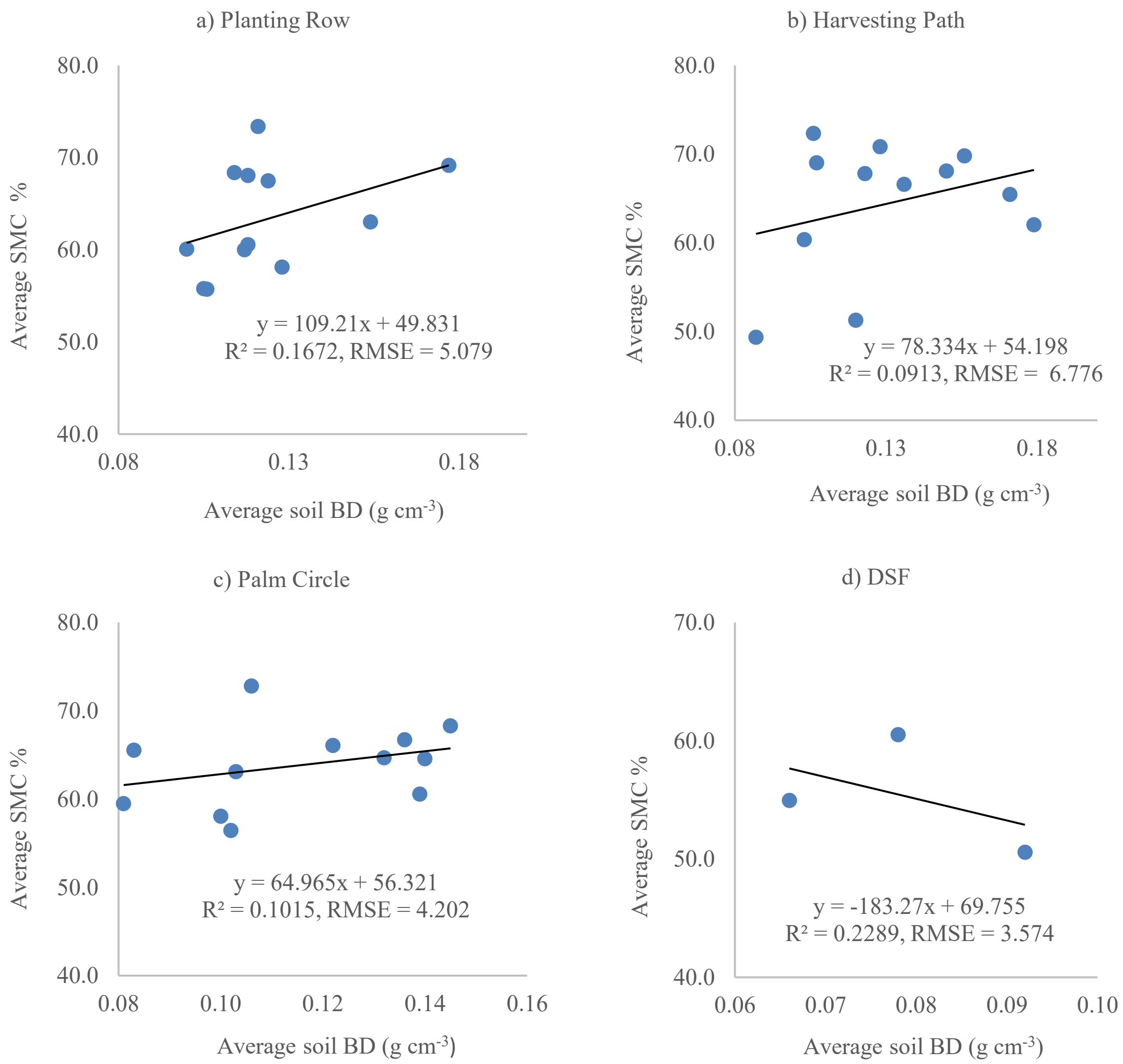


Figure 4.8: Linear regression of average soil BD (g cm^{-3}) with average SMC (%) at OPP management zones; a) planting row, b) harvesting path, c) palm circle and d) drained secondary forest

4.3.6 Discussion: Effect of Drainage and Soil Compaction on Soil Moisture Content

The mean WT of the study site is in the range of (-68.7 ± 1.79) cm found at DSF to (-43.9 ± 6.29) cm at Q5-Q8. The data is comparable to the WT range (50-75 cm) from the peat surface suggested for a good water management system for oil palm on deep peat (Melling et al., 2009). Based on a study on peat soil in North Sumatra, Indonesia by Winarna et al. (2015), WT management between 40 – 60 cm could retain higher SMC and avoid the upper soil layer from hydrophobicity. Moreover, WT in the 40- 60 cm range will increase oil palm productivity, restrict CO_2 emissions and retains soil moisture in the upper layer (Ginting et al.,2016).

The lowest soil bulk density (BD) was found at DSF in comparison to Q1-Q4, Q5-Q8 and Q9-Q12 at 0-75 cm soil depths, which is comparable to other studies for peat soil. For example, a study by Adhi et al. (2020) in Indonesia reported the highest peat soil BD (0.09 – 0.15) g cm^{-3} in OPP compared to secondary forest (0.07 – 0.12 g cm^{-3}) at 0-30 cm soil depths. Other than that, the soil BD data of the OPP in this study also exhibited decreasing value moving down the soil profile for 0-100 cm soil depths, and at 0-75 cm soil depths for DSF. Similar results were obtained by Ngau et al. (2022) for peat soil study at 0-200 cm soil depths which reported a decrease in soil BD for OPP and secondary forest moving down the soil profile.

The OPP sampling points reported higher soil BD suggesting the effects of soil compaction activities such as mechanical farming and foot traffic (Nawaz et al., 2013), which could be attributed to the changes in soil structure and reduction of soil pore space that occurred due to soil compaction increasing soil BD (Shaheb et al., 2021). Other than that, higher soil BD at OPP suggest the effect of higher mean WT as compared to DSF. A review study by Kunarso et al. (2022) revealed that BD between different land uses reported higher values in the drained peat as compared to the forest sites. High peat soil BD in drained sites and at surface layers is influenced by WT and occurs where the position of the WT tends to be below the surface throughout the year.

The mean SMC increases with soil depths for the OPP sampling points (Q1-Q4), (Q5-Q8) and (Q9-Q12). A similar result was reported by Ma et al. (2011) in which SMC rises with the increase of soil depth layer. According to Ngau et al. (2022), the increase of soil moisture with depths was due to the submersion of peat below the WT. At the 10-20 cm soil depths, the mean SMC is between 33.1 – 57 %, within the range reported by Taufik et al. (2023), based on a study in Indonesia peatlands.

A significant difference ($p<0.05$) in SMC (%) was found between the respective OPP sampling points (Q1-Q4), (Q5-Q8) and (Q9-Q12) with DSF sampling points at the 10 – 40 cm soil depths, suggesting the influence of soil compaction., consistent with the findings by Tonks et al. (2017) and Ngau et al. (2022). Enhanced peat decomposition, potentially in combination with compaction from machinery resulted in greater shear strength and lower SMC in the surface peat layer at oil palm sites (Tonks et al., 2017). Moreover, higher soil BD influences the rate of water movement through peat (Othman et al., 2018), which could reduce soil porosity and soil water infiltration rate, thus affecting SMC.

However, there was no significant difference ($p < 0.05$) found with regards to SMC between the OPP sampling points (HP and PC) with DSF at 50-60 cm soil depths. The mean WT of the study area is between the 40-60 cm range could have influenced the SMC at the 50-60 cm soil depths. Lastly, the SMC values found between the OPP and DSF sampling points at the 90-100 cm soil layer were also insignificant ($p <0.05$), suggesting the effect of peat submersion below the WT (Ngau et al., 2022).

4.4 Objective 2: Influence of Replanting and Fertilizer Application on OPP Groundwater Quality with comparison to DSF

4.4.1 Temporal and Spatial Values of Groundwater pH and Nutrient Concentrations

The temporal and spatial values of groundwater pH and nutrient concentrations in the wet and dry seasons are depicted in Figures 4.9 and 4.10. A significant trend was observed in which groundwater pH, K^+ and Cl^- concentration at DSF were the lowest throughout the years (Figures 4.9a-f) across both the wet and dry seasons compared to the OPP (Q1-Q4, Q5-Q8 and Q9-Q12). DSF's lower groundwater pH and ion concentrations might reflect higher organic acid inputs and reduced leaching in an undisturbed peat system (Wang et al., 2019; Han et al., 2021; Zhang et al., 2020).

A sharp increase in groundwater pH was recorded in the wet season of the year 2022 (Figure 4.9a) in which the groundwater pH was the highest throughout the study period at the OPP respectively (Q1-Q4 = 4.05, Q5-Q8 = 4.42 and Q9-Q12 = 4.84). Groundwater pH exhibits a positive correlation with NO_3^- in the wet season (Anggat et al.,2024), such that the increase in pH would increase NO_3^- concentration in groundwater and vice versa. According to Yang et al. (2022), redox condition and pH benefited the nitrification which suggests the increase of NO_3^- in groundwater (Figure 4.10a).

The OPP sites (Q1-Q4, Q5-Q8, Q9-Q12) dominated the DSF site for the highest concentration of annual mean of groundwater K^+ and Cl^- throughout the study period. The higher pH, K^+ and Cl^- values at the OPP could be attributed to fertilizer leaching into the groundwater or drainage which alters groundwater chemistry (Anggat et al., 2024).

The highest groundwater NO_3^- concentration (Figure 4.10a) was also recorded in the wet seasons of 2022 for Q1-Q4 (8.11 mg L^{-1}) and Q5-Q8 (3.36 mg L^{-1}) which suggest the leaching of nutrients from soil into the groundwater facilitated by high rainfall (Adnani et al., 2020; Anggat et al., 2024). However, no significant trend was observed between NO_3^- annual mean concentrations at DSF and OPP (Q1-Q4, Q5-Q8, Q9-Q12) throughout the study period both in the wet and dry seasons (Figure 4.10a-b). A study by Speiran et al. (1998) indicates that in addition to the presence of forest buffers, a range of natural factors such as soil texture, organic matter content, and groundwater flow paths affect the fate of NO_3^- in groundwater. The insignificant differences in NO_3^- regardless of DSF and OPP could also be due to leaching which is known to be high in tropical peat soils (Muniandy et al., 2009).

Soluble NH_4^+ ranges from 0.25 mg L^{-1} at Q5-Q8 to 1.42 mg L^{-1} at DSF in which both values are found in the wet season of 2011 (Figures 4.10c-d). The groundwater NH_4^+ could result from nitrogen-containing fertilizer leaching at OPP (Ah Tung et al., 2009; Hidayat & Pangaribuan, 2017) and anaerobic decomposition of organic matter, which leads to the production of NH_4^+ (Szabo et al., 2014).

The maximum value of soluble PO_4^{3}- (6.83 mg L^{-1}) is also found in the wet season of 2011 at Q1-Q4 (Figure 4.10e) while the minimum value (0.07 mg L^{-1}) is found at Q5-Q8 in the dry season of 2012 (Figure 4.10f). Most groundwater samples at DSF are below the detection limit (< 0.00 mg L^{-1}) for soluble $PO_4^{3-.}$ According to Speiran et al. (1998), forests provide buffers that remove P and sediment from surface runoff, explaining the very low level of PO_4^{3-} in the DSF groundwater. Furthermore, the higher soil organic matter at DSF could bind more nutrients, resulting in less PO_4^{3-} leaching in groundwater, as compared to OPP.

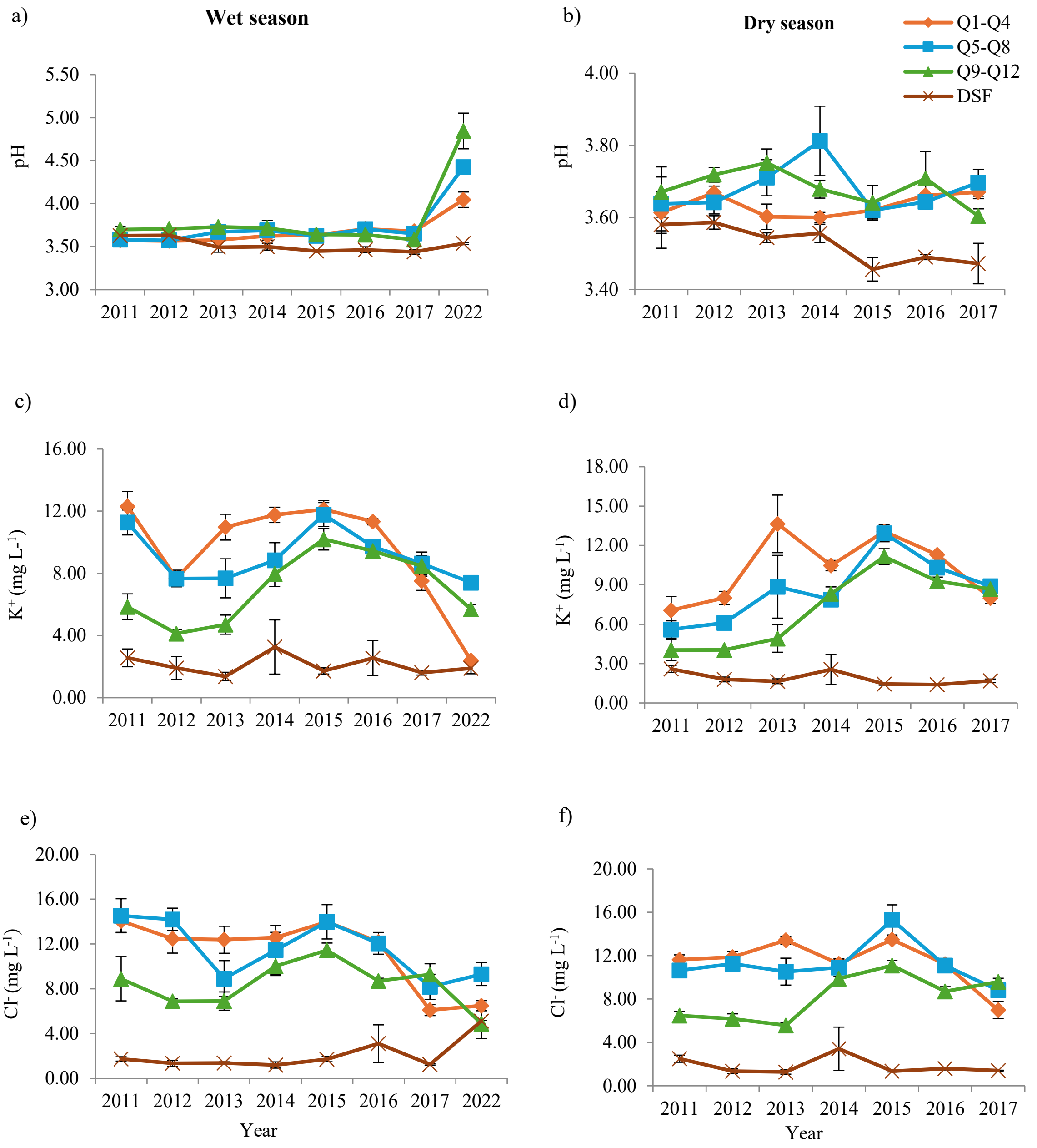


Figure 4.9: Summary of temporal and spatial values of groundwater pH, soluble K^+ and soluble Cl^- concentrations in the wet and dry seasons

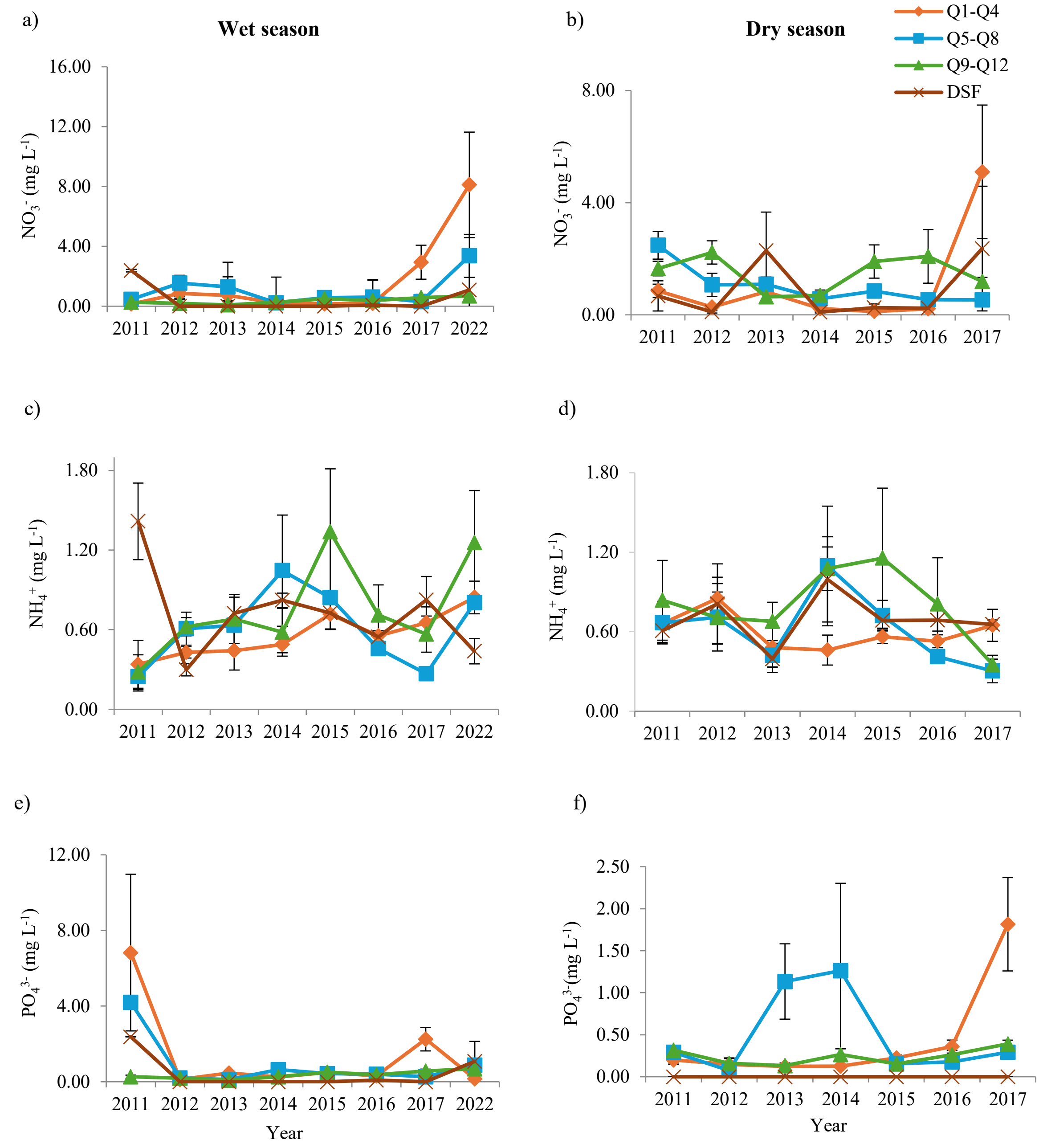


Figure 4.10: Summary of temporal and spatial values of groundwater soluble NO_3^-, NH_4^+ and PO_4^{3-} in the wet and dry seasons

4.4.2 Seasonal Rainfall Influence on Groundwater Chemistry

Based on the previous study using Pearson correlation analysis by Anggat et al. (2024), the groundwater pH, K^+, Cl^- and PO_4^{3-} at the OPP showed no significant correlation with rainfall except for NO_3^- ($r = 0.343$, $p < 0.05$) and NH_4^+ ($r = -0.356$, $p < 0.05$). The study suggested that the high mean NO_3^- content in the groundwater (14.07 mg L^{-1}) obtained in September 2017 contributed to the high correlation between the total monthly rainfall and groundwater NO_3^- concentration. The application of urea fertilizer to palm trees could have influenced the high amount of NO_3^- leaching into the groundwater, facilitated by rainfall (Marwanto et al., 2018). On the other hand, the moderate negative correlation between rainfall and NH_4^+ concentrations in groundwater at Q5–Q8 in the wet season implies that NH_4^+ concentrations in groundwater decreases when rainfall increases. The high rainfall during the wet season could have decreased mineralization rates of N from fertilizer in soil (Zhang et al., 2020), and this explained the decrease of NH_4^+ concentrations leached into groundwater.

4.4.3 Water Table Fluctuations Influence on Groundwater Chemistry

In this study, a significant difference ($p < 0.05$) was found between the wet and dry seasons for the WT data based on the independent t-test results (Table 4.1). Nevertheless, the results of Pearson correlation analysis only showed significant correlations between the WT and groundwater K^+ and NH_4^+ concentration at the OPP (Anggat et al., 2024). Moderate negative correlation between the WT and K^+ concentration ($r = -0.386$, $p < 0.05$) at Q1–Q4 and ($r = -0.348$, $p < 0.05$) at Q9–Q12 were found in the wet season. The study suggested that the monovalent cations K^+ in the soil are leached more easily (Marwanto et al., 2018) and the cation exchange capacity of peat soil organic matter is extremely low at low soil pH (<4.0), causing K^+ leach immediately through desorption mechanisms (Osaki et al., 2021).

Meanwhile, a moderate negative correlation (r = −0.380, $p < 0.05$) was found between the WT and NH_4^+ at Q5–Q8 in the dry season, showed that the WT at the OPP also significantly influenced NH_4^+ concentrations in the groundwater (Anggat et al., 2024). The study suggested that the decrease in WT would increase NH_4^+ concentration in groundwater and vice versa and could be associated with active denitrification due to anaerobic bacteria (Ishaku et al., 2012).

4.4.4 Discussion: Influence of Replanting and Fertilizer Application on Groundwater Quality

Based on the results of the chemical analysis, the groundwater is consistently acidic with a mean pH < 3.45. Peat groundwater is naturally acidic, and this could be attributed to the acidic nature of peat soil (Kononen et al., 2015). DSF exhibited the lowest groundwater pH in comparison to the OPP sampling points (Q1-Q4), (Q5-Q8) and (Q9-Q12). Higher groundwater pH in the OPP points suggest the effect of fertilizer application such as urea. According to Nadarajan and Sukumaran. (2021), hydrolysis of urea could increase soil pH. The application of magnesium fertilizer could also be attributed to the higher groundwater pH in the oil palm sampling points (Hidayat & Pangaribuan, 2017).

Nitrate, NO_3^- is possibly the most widespread groundwater contaminant globally, dangerous to human health and contributing to eutrophication (Bhatnagar & Sillanpaa, 2011). In this study, the annual mean groundwater NO_3^- concentration observed does not exceed the WHO guideline (10 mg L^{-1}), set by the World Health Organization (2022), and there was no significant difference observed between mean groundwater NO_3^- obtained in the OPP sampling points and DSF. The highest annual mean for groundwater pH (4.84) and NO_3^- concentration (8.11 mg L^{-1}) recorded in the year 2022 at Q9-Q12 and Q1-Q4 respectively, could be due to loss of soil organic matter for nutrient adsorption due to land clearing for oil palm replanting (Goh et al., 2003) and redox reaction which influence pH and NO_3^- relationship in the wet season (Yang et al., 2022; Anggat et al., 2024). The high annual mean concentrations of K^+ and Cl^- in groundwater at the OPP compared to the DSF may result from the leaching of MOP fertilizer nutrients into the groundwater (Islam & Mostafa., 2021). The moderate to high positive correlations between K^+ and Cl^- in groundwater (Anggat et al., 2024), further support the findings. The groundwater nutrients within OPP remained below the critical values for drinking water set by the WHO, except for K^+ concentration (12.9 mg L^{-1}) during the dry season of 2013, which surpassed the WHO guideline of K^+ (12.0 mg L^{-1}). However, the K^+ concentration in water does not impose a health risk when consumed (World Health Organization, 2022).

Overall, there is no significant trend observed for the annual mean of soluble NO_3^-, NH_4^+ and PO_4^{3-} in the wet and dry seasons between the OPP and DSF, suggesting that factors such as soil organic matter and its decomposition by anaerobic bacteria with the high nutrient leaching in peat soil (Speiran et al., 1998; Muniandy et al., 2009; Szabo et al., 2014) could influence the soluble NO_3^-, NH_4^+ and PO_4^{3-} concentrations in groundwater over the wet and dry seasons.

4.5 Objective 3: Statistical Correlation between Soil Moisture Content and Groundwater Quality

4.5.1 Correlation between Groundwater Chemical Parameters and Groundwater Quality

The Pearson correlation between groundwater chemical parameters and SMC (%) obtained in January 2022 was studied. At Q1-Q4, high negative correlations (significant at $p < 0.01$) were obtained between SMC and soluble Cl^- ($r = -0.715$), and soluble PO_4^{3-} ($r = -0.736$) obtained at PC and PR respectively (Table 4.5) suggests increasing SMC decreases groundwater soluble Cl^- and PO_4^{3-} at Q1-Q4 and vice versa. Moderate negative correlations were obtained between SMC and soluble K^+ ($r = - 0.570$, $p < 0.05$) (Table 4.5), total P ($r = -0.470$, $p < 0.05$), total K ($r = -0.572$, $p < 0.01$) at HP (Table 4.6), while moderate negative correlations between SMC and pH ($r = 0.592$, $p < 0.01$), electrical conductivity ($r = -0.590$, $p < 0.01$) and total Zn ($r = 0.524$) were found at PC.

The high correlation between SMC and groundwater chemical parameters at Q5-Q8 was only found with total K ($r = -0.726$, $p < 0.01$) at PC. Moderate correlations were obtained between SMC and electrical conductivity ($r = -0.680$, $p < 0.01$), soluble Cl^- ($r = -0.603$, $p < 0.01$), soluble NH_4^+ ($r = -0.652$, $p < 0.01$), soluble PO_4^{3-} ($r = -0.551$, $p < 0.05$), soluble SO_4^{3-} ($r = -0.496$, $p < 0.05$), soluble K^+ ($r = -0.56$, $p < 0.05$) (Table 4.3), total P ($r = -6.40$, $p < 0.01$), total K ($r = -0.563$, $p < 0.01$) and total Mn ($r = -0.503$, $p < 0.05$) at PR (Table 4.6). Moderate significant correlations were obtained between SMC and electrical conductivity ($r = -0.484$, $p < 0.05$), soluble NH_4^+ ($r = -0.541$, $p < 0.05$), soluble K^+ ($r = -0.643$, $p < 0.01$) (Table 4.5), total P ($r = -0.529$, $p < 0.05$) and total K ($r = -0.574$, $p < 0.01$) at HP (Table 4.6). Moderate significant correlation values were obtained between SMC and soluble SO_4^{3-} ($r = -0.548$, $p < 0.05$), soluble K^+ ($r = -0.691$, $p < 0.01$) (Table 4.5), and total Fe ($r = 0.522$, $p < 0.05$) at PC (Table 4.6).

Total Fe ($r = -0.455$, $p < 0.05$) was moderately correlated with SMC at PR zone of Q9-Q12 (Table 4.6). Groundwater pH ($r = -0.614$, $p < 0.01$), soluble Cl^- ($r = -0.517$, $p < 0.05$), soluble Na ($r = -0.470$, $p < 0.05$), soluble K ($r = 0.574$, $p < 0.01$) (Table 4.5) and total K ($r = 0.597$, $p < 0.01$) were moderately correlated with SMC at HP zone of Q9-Q12 (Table 4.6), while pH ($r= -0.459$, $p < 0.05$), soluble NO_3^- ($r = 0.553$, $p < 0.05$), soluble SO_4^{3-} ($r = -0.473$, $p < 0.05$), soluble Na^+ ($r= -0.450$, $p < 0.05$) were moderately correlated with SMC at PC zone of Q9-Q12 (Table 4.5).

At DSF, high positive correlations were found between SMC and electrical conductivity ($r = 0.959$, $p < 0.01$) (Table 4.5) and total P ($r = 0.918$, $p < 0.05$ (Table 4.6). A high negative correlation was only found between SMC and soluble NH_4^+ ($r = - 0.982$, $p < 0.01$) (Table 4.5).

Table 4.5: Correlation values between SMC (%), groundwater pH, electrical conductivity and groundwater soluble nutrients at Q1-Q4, Q5-Q8, Q9-Q12 and DSF in January 2022

Q1-Q4	**pH**	**Elec.c**	**Cl$^-$**	**NO$_3^-$**	**PO$_4^{3-}$**	**SO$_4^{3-}$**	**Na$^+$**	**NH$_4^+$**	**K$^+$**	**Ca^{2+}**	**Mg^{2+}**
SMC (PR)	.009	.066	-.199	.387	**-.736****	-.129	-.342	.356	-.619**	-.305	-.084
SMC (HP)	.027	.023	-.245	.385	.043	-.068	-.359	.216	-.570**	-.397	-.091
SMC (PC)	.592**	-.590**	**-.715****	.305	-.250	.262	-.378	.364	-.337	-.115	.092
Q5-Q8	**pH**	**Elec.c**	**Cl$^-$**	**NO$_3^-$**	**PO$_4^{3-}$**	**SO$_4^{3-}$**	**Na$^+$**	**NH$_4^+$**	**K$^+$**	**Ca^{2+}**	**Mg^{2+}**
SMC (PR)	.258	-.680**	-.603**	-.294	-.551*	-.496*	.307	-.652**	-.560*	-.327	-.227
SMC (HP)	-.001	-.484*	-.421	-.289	-.227	-.400	-.077	-.541*	-.643**	-.391	-.321
SMC (PC)	-.175	-.286	-.130	-.238	-.042	-.548*	-.273	-.259	-.691**	.382	.397
Q9-Q12	**pH**	**Elec.c**	**Cl$^-$**	**NO$_3^-$**	**PO$_4^{3-}$**	**SO$_4^{3-}$**	**Na$^+$**	**NH$_4^+$**	**K$^+$**	**Ca^{2+}**	**Mg^{2+}**
SMC (PR)	-.068	.339	-.012	-.009	-.086	.201	.040	.098	-.059	-.097	-.002
SMC (HP)	-.614**	.031	-.517*	.242	-.142	-.221	-.470*	-.301	.574**	-.441	-.166
SMC (PC)	-.459*	-.025	-.366	.553*	.232	-.473*	-.450*	-.420	.227	-.422	-.138
DSF	**pH**	**Elec.c**	**Cl$^-$**	**NO$_3^-$**	**PO$_4^{3-}$**	**SO$_4^{3-}$**	**Na$^+$**	**NH$_4^+$**	**K$^+$**	**Ca^{2+}**	**Mg^{2+}**
R1	.059	.211	-.575	-.854	-	.022	.338	-.804	.427	.601	.637
R2	-.794	**.959****	-.642	.340	-	.624	-.335	-.303	-.840	-.139	-.236
R3	-.323	.404	-.237	-.092	-	.065	-.362	**-.982****	.223	.039	.047

Note: PR: Planting row, HP: Harvesting path, PC: Palm circle, R: Replicate. "*" denotes that correlation is significant at the 0.05 level (two-tailed), and "**" denotes that correlation is significant at the 0.01 level (two-tailed). Numbers in blue shade indicate a high correlation between parameters (r>0.70, r < -0.70).

Table 4.6: Correlation values between SMC (%) and groundwater total nutrients at Q1-Q4, Q5-Q8, Q9-Q12 and DSF in January 2022.

Q1-Q4	**Total P**	**Total K**	**Total Ca**	**Total Mg**	**Total Fe**	**Total Mn**	**Total Cu**	**Total Zn**	**Total Na**
SMC (PR)	-.634**	-.611**	.415	.213	.509*	.245	.214	.252	-.366
SMC (HP)	-.470*	-.572**	.227	.239	.329	-.065	.183	.402	-.358
SMC (PC)	-.040	-.351	.354	.158	.378	.317	.167	.524*	-.389
Q5-Q8	**Total P**	**Total K**	**Total Ca**	**Total Mg**	**Total Fe**	**Total Mn**	**Total Cu**	**Total Zn**	**Total Na**
SMC (PR)	-.640**	-.563**	.111	-.364	.137	-.503*	.368	.112	.321
SMC (HP)	-.529*	-.574**	.158	-.407	.155	-.317	.190	-.048	-.038
SMC (PC)	-.418	**-.726****	-.241	-.130	.522*	-.054	.250	.402	-.222
Q9-Q12	**Total P**	**Total K**	**Total Ca**	**Total Mg**	**Total Fe**	**Total Mn**	**Total Cu**	**Total Zn**	**Total Na**
SMC (PR)	-.032	-.007	.021	-.161	-.455*	-.207	-.178	-.279	.040
SMC (HP)	.002	.597**	-.090	.196	.016	.159	.235	.039	-.391
SMC (PC)	.197	.314	.244	.195	-.284	.224	.346	.211	-.455*
DSF	**Total P**	**Total K**	**Total Ca**	**Total Mg**	**Total Fe**	**Total Mn**	**Total Cu**	**Total Zn**	**Total Na**
R1	.590	.449	-.674	.442	-.062	-.719	-.767	.023	-.701
R2	-.268	-.736	.103	-.446	-.406	-.171	.172	-.755	-.521
R3	.119	.378	-.129	.752	-.399	-.738	-.797	-.274	-.311

Note: PR: Planting row, HP: Harvesting path, PC: Palm circle, R: Replicate "*" denotes that correlation is significant at the 0.05 level (two-tailed), and "**" denotes that correlation is significant at the 0.01 level (two-tailed). Numbers in blue shade indicates a high correlation between parameters ($r>0.70$, $r < -0.70$).

4.5.2 Linear Regression Model

Linear regressions (Figure 4.11) were developed by using SMC (%) and groundwater chemical parameters data with high positive correlation ($r > 0.7$) and negative correlation ($r < -0.7$) (Kannan & Joseph, 2022). The linear regression model has been utilised in many previous groundwater quality studies (Saikrishna et al., 2020; Dargahi et al., 2022; Fernandes et al., 2023) and could be utilised to predict groundwater chemical parameters based on SMC data. In this study, high negative correlations were found between SMC and groundwater PO_4^{3}-, Cl^{-}, total K and NH_4^{+} at the OPP, while a positive correlation only occurred between SMC and groundwater electrical conductivity at DSF. The regression model could be adopted in the study of hydrological processes in tropical peatland, its effect on groundwater quality, and for sustainable agriculture monitoring. It also offers potential for studying soil chemical processes such as soil ionic adsorption and solute transport of tropical peat soil, which is still scarce (McCarter et al., 2018). However, soil properties such as high soil organic matter, soil BD, and soil heterogeneity, particularly of peat soils (Hallikainen et al., 1985; Tomer et al., 1999; Liao et al., 2012; Gulser & Demir, 2015; Rasheed et al., 2022), which influence the soil moisture sensor readings and the groundwater chemical parameters, could restrict the model development as these factors influence the significant correlation between the parameters. Linear regression was chosen for this study due to its greater robustness for small sample sizes, prevents multicollinearity, and illustrates clearer relationships between parameters. Avoiding multicollinearity is important, as high correlations among independent variables can lead to unstable coefficient estimates and misleading results. In this study, analysing SMC against each groundwater parameter individually reduces this risk. While not all parameters may have strictly linear relationships with SMC, linear regression provides a useful first-order approximation to identify dominant trends and potential predictive relationships. Meanwhile, other statistical models, such as multiple linear regression (MLR), require larger datasets to minimize the risk of overfitting and issues of multicollinearity that lead to unstable coefficient estimates (Vatcheva et al., 2016; Shrestha, 2020). The linear regression equations are summarized in Table 4.7.

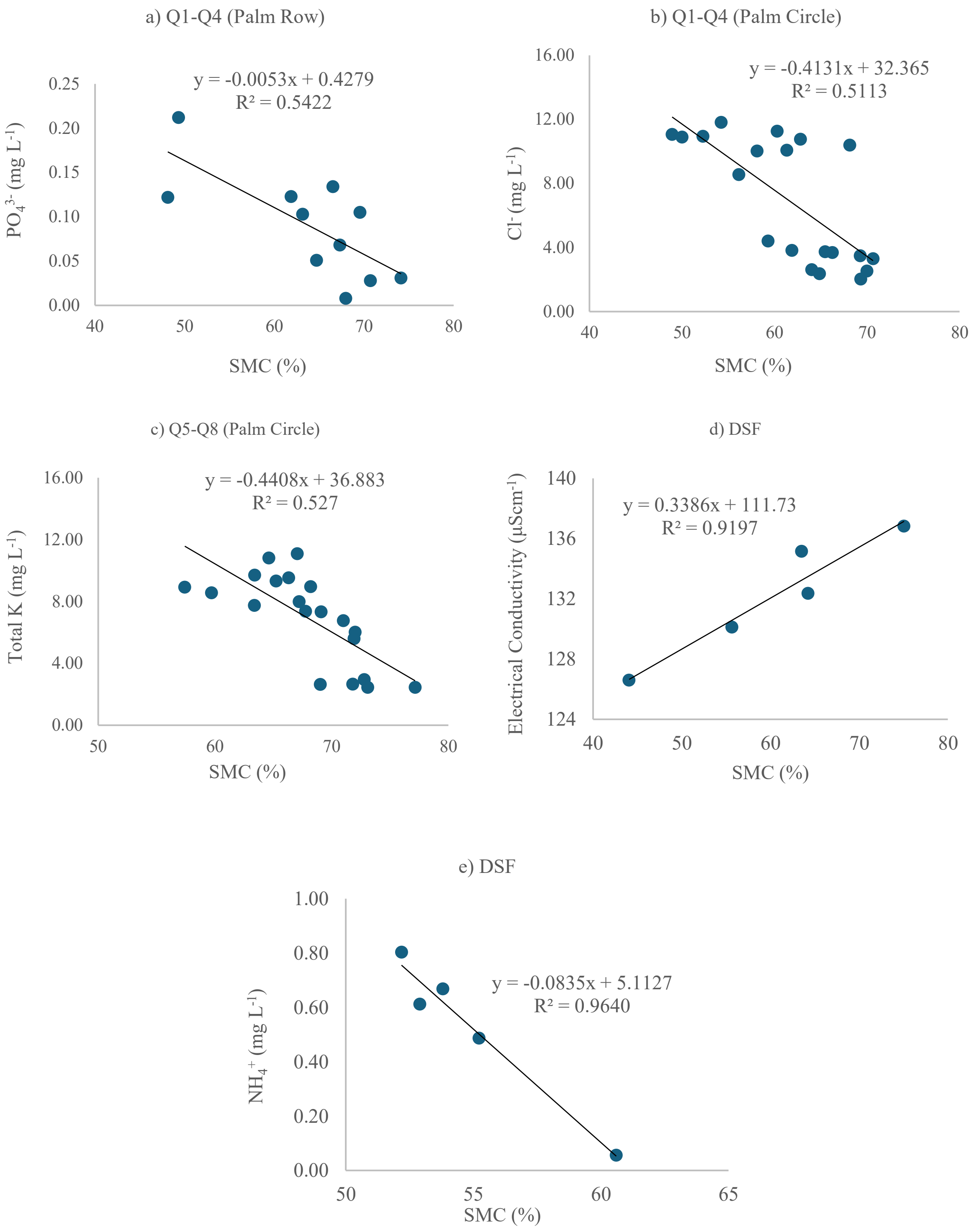


Figure 4.11: Linear regressions between SMC (%) and groundwater chemical parameters data with high correlation (r > 0.7, r <-0.7).

Table 4.7: Regression model for high correlations between SMC (%) and groundwater chemical parameters

Sampling Points	**y**	**x**	**r**	**a**	**b**	**Regression Equation**	**R^2**
Q1-Q4 (Planting Row)	PO_4^{3-}	SM	-0.736	-0.0053	0.4279	PO_4^{3-} = -0.0053(SM) + 0.4279	0.5422
Q1-Q4 (Palm Circle)	Cl^-	SM	-0.715	-0.4131	32.365	Cl^- = -0.4131(SM) + 32.365	0.5113
Q5-Q8 (Palm Circle)	Total K^+	SM	-0.726	-0.4408	36.883	Total K^+ = -0.4408(SM) + 36.883	0.527
Drained Secondary Forest (DSF)	EC	SM	0.959	0.3386	111.73	EC = 0.3386(SM) + 111.73	0.9197
	NH_4^+	SM	-0.982	-0.0835	5.1127	$NH4^+$ = -0.0835(SM) + 5.1127	0.9640

4.5.3 Linear Regression Model Evaluation

Figure 4.12 summarizes the regression between observed and predicted groundwater chemical parameters, with RMSE values of 0.0383 mg L^{-1} (PO_4^{3-}), 2.638 mg L^{-1} (Cl^-), 1.950 mg L^{-1} (Total K), 1.029 µS cm^{-1} (electrical conductivity), and 0.0484 mg L^{-1} (NH_4^+). The low RMSE values for PO_4^{3-} and NH_4^+ indicate strong predictive performance, likely due to lower variability in the concentration of these ions within the groundwater samples or a stronger linear relationship between these variables and the predictors used. In contrast to other parameters, Cl^- and Total K show higher RMSE values, reflecting reduced model reliability for these parameters. Factors such as complex geochemical behaviors, greater natural variability, or the influence of anthropogenic sources such as agricultural runoff might not be fully captured by the model (White & Broadley, 2001; Islam & Mostafa, 2021;

Wang et al., 2023). Consequently, predictions for these parameters should be interpreted as indicative trends rather than precise estimates.

To further evaluate the performance of the regression model, residual plots are provided in Figure 4.13. These plots represent the residuals which are the differences between observed and predicted values and provide insight into the model's estimation behavior. Positive and negative estimate errors indicate overestimation and underestimation, respectively. Examining residuals could assess model performance, accurately predict target variables, identify potential outliers and anomalies in the dataset. For example, PO_4^{3-} and NH_4^+ show narrow residual ranges (–0.06 to 0.05 mg L^{-1} and –0.08 to 0.05 mg L^{-1}, respectively), indicating consistent prediction accuracy. Conversely, wider residual ranges for Cl^- (–3.46 to 6.19 mg L^{-1}) and total K (–3.82 to 3.77 mg L^{-1}) reflect greater deviations from observed values and lower predictive reliability (Mokhtar et al., 2022; Irwan et al., 2025). These wider residuals also likely reflect spatial heterogeneity in the soil or localized variations in nutrient leaching, which are common in tropical peatlands due to uneven compaction, drainage, and fertilizer application. Hence, while the regression models capture general trends, caution is needed when interpreting predictions for highly variable parameters such as Cl^- and Total K. Furthermore, examining the residual plots helps to identify potential outliers or data anomalies (Irwan et al., 2025).

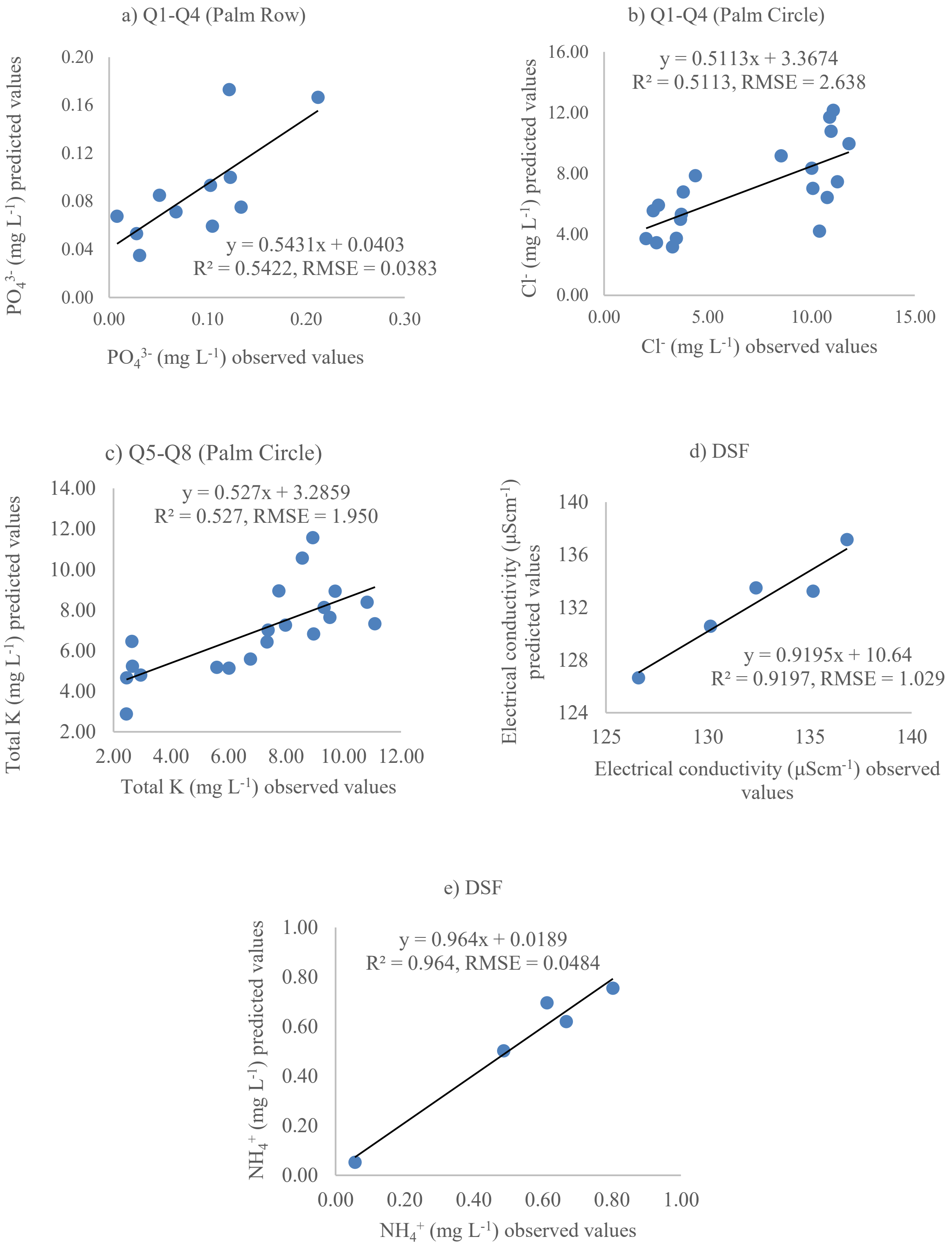


Figure 4.12: The linear plot of the groundwater chemical parameters observed and predicted values

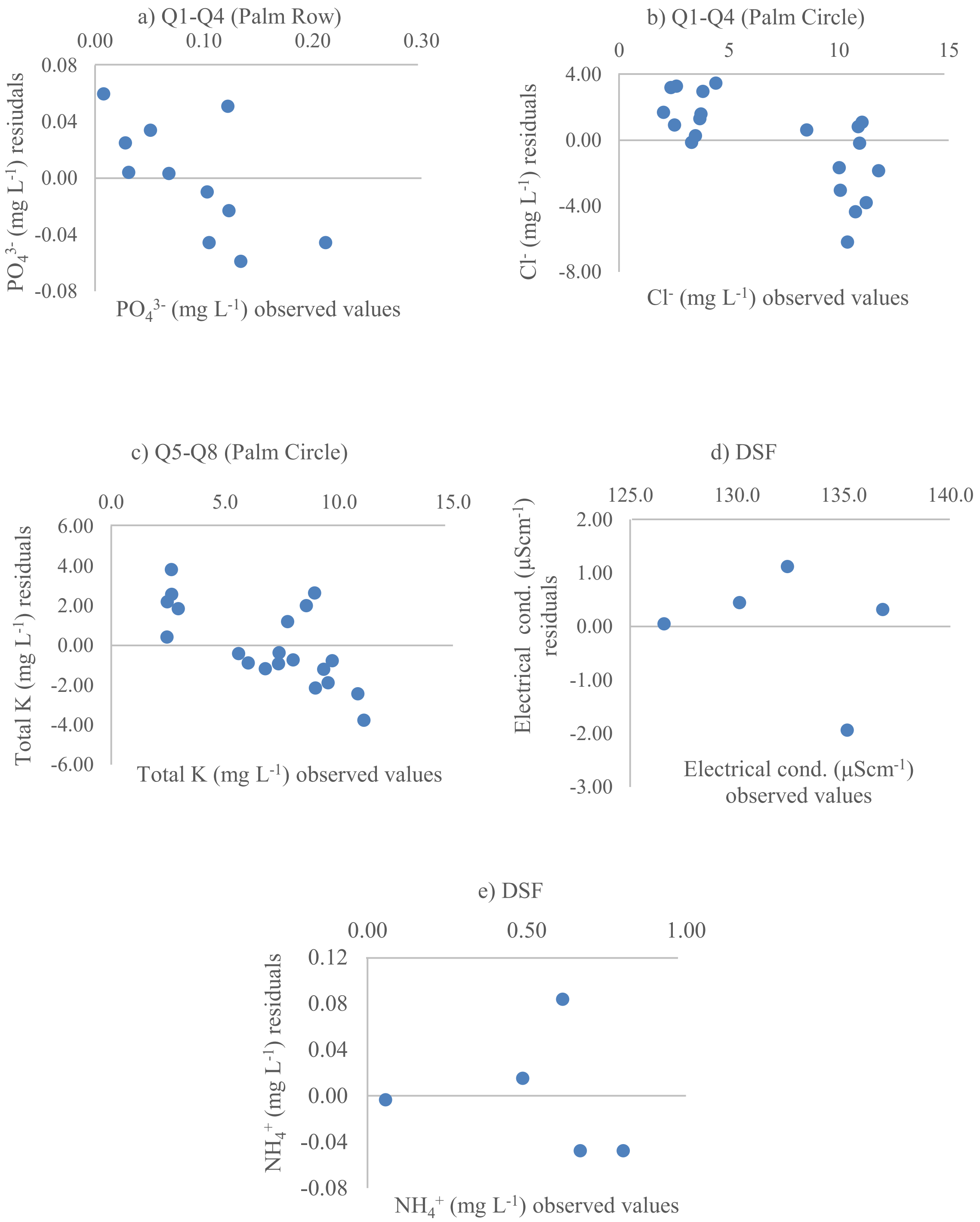


Figure 4.13: Residual plots between the observed and predicted values of groundwater chemical parameters

4.5.4 Discussion: Influence of Soil Moisture Content on Groundwater Chemical Properties

Regression-based analysis between SMC (%) and groundwater chemical parameters at the OPP shows high negative correlations with soluble PO_4^{3-} (r = -0.736), Cl^- (r= -0.715) and total K^+ (r = -0.726), all significant at $p < 0.01$ respectively. This indicates that decreasing SMC in agricultural soils could increase these nutrient concentrations in water bodies.

SMC influences groundwater soluble PO_4^{3-} as a high negative correlation ($p < 0.01$) was found between SMC and soluble PO_4^{3-} in groundwater of the OPP (Q1-Q4), indicating that decreasing SMC could increase soluble PO_4^{3-} in groundwater and vice versa. Studies have shown that despite the high absorption capacity of the underlying soils, significant concentrations of phosphorus (P) can still be found in the drains, indicating the presence of preferential flow that occurs through permanent gaps in the field and may develop more in the dry season (Ebrahimi & Ojani, 2024). Moreover, water stress reduces plant P uptake and use efficiency from fertilizer, and maximum P uptake is only reached under well-watered conditions (Chtouki et al., 2022). Hence, the result suggests that reducing SMC could reduce the P uptake of plants and more P concentration could eventually leach down from soil into groundwater instead.

SMC also influences groundwater Cl^- concentrations as a high negative correlation ($p < 0.01$) was found between SMC and Cl^- concentration in groundwater of the OPP (Q1-Q4). When SMC increases, the concentration of Cl^- in groundwater decreases and vice versa, as reflected in the negative correlation between SMC and Cl^-. The Cl^- ions found in groundwater could originated from rainfall, irrigation water (Wang et al., 2023) and fertilizer sources applied to oil palm trees such as Muriate of Potash (MOP), KCl-containing fertilizer

(Islam & Mostafa, 2021) which is one of the main fertilizers applied in the plantation. According to White and Broadley (2001), Cl^- anion does not form complex readily and shows little affinity in its adsorption to soil components. Thus, Cl^- movement in soil is largely determined by water flows. In addition, SMC could decrease the chlorine (Cl_2) transport rate in groundwater (Hearn et al., 2014), and this might explain the negative correlations between SMC and Cl^-. Cl^- is consumed during the evapotranspiration process (Hayashi et al., 1998), accumulates within the unsaturated zone above the WT during the drying phase, and is solubilized back into groundwater during the rewetting phase, increasing its concentration (Renaud et al., 2023). However, there was no significant correlation found between SMC and groundwater Cl^- at DSF, suggesting that the evapotranspiration process at DSF might be influenced by the larger forest canopy and less compacted soil at DSF due to low soil BD, which decreases water capillary rise (Tarigan et al., 2020), consequently reducing Cl^- loss during evapotranspiration and solubilizing into the groundwater instead. Furthermore, there was no KCl fertilizer applied at DSF which could increase the naturally present Cl^- concentrations in groundwater (Islam & Mostafa, 2021).

Regression-based analysis between SMC and groundwater total K shows a strong negative correlation at PC (Q5-Q8), indicating that the increase in SMC reduces groundwater total K and vice versa. In this study, the total K content could originate from the MOP fertilizer (KCl) applied at PC, as K^+ is generally deficient in peat soil (Krishnan et al., 2021). According to Kuchenbuch and Jungk (1986), plant availability of K^+ increases with increasing SMC, thus increasing plant K^+ uptake, consequently reducing K^+ leaching into groundwater (Zeng & Brown, 2000). However, Q5-Q8 has the highest soil pH across the 0-100 cm soil depth which could facilitate K^+ leaching into the groundwater in wet conditions (Osaki et al., 2021). The lowest soil total C, total N and LOI content were also obtained at

Q5-Q8 across the 0-100 cm soil depth, indicating low soil organic matter content that could promote the initial fast rate of K^+ adsorption onto the soil (Wang & Huang, 2001). The low availability of soil organic matter for K^+ adsorption could eventually facilitate K leaching into the groundwater. The former could reverse the negative correlation between SMC and total K^+, such that the increase in SMC would increase K^+ leaching into the groundwater (the SMC and total K correlation would become positive). Hence, the result suggests that the effect of high soil pH and low soil organic matter on soil K^+ leaching is not significant over SMC for soil K retention at Q5-Q8.

Regression-based analysis between SMC (%) and groundwater chemical parameters at DSF shows a strong positive correlation with groundwater electrical conductivity (EC), indicating that the increase in SMC would increase groundwater EC. According to a study by Ratshiedana et al. (2023), soil EC is generally influenced by SMC and the high groundwater EC found at DSF could be attributed to the nutrients released from soil organic matter (Othaman et al., 2020). This suggests the effect of soil EC on groundwater EC at DSF.

On the contrary, the regression-based analysis at DSF has obtained a strong negative relationship between SMC and groundwater-soluble NH_4^+ concentrations. Thus, the increase in SMC could decrease the soluble NH_4^+ concentrations in groundwater. SMC could be influenced by rainfall and WT fluctuations. The high rainfall during the wet season could have decreased mineralization rates of N from fertilizer in the soil, which explained the decrease of NH_4^+ concentrations in groundwater (Zhang et al., 2020; Anggat et al., 2024).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study discusses the effect of oil palm cultivation such as (1) soil compaction and drainage for WT management on soil moisture content, (2) the long-term influence of fertilizer application on groundwater quality and (3) the statistical correlation between soil moisture and selected groundwater chemical parameters under an OPP established on tropical peatland. The information obtained in this study provides scientific knowledge for the improvement of OPP management and sustainability. The result of the first study objective reflects that the degree of soil compaction, which was measured via soil BD while drainage for WT management, influences SMC. All the OPP sampling points exhibited higher soil BD values as compared to DSF due to soil compaction and lower soil organic matter. The differences in SMC between the respective OPP sampling points and DSF at the 10 – 40 cm soil depth are significant, suggesting the influence of soil compaction. Moreover, high peat soil BD in drained sites and at surface layers could be influenced by WT and occur where the position of the WT tends to be below the surface throughout the year. In comparison to the OPP sampling points, the DSF sampling points exhibited higher SMC in the surface soil layer, which is consistent with previous studies.

This study also provides the long- term groundwater chemical parameters data under the OPP and DSF. The result showed significant trends that fertilizer application caused higher nutrient K^+ and Cl^- concentrations and decreased the acidity in groundwater under the OPP, as compared to that of the DSF. In addition, land clearing for oil palm replanting increased groundwater pH and NO_3, which may be due to loss of soil organic matter following land clearing. Hence, the result could be used to improve the current fertilizer management practice in the OPP for sustainable groundwater management.

The SMC and the selected groundwater chemical parameters statistical correlations were evaluated in this study. The results showed that SMC has high to moderate significant correlations with groundwater chemical parameters, suggesting that the peat soil properties including SMC influence the soil nutrient transport into the groundwater. Linear regression models were developed based on high correlation values and could be utilized to predict the effect of SMC on groundwater electrical conductivity, PO_4^{3-}, Cl^-, total K and NH_4^+. Overall, the optimal SMC (within the 40% to 75% range) obtained in this study does not increase groundwater PO_4^{3-}, Cl^-, total K, and NH_4^+, but increases groundwater electrical conductivity and these could be influenced by factors such as preferential flow, ion adsorption, rainfall, WT, and nitrification rate. Hence, this study provides insights that may help address the research gap in the study of peat soil solute transport, which remains limited.

5.2 Recommendations

The data obtained from this study could be used as the baseline for further detailed investigation of the tropical peatland ecosystem for agricultural land use, particularly oil palm plantations. A holistic approach considering both climatic and anthropogenic factors is essential to ensure sustainable tropical peatland and groundwater management. Continuous monitoring of soil and groundwater physicochemical parameters is the key to detecting changes in soil health and groundwater nutrient concentrations over time. Additionally, educating and engaging stakeholders such as small-scale farmers, plantation managers, and policymakers is important to raise awareness about sustainable agriculture. For example, farmers and plantation managers could practice controlled traffic farming to avoid random compaction and preserve root zones. Selective soil compaction further limits preferential flow pathways, enhancing nutrient retention. Other than that, WT control paired with fertilizer application near the palm roots could reduce nutrient leaching into the groundwater. For example, fertilizer applications should be scheduled during periods of reduced drainage intensity to minimize nutrient losses. The findings also suggest that controlled WT (drainage) and targeted soil compaction management can reduce nitrogen and phosphorus loss into the groundwater. These practices could be integrated into agricultural policy and regulatory frameworks. Sustainable WT control, which influences SMC, reduces greenhouse gas emissions and soil subsidence, which are detrimental to ecosystems.

Future work could include long-term, monthly monitoring and modelling framework that includes both dry seasons and transitional periods. Long-duration monitoring could provide significant trends, identify critical hydrological and nutrient thresholds. For example, the soil physicochemical data, groundwater chemical parameters and hydrological data such as rainfall and WT could be used to construct or calibrate existing hydrological and nutrient transport models, plan fertilizer application schedules and drainage management such as control of WT in the plantation, by considering the wet and dry seasons and replanting activities to ensure sustainable agriculture and serve as decision-making tools. Lastly, studies involving microbial communities and nutrient cycling should be added or explored, since nutrient transformations in peatlands are strongly mediated by microbial activity. Techniques such as metagenomic sequencing, enzyme assays, and isotopic tracing can provide insights into how microbial processes are influenced by WT fluctuations, soil compaction, and replanting. This could inform strategies for managing nutrient availability and minimizing losses through microbial optimization.

5.3 Study Limitations

Overall, this study has fulfilled its objectives based on the findings and discussion. However, there are a few limitations to be considered in this study. The soil moisture study was only conducted in the wet season and for a short duration. The post-replanting observation period was also relatively short, which was only within 6 months duration, limiting the ability to capture medium- to long-term changes in soil and groundwater dynamics as the new oil palm canopy matures. Besides, the study was conducted at a single site in Sarawak, Malaysia and therefore lacks replication across different peatland regions, limiting the generalizability of the findings to other areas with varying peat properties, climate patterns, or plantation histories. Several potentially confounding variables such as vegetation type, microtopography, and root density, which can influence water retention, nutrient cycling, and nutrient leaching were not fully controlled or considered in this study.

In addition, the variables investigated are influenced by multiple interacting factors such as soil heterogeneity, drainage conditions, and temporal variability, which may result in non-linear behaviour. Linear regression was applied as an initial exploratory approach to evaluate the direction and strength of association. The low R^2 values between SMC-WT and SMC-BD suggest that non-linear models, such as polynomial or exponential relationships, may better describe the system. Although the R^2 values are low, this does not necessarily indicate the absence of a relationship, particularly in field-based peat soil and groundwater systems that are influenced by multiple interacting factors and high spatial variability. The observed correlations indicate weak to moderate linear associations suggest indicative relationships rather than strong predictive relationships. The limitations associated with low R^2 values have been acknowledged, and future studies are recommended to use larger datasets and alternative statistical approaches.

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APPENDICES

Appendix A: Journal Publications

1. **Anggat, F. U**., Lim, S. F., Mah, Y. S., Busman, N. A., Maie, N., Sangok, F., & Melling, L. (2024). Long-term rainfall and water table influence on groundwater nutrient dynamics from an oil palm plantation. *Water Science*, 38(1), 569-586.

Appendix B: Abstract and Proceedings

1. **Anggat, F. U**., Busman, N. A., Maie, N., Sangok, F., & Melling, L., Lim, S. F., Mah, Y. S. (2024). Comparative analysis of long-term mineral fertilizer impact on groundwater nutrients in an oil palm plantation and a drained secondary forest on tropical peatland. Centennial Celebration and Congress of the International Union of Soil Sciences (IUSS 2024), Florence, Italy, 19th-21st May 2024
2. **Anggat, F. U**., Busman, N. A., Maie, N., Sangok, F., & Melling, L., Lim, S. F., Mah, Y. S. (2023). Groundwater level influence on selected soil and groundwater physicochemical properties in an oil palm plantation. International Soil Science Conference (SOILS 2023), Kangar, Perlis, 9th-11th May 2023