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BOOK

SOILS 2026

International Soil Science Conference 2026

7 - 9 April 2026

Raia Hotel, Kuala Terengganu, Malaysia

Theme: Global Challenges of Food, Climate and Sustainability in Tropical Soils

Editors

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Malaysian Society of Soil Science (MSSS)

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PREFACE

It is my distinct honour to present the official proceedings of the SOILS 2026 conference. This volume constitutes a rigorously curated compilation of extended abstracts, documenting advanced research and contemporary methodologies situated at the intersection of soil management, global climate dynamics, and agricultural resilience.

Deliberating under the theme "Global Challenges of Food, Climate and Sustainability in Tropical Soils", the contributions assembled herein reflect the imperative to address the complex ecological pressures unique to tropical soil systems. As global food demands intensify alongside climate variability, the strategic stewardship of tropical soils becomes pivotal to international sustainability frameworks. The scholarly works presented in this volume address critical domains, including soil fertility management, carbon storage, digital pedometrics, and ecosystem rehabilitation, offering empirical evidence and strategic models tailored to the humid tropics.

It is the editorial board's objective that this volume serves as a definitive reference for researchers, agricultural practitioners, and policy formulators dedicated to advancing sustainable soil management and reinforcing global environmental resilience. I express my profound gratitude to the contributing authors for their academic rigor, to our panel of reviewers for their thorough evaluations, and to the editors of the SOILS 2026 Proceeding Book for their operational support in bringing this publication to fruition.

ASSOC. PROF. ChM. DR. YONG SOON KONG
Chief Editor
SOILS 2026 PROCEEDINGS BOOK

7 April 2026

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ORGANIC CARBON AND NITROGEN COMPOSITIONS IN FORENSIC SOILS ASSOCIATED WITH HUMAN DECOMPOSITION ACROSS VARIABLE POST-DEPOSITIONAL INTERVALS (PDI)

Ismail, S.S.[1,2*], Bull, I.D.[2], Evershed, R.P.[2]

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INTRODUCTION

The survival of cadaveric-derived components and any related substances associated with burial activity has been studied by analysis of soils collected from several crime scenes and a laboratory-based simulated burial experiment. With the collaboration of the Royal Malaysia Police (RMP), a sampling trip to several states of Peninsular Malaysia was conducted to collect the soils relating to actual crime scenes and matters related to the sites. The primary interest in these samples was to investigate the relationship between the decomposition process, which occurs under suitable environmental conditions, and changes in soil elemental compositions. Such information is of vital importance since burial interval durations can span between a few hours in time and thousands of years; therefore, a better understanding of the association between the soil physicochemical alteration and prolonged burial will facilitate any attempts to reconstruct the chronology of crime scene reconstruction.

MATERIALS AND METHODS

Sampling strategy

Eleven cases were identified as being cases of particular interest for further scientific analysis. The cases represented a wide range of PDI, ranging from a few days after death to more than sixty years of interval. Soils were collected from underneath specific anatomical parts of the deceased, e.g. abdomen, head or leg, which were believed to be areas contributing large quantities of organic matter to the soil. In addition, soils were also collected from other points of each grave, for instance, the grave wall and floor, especially for the cases with a longer PDI, where no remains were present at the time of sampling. The location of the body in the grave upon recovery was identified with the assistance of photographs, police reports and the police officers who were involved in the cases. Soils which have been taken approximately one meter from the body were regarded as 'control' samples throughout the analysis. Accordingly, the documentation of the soils with the date of sampling and area of the body/grave where samples were collected was systematically recorded. Soils were stored in a freezer before subsequent analyses.

Elemental analysis

Elemental analyses were carried out using a Eurovector EA 3000 Elemental Analyser to determine total carbon, hydrogen and nitrogen compositions of soils. Inorganic carbon (IC) content was determined using a Modified Coulomat 702 analyser, which employed a coulometric cell for measurement. Total organic carbon (TOC) was calculated by the subtraction of total IC from total carbon. Each sample was analysed in triplicate.

RESULTS AND DISCUSSION

The TOC content of RMP soils ranged from 0.6% to 3.2% of soil dry weight, with a mean of 1.6%. A total of 5 soils had values falling within the 2-4% range, a high organic content for the typical organic horizon (0-1 cm) of the soils (Figure 1). The highest TOC percentage was recorded for RMP2body (3.2%), where soil from beneath the victim's body was collected. During the recovery, the body of the victim was almost completely decomposed in direct contact with the underlying soil (it was not covered by the clothes). The majority of the cadaver-derived matter was likely transferred into the soil. The RMP4*body* soil also exhibited a high proportion of organic C (2.8%). This high percentage suggests that the decomposition likely occurred more rapidly in the body/abdomen area of the victims. The slight fluctuations in the percentage of TOC content observed amongst the cases were independent of the estimated PDI. The percentage TOC content could also not be explained by the area of the body where the samples were collected. For instance, the soils of RMP3*body* and RMP3*leg* contained 1.7% and 1.0% of TOC contents, respectively.

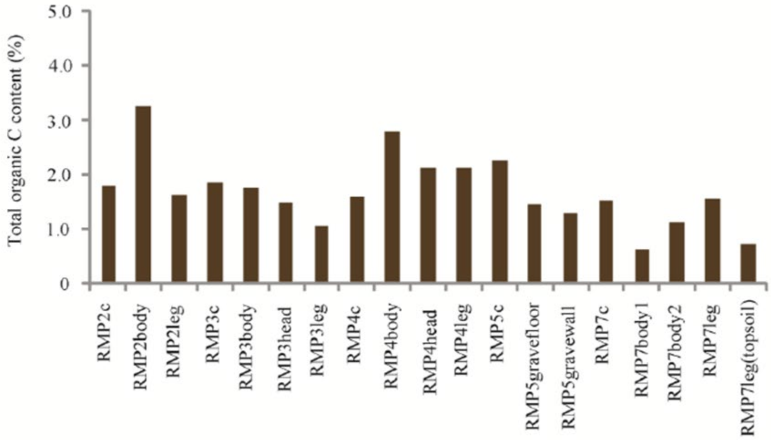

Figure 1 Bar chart illustrating the percentage of organic carbon extracted from the forensic soils

All of the RMP soils yielded relatively low percentages of N. The N content of these soils ranged from 0.1% to 0.3% of dry soil, with a mean of 0.2%. Nitrogen contents were substantially lower than values commonly reported for highly organic soils, i.e. 2–4% (Figure 2).

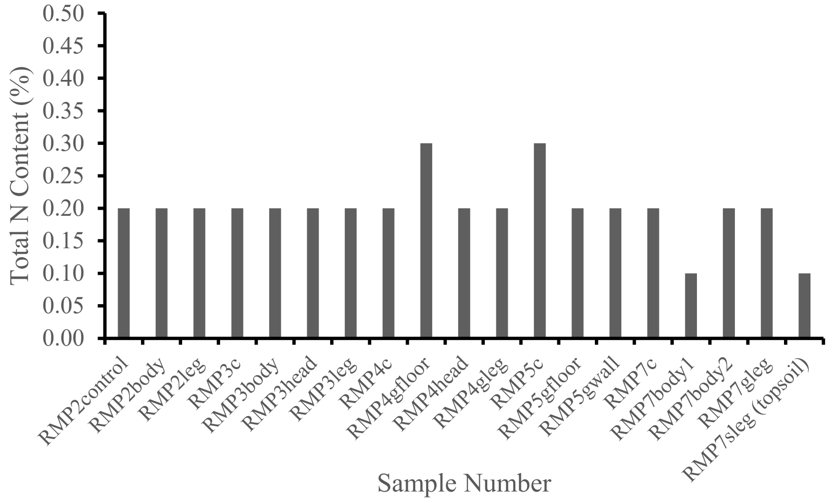

Figure 2 Bar chart illustrating the percentage of organic nitrogen extracted from the forensic soils

Figure 3 provides empirical evidence of a moderately strong linear association between nitrogen and organic carbon content. It highlights the interconnectedness of nutrient cycles in soil systems. The trend line shows that as nitrogen content increases, organic carbon content also tends to rise. This suggests a direct association between the two variables. Nitrogen and carbon are fundamental components of organic matter. Their correlation reflects the biochemical coupling of nutrient cycles, where nitrogen availability often enhances organic matter accumulation and stabilisation.

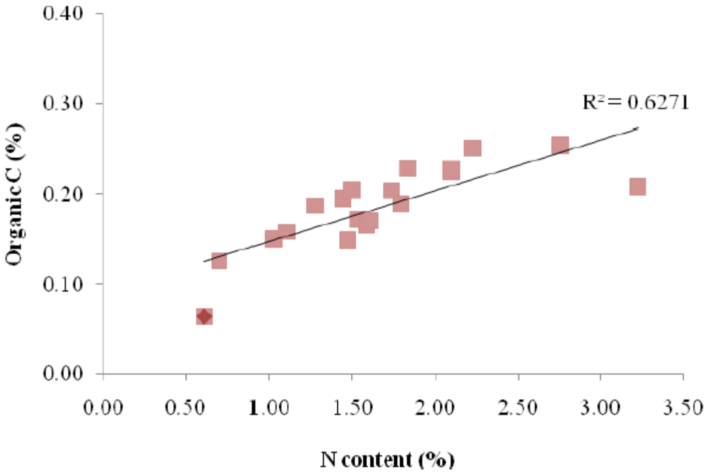

Figure 3 Plots of percentage organic C content against percentage N content of the forensic soils (RMP). The black line shows the trend line when data from all of the soils are integrated into the plot

CONCLUSION

The widespread anthropogenic introduction of chemical components, potentially cadaver-derived, was evident by the higher percentage of organic C and N contents extracted from the experiment and RMP compared to those of their control soils. The percentage TOC and N contents of forensic RMP soils were relatively low. Variation in the percentage contents of the elements appears to be independent of PDI, whereby the elevated percentage content was also observable in the soils with longer PDI.

ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to the Ministry of Higher Education (MOHE), Malaysia, for the scholarship. Special thanks to the members of the Organic Geochemistry Unit (OGU), University of Bristol, for their continuous support, teamwork, and valuable input throughout the process. Our heartfelt thanks go to Universiti Malaysia Terengganu (UMT) for providing the resources that made this work possible. We extend our appreciation to the Royal Malaysia Police (PDRM) for their cooperation and support, which contributed significantly to the success of this study

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CHARACTERIZATION OF ENDOSULFAN-DEGRADING *Streptomyces* spp. ISOLATED FROM A TROPICAL SOIL

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INTRODUCTION

Chemical pesticide use threatens soil health, fertility, and microbial diversity (Zhou *et al.*, 2025). In Malaysia, organochlorine pesticides (OCPs) remain detectable in vegetable products (Bibi *et al.*, 2026) and are linked to significant health risks, such as type-2 diabetes (Chen *et al.*, 2024). Among OCPs, endosulfan is particularly concerning due to its high acute toxicity and incomplete mineralization in natural conditions (Paíga *et al.*, 2021). Despite a global ban, its persistence results in continued presence in soil ecosystems (Zhao *et al.*, 2012, Rodríguez-Seijo *et al.*, 2025). Endosulfan is highly toxic and transferable to higher food chain, if not metabolized by indigenous soil microbes (Kumar *et al.*, 2008). Endosulfan can be degraded via two possible ways: an oxidative pathway that yields the more toxic endosulfan sulfate and hydrolytic pathway producing less toxic metabolite such as endosulfan diol (Kullman & Matsumura, 1996; Kataoka & Takagi, 2013; Ozdal *et al.*, 2017). Microorganism-assisted treatment offers a sustainable approach to mitigate this contamination. Yet, enzymes involved in endosulfan biotransformation are severely lacking. This study aimed to characterize two *Streptomyces* spp. capable of degrading endosulfan isomers using bioconversion and multi-omics analysis.

MATERIALS AND METHODS

Soil sampling and isolation of bacteria

Soil samples were collected from a tea plantation and the Habu water catchment site in Cameron Highlands, Pahang, Malaysia, at locations with a history of pesticide application (Saadati *et al.*, 2014). Actinomycetes were screened on starch mineral agar (Ekundayo *et al.*, 2014) supplemented with cycloheximide (20 µg/mL) and nalidixic acid (30 µg/mL). Each bacterial isolate was subjected to preliminary screening according to their growth on solid media (SFM) supplemented with endosulfan as a sulfur source. Out of 25 bacteria isolated, two isolates (S9 and S12) were selected based on better growth performance on SFM for functional characterization.

Bio-conversion experiments

Resting cell assays were performed to assess the endosulfan-degrading ability. 20 µg/mL of α− or β−endosulfan was added into a sterile test tube, before adding the cell suspension mixture prepared as follows: isolates were inoculated in 120 mL 1/5 LB before incubation at 30°C (200 strokes/min) until OD_{600} reached 1.5~2. The resultant culture was centrifuged at 5,000 x *g* for 6 min at 16°C to remove the medium and washed twice with either carbon-free medium (CFM, Omori *et al.*, 1992) or sulfur-free medium (SFM, Mohanasrinivasan *et al.*, 2013) before being concentrated 10-fold in either CFM or SFM. For the abiotic control, only CFM or SFM was added to the test tube, and the resulting mixture was incubated in a similar manner. After 20 days, three independently prepared mixtures were sacrificed to measure the residual endosulfan isomers.

Quantification of residual endosulfan

Endosulfan and its metabolites were extracted twice from sample cultures and spiked authentic standards using hexane and acetone (80:20, v/v) with a fluoranthene internal standard (Mir *et al.*, 2017). Dried extracts were dissolved in 1 mL acetonitrile and quantified via HPLC (Hitachi Elite LaChrom L2455 DAD; Pegasil ODS SP100 column) at 214 nm using an isocratic acetonitrile and water (70:30, v/v) mobile phase at 1 mL/min. Metabolite identification was confirmed using a 3200 QTrap LC-MS/MS system (AB SCIEX) in negative electrospray ionization mode. Specifically, endosulfan diol was assigned using multiple reaction monitoring (MRM) scanning to track the transitions of the parent ion (monoisotopic mass 357.865) to daughter ions m/z 212.9 and 284.9. The sample metabolites were dissolved in 200 µL LC-grade methanol prior sample acquisition. Methanol (blank), endosulfan sulfate (10 ppm), and α-endosulfan (10 ppm) were injected as negative controls to validate the method described above.

Genomic and transcriptomic analyses

Whole-genome sequencing was performed using an Illumina MiSeq platform, with open reading frame (ORF) prediction and annotation conducted via RAST v2 (Aziz *et al.*, 2008). Local BLAST searches queried the draft genomes of the isolated strains against the amino acid sequences of Esd (GenBank ID: AAN06820) and Ese (GenBank ID: AAZ38133). Deduced sequences exhibiting >80% coverage and high identity were subsequently aligned using MEGA. For transcriptomic analysis, RNA was extracted using an RNeasy column (Qiagen) from duplicate cell cultures grown in SFM and CFM. These cultures were harvested on day 15, consistent with the resting cell assay conditions, and analyzed via RNA-seq to identify differentially expressed genes (Laothamteep *et al.*, 2021).

RESULTS AND DISCUSSION

Endosulfan degradation potential by strains S9 and S12

After 20 days of incubation, strain S12 degraded 99% (α) and 93% (β) of endosulfan in sulfur-free medium (SFM), while degradation in carbon-free medium (CFM) reached 68% (α) and 80% (β). A similar trend was observed for strain S9, which degraded 96% (α) and 92% (β) in SFM, while degradation in CFM reached 40% (α) and 70% (β). The higher consumption in SFM suggests both strains utilize endosulfan as a primary sulfur source, based on the remaining residual endosulfan concentration in both mediums (Figure 1).

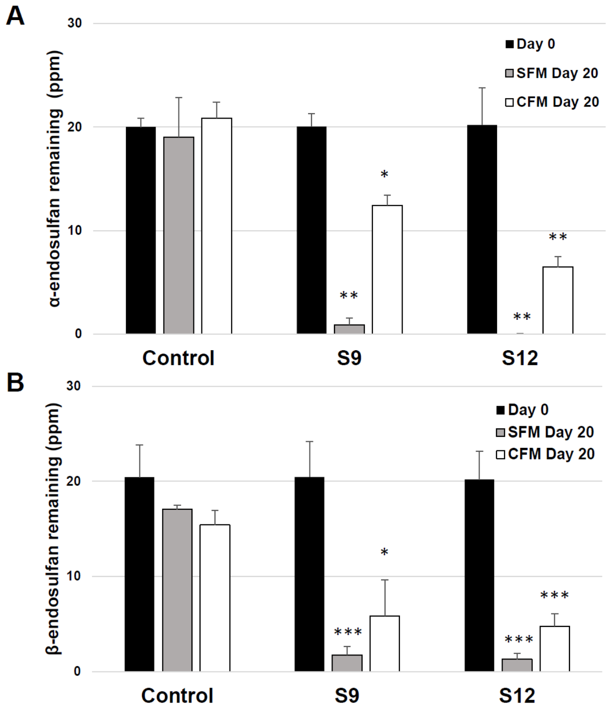

Figure 1 Residual endosulfan isomers, (A) α-endosulfan and (B) β-endosulfan recovered from resting cell cultures of S9 and S12. Control samples served as abiotic control. Data is expressed as mean ± deviation from three biological replicates. $P< 0.05$ is considered statistically significant. Statistical significance levels: ∗:$P < 0.05$, ∗∗:$P < 0.01$, and ∗∗∗:$P < 0.001$

Metabolite identification

HPLC and LC-MS/MS analyses identified endosulfan diol as the single intermediate metabolite (Figure 2). The m/z value of endosulfan diol (212.9 and 284.9) matched the m/z value of the metabolite produced by S9 and S12 (Figure 3), confirming a hydrolytic pathway (Ding et al, 2024, Zaffar et al, 2018, Sutherland et al, 2002).

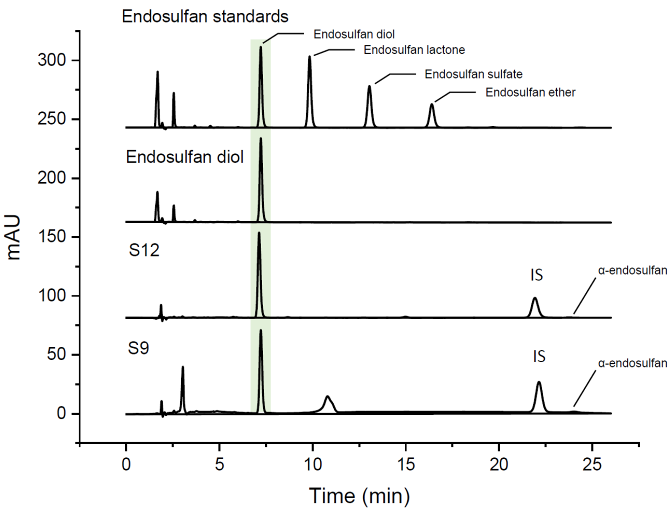

Figure 2 Representative chromatographs showing retention time of α-endosulfan metabolites produced by S9 and S12 at day 20 (green shaded) against endosulfan metabolites standards. The standard mixtures contain endosulfan diol, endosulfan lactone, endosulfan sulfate, and endosulfan ether at 20 ppm. IS represents the internal standard, fluoranthene

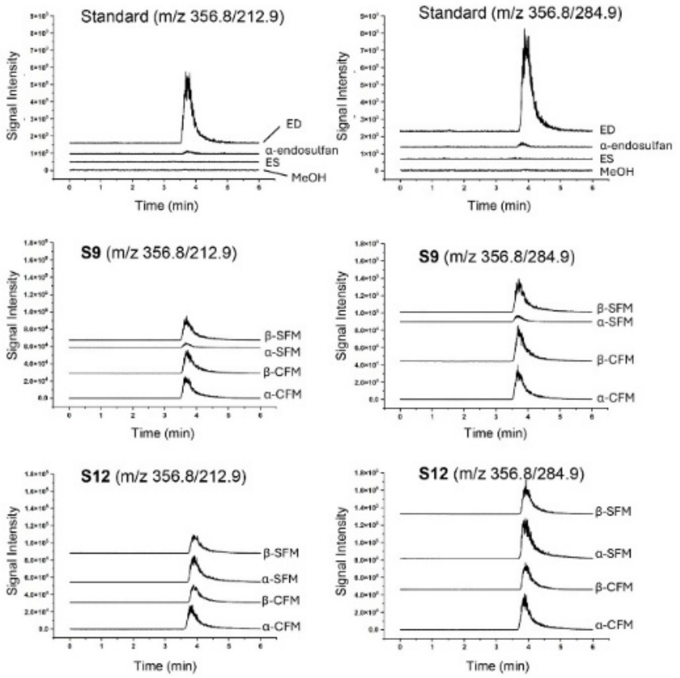

Figure 3 LC-MS/MS chromatograms of S9 and S12 metabolites

Multi-omics analyses

Draft genome analyses show that S9 has a larger genome of 8.79 Mbp (71.6% GC content, 9,292 ORFs) compared to S12 with a genome size of 7.36 Mbp (72.4% GC content, 8,082 ORFs). Based on morphological characteristics, 16S rRNA gene homologies, and genome sequences, both strains were classified as Gram-positive bacteria under the genus *Streptomyces*. Phylogenetic and genomic analyses revealed that strain S9 belongs to *Streptomyces antibioticus*, clustering with the type strain NBRC 12838^T (AB184184) with 100% bootstrap value and sharing a 96.41% Average Nucleotide Identity (ANI). Strain S12 is closely related to *Streptomyces speibonae* strain PK-$Blue^T$ (NR 025212) with a bootstrap value of 75. Genomic mining detected esd/ese homologs (80% similarity and above); however, RNA-seq showed negligible expression ($\log_2$ ratio < 2), indicating they are unlikely to contribute to the transformation. Heatmap analysis (Figure 4) revealed 34 upregulated genes in S9 and 206 in S12 under SFM conditions, predominantly associated with ABC transporters and hydrolases. In CFM, there were 158 upregulated genes in S9 and 186 in S12. Notably, genes involved in sulfur transport (ABC transporters), hydrolases, oxidoreductases, and several hypothetical proteins exhibited distinct expression shifts, suggesting a role in endosulfan transformation and are strain specific. This suggests that novel, uncharacterized genes are likely responsible for the hydrolytic transformation observed in these tropical *Streptomyces* strains and should be further validated via knock-out mutants for confirmation.

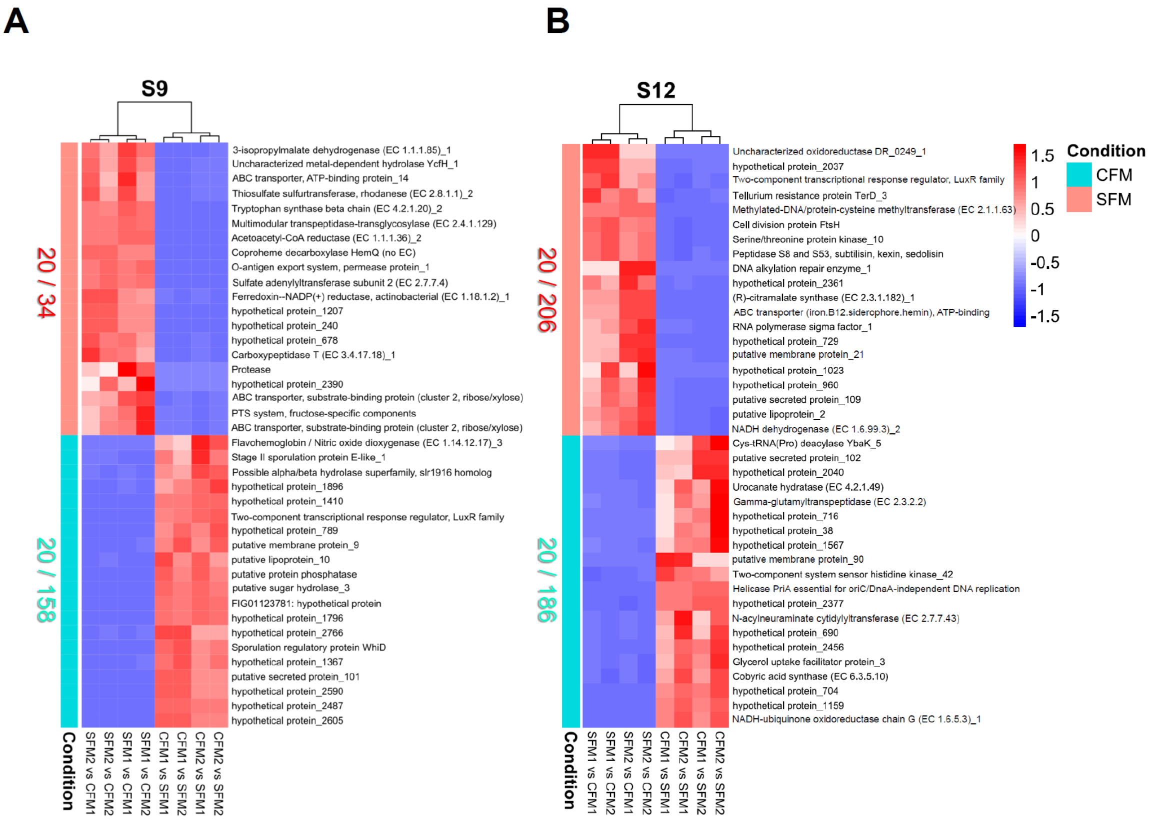

Figure 4 Top 20 upregulated genes in SFM and CFM conditions

CONCLUSION

This report provides evidence of newly discovered *Streptomyces* spp. capable of transforming endosulfan into the less toxic metabolite endosulfan diol, showing the potential of soil microbes to contribute to bioremediation and sustain soil ecosystem functions in contaminated environments. The negligible expression of known *esd/ese* genes suggests the involvement of novel enzymatic candidates that warrant further characterization, highlighting the functional resilience of soil microbial communities.

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ULTRAMAFIC SOIL CARBON SEQUESTRATION UNDER DIFFERENT LAND-USE SYSTEMS AT THE PAHU AGROMINING TRIAL FARM, SABAH, MALAYSIA

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INTRODUCTION

Soil carbon sequestration is increasingly recognized as a vital nature-based solution for mitigating climate change, particularly in tropical landscapes where soil organic carbon (SOC) stocks are among the largest globally (Joseph, 2024). Despite the importance of forest ecosystems, ultramafic soils remain largely underexplored in carbon research due to their unique geochemical properties (Vithanage *et al.*, 2019). These soils are characterized by high heavy metal concentrations, low calcium-to-magnesium ratios, and inherent nutrient limitations (van der Ent *et al.*, 2018). Ultramafic forests represent stable ecosystems that have adapted to these conditions, resulting in persistent soil carbon pools and slow nutrient cycling (De-Castro *et al.*, 2025; van der Ent *et al.*, 2014). Conversely, early-stage agroforestry systems are emerging as sustainable, climate-smart agricultural strategies on ultramafic soils, integrating crops with woody species to maintain ecological functions while supporting livelihoods. Various agroforestry practices are widely recognized for their capacity to enhance SOC particularly in agriculture, forest, mangrove and others (Besar *et al.*, 2020; Podong *et al.*, 2024). Understanding the SOC dynamics during the transition from natural forest to early-stage agroforestry is crucial to determining the viability of these managed systems as long-term carbon sinks. Hence, this study aims to assess and compare soil organic carbon (SOC) stocks between an early-stage agroforestry system and an adjacent natural ultramafic forest. The primary goal is to determine whether transitioning to an agroforestry system can rapidly rebuild or maintain SOC to levels comparable to stable, natural ultramafic forests without intrinsic soil constraints limiting carbon accumulation.

MATERIALS AND METHODS

The research was conducted at the Pahu Agromining Trial Farm in Kg. Pahu Pinawantai Ranau, Sabah, Malaysia, an area characterized by ultramafic soil classified as a Eutric Chromic Cambisol (Nkrumah *et al.*, 2019; Tisserand *et al.*, 2021). The agroforestry system at this site has been established for more than 10 years. The samplings were carried out on August 27th and 30th, 2025. The study compared two land-use types: an early-stage agroforestry system predominantly cultivated with the nickel hyperaccumulator *Phyllanthus rufuschaneyi* alongside shelterbelt species such as *Rinorea bengalensis* and perennial trees, *Callicarpa* sp. and an adjacent ultramafic forest located approximately 200 meters away.

Plot Establishment and Soil Sampling

For each land-use type, three 10 × 10 m temporary sampling plots were established. Within each plot, five replicate soil samples were extracted at a depth of 20 cm using a soil auger. These replicates were thoroughly mixed to form one composite sample of about 1 kg per plot for physicochemical analyses. To prevent cross-contamination of high metal concentrations inherent in ultramafic soils, the auger was rinsed with distilled water between samplings.

Soil Processing and SOC Calculation

The collected soil samples were air-dried, stored in clear plastic bags, and transported to the laboratory. For processing, the soils were oven-dried overnight at 40°C and then lightly ground to pass through a 100-mesh sieve (0.45 mm opening). A 10 g subsample from each was outsourced to the Forest Research Centre (FRC) in Sandakan to analyse total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP). Undisturbed soil samples for bulk density (BD) determination were collected from each sampling location using a stainless-steel core measuring 4 cm in diameter and 7.7 cm in length. The collected core samples were then transferred to the laboratory, where percentage moisture content (% MC) was determined by oven-drying the samples at 40°C to a constant weight to calculate the final dry soil mass. The Total Soil Organic Carbon Stock (SOC) (tC ha^{-1}) was determined as the product of soil organic carbon concentration, soil depth, and bulk density (Chhabra *et al.*, 2003). In terms of chemical analyses, TN was measured using a LECO CN928 Series Combustion Analyzer, while TOC was determined titrimetrically by using a rapid dichromate oxidation method adapted from the Walkley-Black procedure (Nelson and Sommers, 1982).

RESULTS AND DISCUSSION

Statistical analyses were performed using IBM SPSS Statistics, Version 29.0.2.0. The normality of all variables was assessed using the Shapiro–Wilk test. The results indicated that all variables were normally distributed ($p > 0.05$), satisfying the assumption of normality. Therefore, subsequent analyses were conducted using appropriate parametric statistical tests. In Figure 1a, the assessment of SOC dynamics revealed that the mean SOC stocks were higher in the early-stage agroforestry ecosystem (42.20 ± 15.25 tC ha^{-1}) compared to the ultramafic forest ecosystem (30.94 ± 9.44 tC ha^{-1}). However, statistical analysis indicated that this difference was not statistically significant ($p > 0.05$). The early-stage agroforestry system exhibited higher spatial variability in SOC stocks, with a coefficient of variance (CV) of 35.94%, compared to the moderate variability observed in the ultramafic forest (CV = 30.42%). This higher variability in the agroforestry plots is likely attributable to differences in tree species composition, root biomass distribution, litter quality, and active management practices typical of cultivated systems (Smith *et al.*, 2023). The lack of a statistically significant difference suggests that intrinsic soil constraints associated with ultramafic parent material may moderate short-term carbon accumulation, while effectively preventing rapid SOC losses under managed agroforestry interventions. The analysis of SOC stocks revealed higher overall accumulation in early-stage agroforestry systems compared to ultramafic forest environments.

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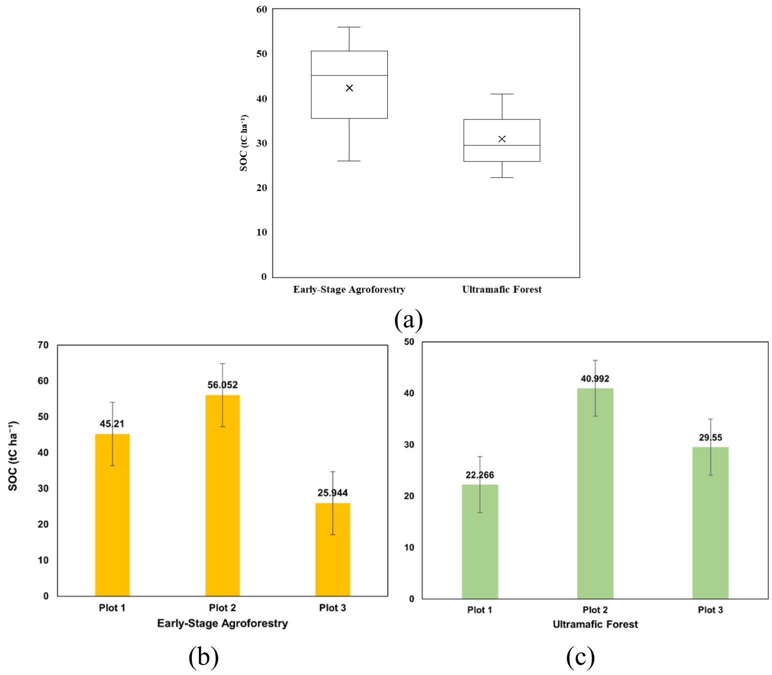

Figure 1 (a) Comparison of Soil Organic Carbon (SOC) across two contrasting land-use systems; early agroforestry and ultramafic forest, (b) Comparative distribution of SOC across three sampling plots under early-stage agroforestry, (c) Comparative distribution of SOC across three sampling plots under early-stage ultramafic forest

This study demonstrated that the early stage agromining agroforestry system at Kg. Pahu maintained soil organic carbon (SOC) levels comparable to those of the adjacent natural ultramafic forest. Although the agroforestry plots recorded a slightly higher mean SOC stock (42.20 t ha^{-1}) than the natural forest (30.94 t ha^{-1}), the difference was not statistically significant ($p > 0.05$). This finding suggests that the establishment of early-stage agroforestry did not result in soil carbon depletion despite land-use modification. This observation is consistent with previous findings from Sabah reported by Awang Besar *et al.* 2020, who compared oil palm–agarwood agroforestry with adjacent tropical forest ecosystems in the Balung River watershed, Tawau. Similarly, they reported that SOC stocks were marginally higher in the agroforestry system (up to 49.75 Mg ha^{-1}) than in the natural forest (36.30 Mg ha^{-1}), although the differences were likewise not statistically significant. The agreement between these independent studies strengthens the evidence that appropriately managed agroforestry systems in Sabah can maintain soil carbon stocks at levels comparable to those of nearby natural forests during the initial stages of establishment. In addition, the ultramafic forest at Kg. Pahu stored substantially higher soil organic carbon (SOC) than the pristine montane heath forest reported from Imbak Canyon, Sabah (Joseph, 2024). The present study recorded a mean SOC stock of 30.94 t C ha^{-1} in the ultramafic forest, which is approximately twice that reported for the montane heath forest in Imbak Canyon (16.76 t C ha^{-1}). Although both ecosystems are characterized by challenging edaphic conditions that restrict vegetation productivity, the contrasting SOC stocks suggest that different soil-forming processes govern carbon stabilization in these environments.

Conversely, the inherently harsh pedological conditions of ultramafic soils often characterized by heavy metal toxicity and macronutrient deficiencies, naturally restrict plant biomass production, thereby limiting organic carbon sequestration potential (van der Ent *et al.*, 2015). Interestingly, the lowest SOC value in the agroforestry area (25.944 tC ha^{-1}), was surpassed by the higher-performing ultramafic forest plots (40.992 tC ha^{-1} and 29.55 tC ha^{-1}). This highlights that while land-use type is a primary driver of SOC dynamics, localised factors such as micro-topography, uneven vegetation distribution, and differing soil depths introduce significant site-specific variability that strongly influences actual carbon storage outcomes in the field (Wang *et al.*, 2021).

CONCLUSION

The findings provide empirical evidence that early-stage agroforestry systems established on ultramafic landscapes can maintain SOC stocks at levels comparable to adjacent ultramafic forests. As soil carbon dynamics remain largely stable during this initial phase of land-use transition, early-stage agroforestry does not compromise soil carbon storage. Nonetheless, it is recommended that the number of soil sampling points be increased to improve spatial representativeness and strengthen the robustness of SOC estimation across heterogeneous ultramafic landscapes.

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ASSESSMENT OF GREENHOUSE GAS EMISSIONS IN TROPICAL PEATLANDS IN MALAYSIA

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INTRODUCTION

Tropical peatlands in Malaysia are among the most important regional ecosystems for global climate change mitigation. Formed over millennia, these natural peatlands act as massive organic carbon reservoirs, characterized by low bulk density, high porosity, and acidic conditions (pH 3.5–5.0). Currently, Malaysia hosts approximately 2.56 million hectares (ha) of peatlands, representing 7.74% of the national land area, with the vast majority (over 64%, or roughly 1.64 million ha) concentrated in the state of Sarawak.

Intense land-use competition has led to heavy agricultural encroachment into these ecosystems. Drainage required for agriculture shatters the anaerobic seal of the peat, triggering severe physical subsidence, acute fire risks, and massive atmospheric greenhouse gas (GHG) oxidation. In 2019 alone, drained peatlands released an estimated 8 million tonnes of CO_2, representing approximately 80.5% of total CO_2 emissions from Malaysia's agricultural sector. To accurately reflect Malaysia's progress towards its Nationally Determined Contributions (NDC 3.0), comprehensive spatial tracking is required. This study aims to quantify land-use transitions across Malaysian peatlands between 2019 and 2025 and assess the subsequent dynamics of Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O) fluxes stemming from these anthropogenic disturbances.

MATERIALS AND METHODS

This study utilized a combination of remote sensing geospatial analysis and intensive ground-truthing to map land use and land cover (LULC) changes and estimate subsequent GHG emissions.

Geospatial and LULC Matrix Analysis

Spatial transitions were quantified using Sentinel-2 composite satellite imagery for the years 2019 and 2025. The LULC classification was conducted via the Google Earth Engine (GEE) platform by using Random Forest Classifier. The spatial classification focused on six primary land-use categories: Forestland, Cropland, Grassland, Wetland, Settlements, and Other Land. The 1,000 points were distributed among Forest (402), Cropland (292), Wetland (201), and Settlements (105). Google Earth satellite imagery served as the reference training dataset for this validation. A confusion matrix based on 1,000 reference points generated an overall accuracy of 94% (Kappa statistic: 0.91).

Ground-Truthing and Soil Sampling

Field verification was conducted at 18 sampling points across Malaysia, targeting locations spanning intact forests (10 points), croplands (oil palm and rubber) (6 points), and settlements (2 points). A Russian Peat Sampler was used to extract intact soil cores without disrupting the soil profile, confirming peat depths ranging from 0.6 to 2.0 m. The organic soils evaluated in this study are classified as Histosols according to the USDA Soil Taxonomy. Peat characteristics were visually assessed and classified based on fiber decomposition into fibric, hemic, and sapric materials (equivalent to Fibrists, Hemists, and Saprists suborders in the USDA Soil Taxonomy).

GHG Emission Estimation

Greenhouse gas fluxes were evaluated using the 2006 IPCC Guidelines and the 2014 IPCC Wetlands Supplement (Tier 1), augmented by localized Malaysian studies (Tier 2/3) to account for precise regional variations in N_2O and drainage-derived CH_4. Emissions were standardized into CO_2 equivalents (CO_2e) using Global Warming Potential (GWP) metrics from the IPCC Fifth Assessment Report (AR5), utilizing a 100-year horizon (CH_4 = 28; N_2O = 265).

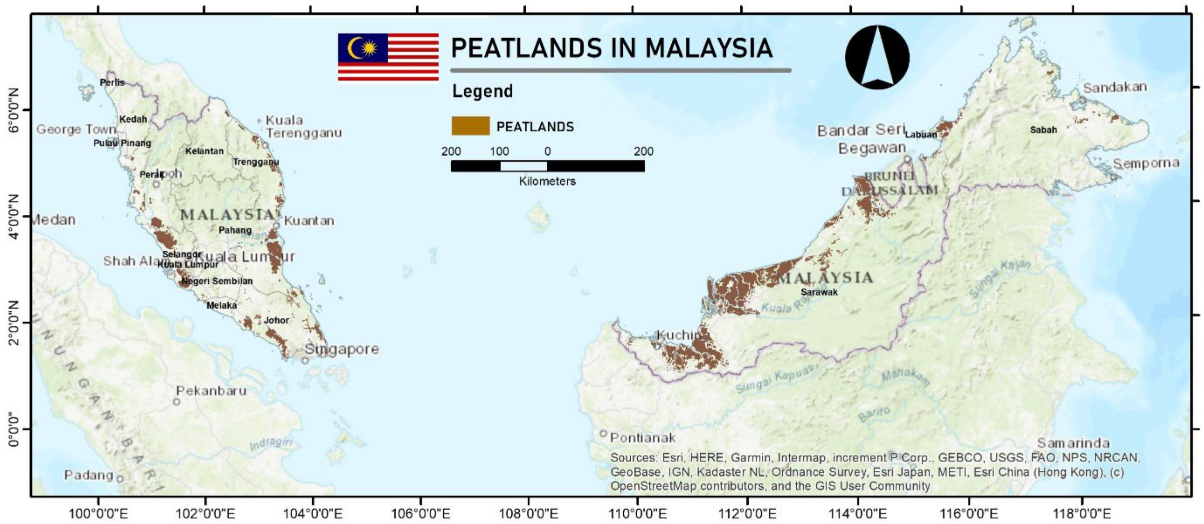

Figure 1 Distribution of peatlands in Malaysia

RESULTS AND DISCUSSION

Land Use and Land Cover Transitions (2019–2025)

The LULC matrix reveals a severe and continuous depletion of natural peat swamp forests. Between 2019 and 2025, total Forestland situated on peat declined from 1,272,543 ha to 911,926 ha, representing an absolute loss of 360,617 ha. These changes are summarized in Table 1 and depicted in Figures 2 & 3. This unidirectional deforestation was primarily driven by the expansion of Cropland (+117,693 ha), Grassland (+149,013 ha), and rapid urbanization resulting in a near doubling of Settlements (+83,640 ha). Sarawak constituted the epicenter of agricultural conversion, transforming roughly 112,202 ha of various peatlands directly into oil palm plantations.

Table 1 Land Cover Changes on Malaysian Peatlands from 2019 to 2025, in hectares (ha)

Land Cover	2019 Area	2025 Area	Change
Forestland	1,272,543	911,926	-360,617
Grassland	226,760	375,773	+149,013
Cropland	615,934	733,627	+117,693
Settlements	91,642	175,282	+83,640
Other Land	17,853	38,827	+20,973
Wetland	60,251	49,548	-10,703

Note: Data derived from Sentinel-2 LULC Classification.

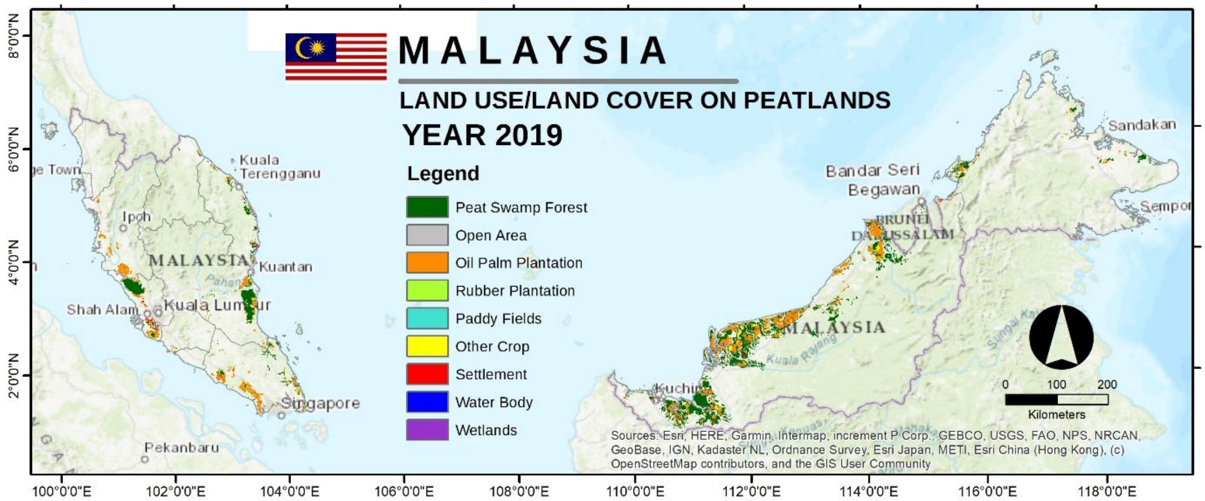

Figure 2 Land use/land cover on peatlands in Malaysia over the year 2019

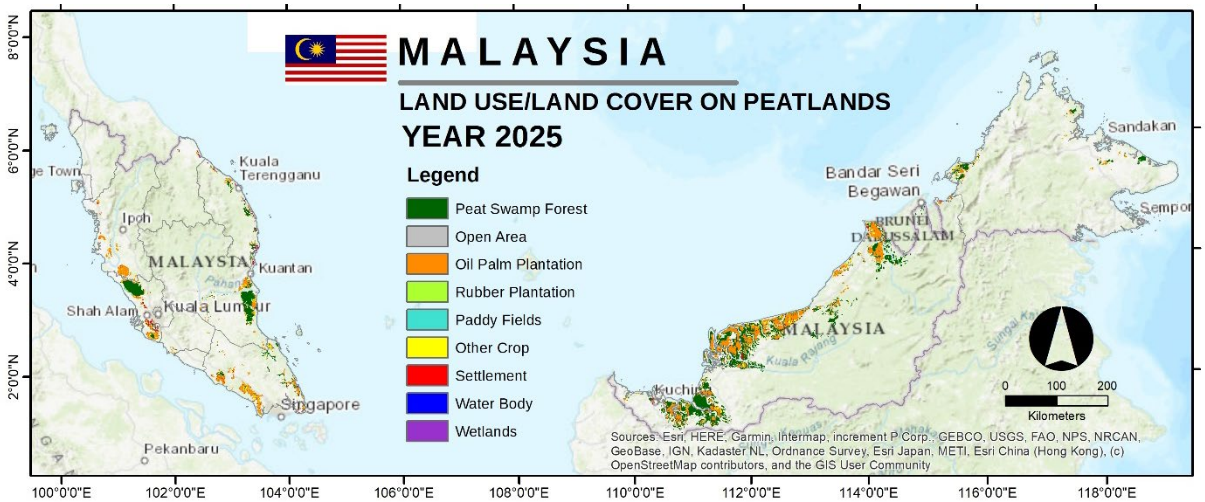

Figure 3 Land use/land cover on peatlands in Malaysia over the year 2025

Greenhouse Gas Emission Dynamics

The disruption of natural peatland hydrology completely alters the carbon equilibrium, transforming the land from a net sink into a potent source of emissions (IPCC, 2014).

a) Carbon Dioxide (CO_2): Drainage stimulates microbial oxidation. The established emission rate for oil palm on drained peat in Malaysia is between 41 and 43 t CO_2e/ha/year, aligning closely with the IPCC Tier 1 default of 40 t CO_2e/ha/year. Deep drainage for species like Acacia dramatically increases this to 73 t CO_2e/ha/year.
b) Methane (CH_4): While overall surface CH_4 drops in aerobic drained soils, agricultural drainage ditches serve as warm, anaerobic hotspots, releasing up to 2.78 kg CH_4 (as CO_2e) per hectare daily.
c) Nitrous Oxide (N_2O): A critical finding is the massive spike in N_2O due to fertilizer application and fluctuating water tables. Conversions from natural forest to oil palm escalate emissions from 6.5 kg N_2O/ha/year to 21.9 kg N_2O/ha/year, posing a disproportionate climate warming impact given N_2O's GWP of 265.

Cumulatively, an estimated 93,357 ha converted specifically to agriculture during this period contributed approximately 13.5 million tonnes of CO_2e over an average three-year conversion lifecycle (Table 2). The 93,357 ha was derived by calculating the specific area of natural Peat Swamp Forests that was directly cleared and converted into two specific agricultural categories: Oil Palm Plantations (50,677.45 ha) and Other Crops (42,679.89 ha). This 93,357-hectare figure specifically isolates the direct deforestation of pristine peatlands. It was utilized for the cumulative emission estimates because converting untouched, natural peat swamp forests (which operate as a net carbon sink) into drained agricultural plantations shatters the anaerobic seal of the peat, immediately turning the land into a massive new carbon source. Conversely, the +117,693 ha shown in Table 1 represents the overall net increase in the broader "Cropland" category across the entire LULC matrix.

Despite these intense localized emissions, aggressive afforestation and robust preservation of the remaining Permanent Reserved Forest (PRF) allowed Malaysia's overall Land Use, Land-Use Change and Forestry (LULUCF) sector to maintain a net sink status (-223,000 Gg CO_2e projected in 2025). However, the "invisible" chronic emissions from drained agricultural peatlands represent the sector's greatest vulnerability.

Table 2 Estimated Cumulative Emissions from Peatland Converted to Agriculture* (2019–2025)

Greenhouse Gas	Estimated Annual Emission (once fully converted by 2025)	Estimated Total Cumulative Emission (2019–2025)	Calculation Basis
CO_2	3.73 Mt	11.20 Mt	93,357.34 ha × 40 t CO_2/ha/year.
CH_4	3,383 tonnes CH_4 (94,730 t CO_2e)	10,149 tonnes CH_4 (284,190 t CO_2e)	93,357.34 ha × 2.78 kg CH_4 (as CO_2e)/ha/day from drainage ditches.
N_2O	2,544 tonnes N_2O (674,160 t CO_2e)	7,632 tonnes N_2O (2.02 Mt CO_2e)	Oil Palm (50,677.45 ha) × 21.9 kg/ha/year + Other Crops (42,679.89 ha) × 33.6 kg/ha/year
TOTAL	**4.5 Mt CO_2e**	**13.5 Mt CO_2e**	Total cumulative/3 years

**Note*:

- The remaining 17,000 ha converted to settlements, open areas, and wetlands are excluded from this specific calculation to maintain a conservative estimate, as specific emission factors for those exact categories are not available.
- Assuming a steady, linear rate of land clearing over the 6-year period (meaning the converted land emitted greenhouse gases for an average of 3 full years)

CONCLUSION

The significant loss of over 360,000 ha of forestland on Malaysian peatlands between 2019 and 2025 underscores the intense agricultural and urban pressures facing these sensitive Histosols. While Malaysia's LULUCF sector successfully functions as a net carbon sink, the continuous oxidation of drained peatlands drastically limits the nation's mitigation potential. To satisfy the ambitious absolute emission reduction targets outlined in NDC 3.0, future land-use policy must revolve around three prescriptive pillars: halting the conversion of the remaining 911,926 ha of intact forestland, enforcing strict Water Best Management Practices (BMPs) in existing croplands to raise water tables, and targeting degraded areas for active hydrological rewetting. Future research should prioritize high-resolution, long-term spatial projections and the formalization of Tier 3 MRV frameworks that fully integrate N_2O and drainage-ditch CH_4 fluxes.

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IMPACT OF APPLYING GYPSUM ON SOIL FERTILITY AND CROP GROWTH/PRODUCTION

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INTRODUCTION

Highly weathered soils of the tropical regions are taxonomically classified as Ultisols and Oxisols. In Peninsular Malaysia, the clay fraction of the soils are dominated by low activity clays such as kaolinite and sesquioxides (gibbsite, goethite and hematite) (Tessens and Shamshuddin, 1983). Thus, their cation exchange capacity (CEC) is low, resulting in loss of applied nutrients via leaching under intense rainfall. Soil pH ranges from 4 to 5, with the former mostly lower than the latter (Shamshuddin and Fauziah, 2010). Using state-of-the-art agro-tech, oil palm and rubber can be grown sustainably, producing good yield. Research conducted in Malaysia found that soil fertility can be enhanced via applying gypsum at appropriate rate and time (Shamshuddin and Ismail, 1995). This paper explains critically how soil fertility improves that enhances crop growth when gypsum is applied into the soils.

MATERIALS AND METHODS

In essence, gypsum (natural or otherwise) is a fertilizer containing Ca and S, which are required by crops in high amounts to sustain their productivity. This review paper is a summary of the results of studies conducted over the years on highly weathered soils in Peninsular Malaysia using the material. The studies began with a field trial on natural gypsum, using maize as the test crop. It was carried out on an Ultisol in Puchong (Selangor). This was followed by a leaching experiment as well as an agronomic trial on maize conducted on an Oxisol sampled from Prang Besar Estate, located at the present day Putrajaya. The next studies were carried out in a glasshouse (oil palm seedlings), followed by a field trial for two years conducted on an Ultisol cropped to oil palm in Bera (Pahang). It was to determine the impact of Mg-gypsum (a factory by-product) application on the growth and production of oil palm as well as palm oil quality. Environmental impact analysis of applying the material in the studied area was critically assessed. The final study was conducted in a glasshouse in UPM to determine the effects of applying Mg-gypsum on rubber seedlings planted on Ultisols and Oxisols.

Chemical composition of the materials

The formula for natural gypsum found as geological deposits and that pedologically mineralized under sea water influence (mangrove swamps) is $CaSO_4.2H_2O$. The typical pH of natural gypsum is 6.7. Gypsum is also available in Malaysia as an industrial by-product. Besides containing Ca and S, this synthetic gypsum is enriched with Mg – for that reason, it is called Mg-gypsum. Alkaline in nature, with pH >7, Mg-gypsum is an excellent source of S, Mg and Ca for agriculture. The material contains 5-6% Mg and about 20% Ca; thus, comparable in composition to that of Ground Magnesium Limestone (GML).

Impact of applying natural gypsum on Oxisol

GML is normally applied into the topsoil of Oxisols to alleviate their acidity. The subsoil gets minimal benefit from lime application; thus, plant roots growing in that zone are subjected to low pH stress as well as Fe^{2+}, Al^{3+} or Mn^{2+} toxicity. According to Shamshuddin and Ismail (1995), if GML was applied in combination with natural gypsum, the top- and subsoil acidity as well as the above-mentioned toxicity problems could be significantly alleviated. An increase in negative charge was also observed during the process (Figure 1). This means that adding natural gypsum into a highly weathered soil (Oxisol), containing high amount of goethite and/or hematite, improves its fertility (Shamshuddin, 2022).

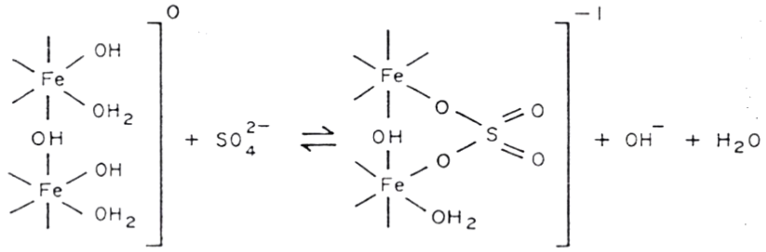

Figure 1 Impact of applying natural gypsum on soil properties

Natural gypsum readily dissolves in water, making Ca^{2+} available for crop uptake. Its presence in soil solution would slightly reduce the toxic effect of Al^{3+} on plant roots. Note that Ca^{2+} present in the soil solution will eventually replaces Al^{3+} on soil exchange complex. The Al^{3+} so available slowly, but surely reacts with SO_4^{2-} to form $AlSO_4^+$. This aluminum species is known to be non-toxic to plant roots growing in soil. The chemical reaction taken place is:

$$Al^{3+} + SO_4^{2-} \rightarrow AlSO_4^+$$

Effects of Mg-gypsum application on oil palm

Ayanda *et al.* (2020) conducted a field trial to determine the effects of applying Mg-gypsum on the growth and production of oil palm planted on an Ultisol in Bera, Pahang (Figure 2). For all we know, oil palm is acid-tolerant. The critical pH to sustain its growth and/or production is 4.3. When soil pH is raised to the level >5, oil palm is no longer affected by soil acidity. Besides, it no longer suffers from Al^{3+} (the pKa is 5) and/or Fe^{2+} (the pKa is 4.58) toxicity. This is because the toxic ions will be precipitated as inert hydroxides when soil pH is >5.

Figure 2 Effects of Mg-gypsum application on oil palm grown on an Ultisol in Bera, Malaysia

Due to the high cost of applying kieserite (to supply Mg) or GML (Mg and Ca) for oil palm cultivation, a cheaper substitute should be looked into. For all intents and purposes, Mg-gypsum is found to have beneficial properties that makes it a potential alternative. The alkaline industrial by-product contains high amount of Mg, Ca and S, with some calcium carbonate (Ayanda *et al.*, 2021). Applying Mg-gypsum on an Ultisol sustains oil palm growth, giving comparable impact to that of kieserite or GML (Ayanda *et al.*, 2020). Continuous Mg-gypsum application would eventually reduce soil acidity prevalent in the tropical regions of the world where oil palm is mostly cultivated. Soil pH increase due to Mg-gypsum application was found to have enhanced the growth of oil palm seedlings planted in a glasshouse.

Mg-gypsum treatment concomitantly increased soil exchangeable Ca and Mg. Applying Mg-gypsum at an appropriate rate improved soil fertility that enhanced the growth of the oil palm seedlings. The palm grew better at soil pH >5 than that at lower pH, where it might be suffering from low pH stress and/or due to Al^{3+} as well as Fe^{2+} toxicity. The height of the oil palm seedlings in the nursery increased with increasing exchangeable Ca.

Stepwise regression analyses showed that a significant relationship existed between soil pH, exchangeable Ca and exchangeable Mg and the height of oil palm seedlings (Ayanda *et al.*, 2020). Soil pH is the most important factor controlling the growth of the oil palm seedlings, based on plant height. Further result showed that soil pH was positively correlated with exchangeable Ca, which means that as Ca in the soil increased, soil pH was raised to the level dependent on the rate of the Mg-gypsum applied. The quality of palm oil and the surrounding environment were not affected by the application of Mg-gypsum (Sahibin *et al.*, 2019)

Effects of Mg-gypsum application on rubber

Ayanda (2021) conducted a study and concluded that Mg, S and Ca released by Mg-gypsum were available for uptake by rubber seedlings planted on Ultisols and Oxisols. Part of the nutrients were found to be transported to the subsoil. This resulted in alleviation of soil acidity in that zone. Thus, the growth of rubber seedlings was enhanced by Mg-gypsum treatment.

CONCLUSION

The fertility of highly weathered soils in Malaysia containing oxides/hydroxides of Fe is enhanced by application of natural or synthetic gypsum. The latter is an important source of Mg, Ca and S (macronutrients), required by oil palm and rubber. Gypsum enriched with Mg has a great potential in agriculture, especially as a fertilizer, supplying Mg (for photosynthesis) and S (for oil production in fruitlets). Applying Mg-gypsum in oil palm and rubber plantations will enhance soil fertility via increasing plant nutrients as well as raising soil pH. The industrial by-product is safe for land application and is an effective soil ameliorant. Its land application does not impact palm oil quality negatively, nor does it causes environmental degradation.

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REGULATING POTASSIUM SORPTION IN TROPICAL ACIDIC SOILS USING CALCIPRILL AND SODIUM SILICATE

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INTRODUCTION

In the tropics, the formation of highly weathered acidic soils (pH<5.5) is driven by excessive rainfalls and warm temperatures. This causes the significant losses of potassium ions (K^+) *via* leaching because of its displacement with the excessive hydrolyzed aluminium (Al^{3+}) and iron (Fe^{3+}) ions on the soil exchangeable sites, thus reducing the K^+ uptake and use efficiency by the plants (Kuo *et al.*, 2020). Paramisparam *et al.* (2023) reported that the heavy use of potassic fertilizers without amending these acidic soils through the use of organic and inorganic amendments is agronomically ineffective, expensive, and environmentally unfriendly. In fact, the fertility and productivity of these highly weathered acidic soils could be restored through the use of organic and inorganic amendments such as charcoal and sago bark ash (Paramisparam *et al.*, 2023), chicken litter biochar (Palanivell *et al.*, 2020), clinoptilolite zeolite (Palanivell *et al.*, 2021), and straw incorporation (Zhu *et al.*, 2022).

There are two common adsorption isotherms used to describe the adsorption behavior of K^+ in soils: Langmuir and Freundlich isotherms. Ragadhita and Nandiyanto (2021) reported that the assumptions of Langmuir isotherm include: (i) monolayer adsorption on homogenized surface with uniform energy; (ii) each adsorbent site retains only one adsorbed ion and zero interaction between the adsorbed ions; and (iii) adsorption reaches maximum and no further adsorption occurs when all the exchangeable sites are occupied. On the contrary, Dada *et al.* (2012) claimed that the assumptions of Freundlich's isotherm are as follows: (i) multilayer adsorption on heterogeneous surface through weak bonding; (ii) adsorption varies with the concentrations of added ions; and (iii) binding energy of ions decreases exponentially when the adsorption is completed. It was observed that different types of amendments can influence the adsorption behavior of K^+ in the same soil type. For example, Paramisparam *et al.* (2023) and Palanivell *et al.* (2021) reported that the K^+ adsorption behavior in Bekenu series amended with charcoal, sago bark ash, and clinoptilolite zeolite followed the assumptions of Langmuir isotherm, whereas Palanivell *et al.* (2020) elucidated that the application of chicken litter biochar resulted in the K^+ adsorption followed the assumptions of Freundlich isotherm.

There is dearth of knowledge regarding the application of Calciprill and sodium silicate on regulating K^+ sorption in tropical acidic soils. Calciprill is a 2 to 6 mm granulated calcium carbonate ($CaCO_3$) with higher $CaCO_3$ purity (95%) compared with conventional liming materials, which releases calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions, whereas sodium silicate is a silicon-based fertilizer which dissolves readily in soil water to release sodium (Na^+) and silicate (SiO_3^{2-}) ions. It was hypothesized that these amendments could regulate K^+ sorption by neutralizing excessive H^+ (Chong *et al.*, 2022), suppressing Al^{3+} and Fe^{3+} hydrolysis (Yerima *et al.*, 2020), and improving cation exchange capacity (CEC) (Zhao *et al.*, 2014). The objective of this study was to determine the effects of Calciprill and sodium silicate on: (i) adsorption and desorption and (ii) adsorption behaviour of K^+ in Bekenu series (*Typic Paleudults*). The implication of this study could demonstrate a deeper understanding about the mechanisms of K^+ sorption in the highly weathered acidic soils amended with Calciprill and sodium silicate.

MATERIALS AND METHODS

Soil sampling and amendment preparation

Based on USDA soil classification system, Bekenu series (*Typic Paleudults*) was used in this K^+ sorption study in which it was collected in an uncultivated area in a pedon (1 m × 1 m) with a sampling depth of 0.2 m in Universiti Putra Malaysia Sarawak (03°20'N, 113°07'E). The collected soil was then air dried, manually crushed, sieved to pass a 2 mm sieve, and bulked for homogenization. The Calciprill and sodium silicate were supplied by Omya Asia Pacific Sdn. Bhd. and Humibox Sdn. Bhd., Kuala Lumpur, Malaysia, respectively.

Treatments for potassium sorption study

The sieved soil was weighed at 250 g using a weighing balance for each replicate and kept in a container prior to mixing with the amendments. The application rates of Calciprill and sodium silicate were fixed at 100% targeted calcium saturation (C100) (Cantarella *et al.*, 1998) and average silicon uptake and planting density at 150 kg ha^{-1} (S150) (Malaysian Pepper Board, 2017), based on black pepper (*Piper nigrum* L.) as our test crop. Details of the treatments evaluated are as follows:

C0+S0: Soil without any amendments
C100: Soil + Calciprill at 100% calcium saturation
S150: Soil + sodium silicate at 150 kg ha^{-1}
C100+S150: Soil + Calciprill at 100% calcium saturation + sodium silicate at 150 kg ha^{-1}

Potassium sorption study

A 1,000 mg L^{-1} isonormal K^+ solution (a solution with known quantity of K^+ at specific known concentration) was prepared by dissolving 1.9070 g of oven-dried (60°C for 24 hours) potassium chloride (KCl) in 1 L of 0.01 mol dm^{-3} calcium chloride ($CaCl_2$) solution and further diluted into 250, 500, 750, and 1000 mg L^{-1} K^+. For K^+ adsorption, in four 50 mL centrifuge tubes, 2.0 g of soil was mixed with 20 mL of isonormal K^+ solution. The soil suspensions were shaken at 180 rpm for 24 hours using an orbital shaker, followed by centrifugation at 4,000 rpm for 10 minutes using a bench top centrifuge (Rotina 380, Hettich, North America) to obtain supernatants. The soil samples were washed with ethanol through another centrifugation (4,000 rpm for 10 minutes) to remove the residual K^+ in soil solution, followed K^+ desorption using 20 mL of 2 mol dm^{-3} KCl using similar agitation and centrifugation procedures as described in K^+ adsorption. The amount of K^+ in the supernatants was determined using Atomic Absorbance Spectrophotometer (AAnalyst 800, Perkin Elmer, Shelton, CT, USA). The K^+ adsorption and desorption were determined using the following formula:

$$q_e = \frac{(C_i - C_e) \times V}{w}$$

where q_e = adsorption/desorption capacity at equilibration (mg g^{-1}); C_i = Initial concentration of K^+ isonormal solution (mg L^{-1}); C_e = Equilibrium concentration of K^+ in isonormal solution (mg L^{-1}); V = volume of K^+ isonormal solution added (mL); w = weight of soil sample (g).

Adsorption isotherms for potassium ions

The collected data of K^+ adsorption were fitted into the linear form of Langmuir (Ragadhita and Nandiyanto, 2021) and Freundlich (Dada *et al.*, 2012) isotherms, as follows:

$$\frac{1}{q_e} = \frac{1}{q_{max}} + \frac{1}{q_{max}K_L C_e}$$

where q_e = adsorption capacity at equilibration (mg g^{-1}); C_e = Equilibrium concentration of K^+ in isonormal solution (mg L^{-1}); q_{max} = estimated maximum adsorption of K^+ on the soil surfaces (adsorbent) (mg g^{-1}); and K_L = the constant related to binding energy of K^+ at equilibrium phase.

$$log\ (q_e)\ = log\ (K_F)\ + \frac{1}{n} log(C_e)$$

where q_e = adsorption capacity at equilibration (mg g^{-1}); C_e = Equilibrium concentration of K^+ in isonormal solution (mg L^{-1}); K_F = Freundlich adsorption constant which measures the adsorption capacity (mg g^{-1}); $\frac{1}{n}$ = the constant used to determine if the adsorption process is favorable when the constant in a range between 0 and 1.

The criteria to determine the most suitable isotherm for describing the K^+ adsorption behavior in this study are as follows: (i) lower root mean square error (RMSE); (ii) lower chi-square value (χ^2); and (iii) higher coefficient of determination (R^2) (Palanivell *et al.*, 2020).

Experimental design and statistical analysis

The treatments were arranged in a completely randomized design (CRD) with three replications. The collected data were analyzed using Analysis of Variance (ANOVA) to determine the treatment effects after which mean comparison was performed using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. The relationship between amount of K^+ remaining in the equilibrium solution (Ce) and amount of K^+ adsorbed by the soil colloids (qe) was determined using simple linear regression. The software used was Statistical Analysis System (SAS) version 9.4, Cary, NC, USA.

RESULTS AND DISCUSSION

Calciprill and sodium silicate on potassium adsorption and desorption

Regardless of K^+ concentration, the amounts of adsorbed K^+ by the soils with the amendments (C100, S150, and C100+S150) were significantly higher compared with that of the soil without any amendments (C0+S0) (Figure 1). The significantly lower K^+ adsorption in C0+S0 was due to low pH and CEC, occupation of H^+, Al^{3+}, and Fe^{3+} at the negatively-charged exchangeable sites on soil colloids, and strong hydrogen bond between the 1:1 lattice aluminium-silicate sheets of kaolinite clay minerals (Paramisparam *et al.*, 2023). In contrast, the enhanced K^+ adsorption in the soils with the amendments is related to the improved pH and increased number of the negatively-charged exchangeable sites on the soil colloids. The addition of $CaCO_3$ increased soil pH through neutralization of active H^+ in the soil solution, resulting in the deprotonation of reserve H^+. This chemical reaction results in more negatively-charged exchangeable sites on soil colloids to improve K^+ adsorption. The increased soil pH also desorbs exchangeable Al^{3+} and Fe^{3+} into insoluble Al and Fe hydroxides to unlock the occupied negatively-charged exchangeable sites and increase K^+ retention (Das and Saha, 2014).

Moreover, the dissolution of amendments may contribute to increased negative surface charge and improved cation retention (Chong *et al.*, 2022). Regardless of K^+ concentration, the K^+ desorption in S150 and C100+S150 was significantly higher compared with those of C100 and C0+S0. Moreover, C100 did not significantly increase K^+ desorption compared with that of C0+S0. These findings indicate that Calciprill can reduce K^+ leaching, whereas sodium silicate can release K^+ for crop uptake.

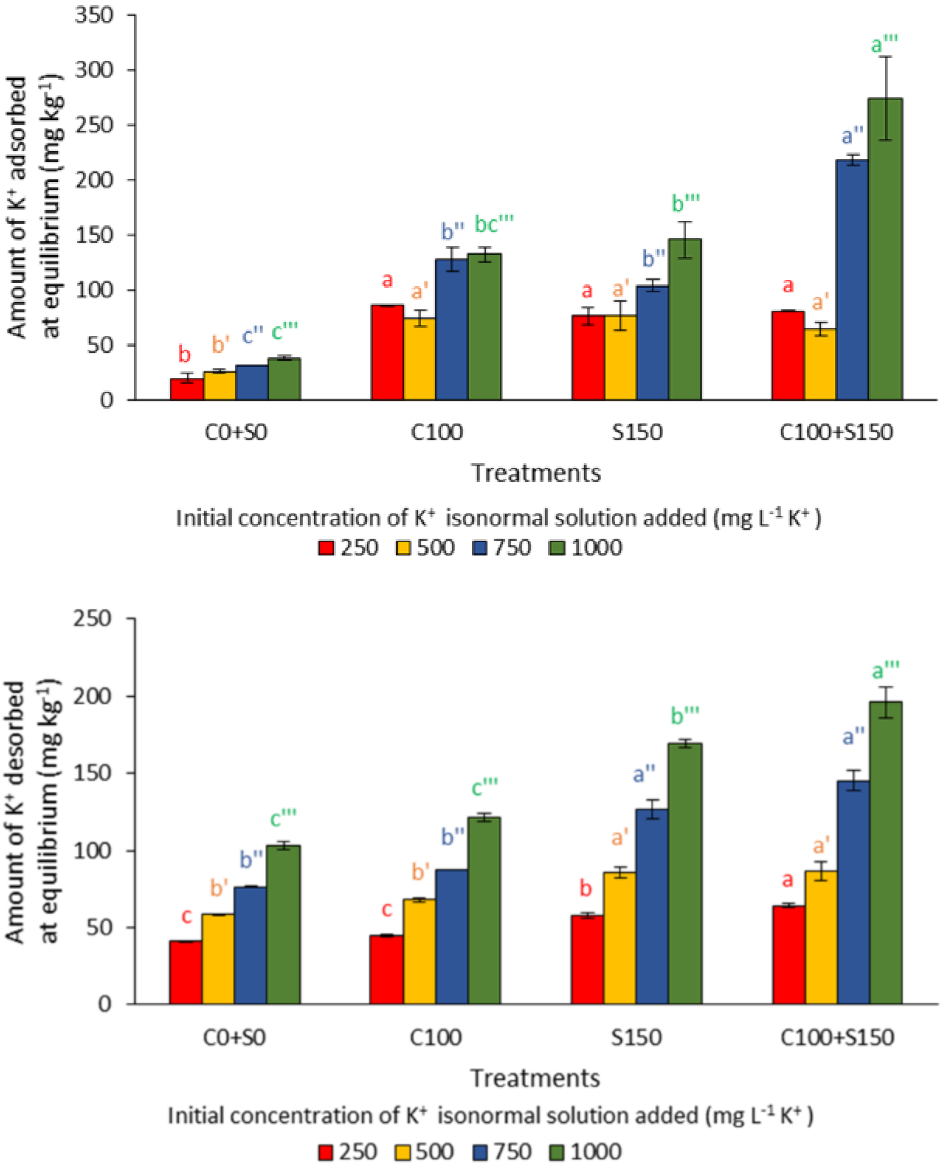

Figure 1 The amounts of K^+ adsorbed and desorbed in relation to treatments at different amounts of added K^+. Means with different letters within the same font colour indicate significant differences between treatments using Tukey's HSD test at $p \leq 0.05$. Error bars represent standard errors.

Adsorption isotherm for potassium ions in the soil amended with Calciprill and sodium silicate

Although Freundlich isotherm exhibited lower R^2 values, the lower χ^2 and RMSE values in Langmuir isotherm suggest that it is the most suitable isotherm for describing K^+ adsorption by Calciprill and sodium silicate (C100, S150, and C100+S150). For the selection of the most suitable adsorption isotherm, RMSE and χ^2 were prioritized over R^2 values. This is because

RSME was used to assess the absolute fit precision, whereas χ^2 was used to determine the random error distribution. Moreover, Ho (2006) stated that relying solely on R^2 in linearized form of adsorption isotherm can be biased because it often fails to demonstrate the actual chemical reactions, whereas Ng *et al.* (2002) stated that RMSE reflects higher reliance and unbiased reflection of data fitting at varying concentrations of isonormal solution used. Conversely, the higher R^2 in combination with lower χ^2 and RMSE values in Freundlich isotherm indicate that it is the most suitable isotherm for describing K^+ adsorption in C0+S0. This observation was further supported by the findings of Palanivell *et al.* (2021) who reported that the adsorption behaviour K^+ in Bekenu series without the inclusion of clinoptilolite zeolite followed the assumptions of Freundlich isotherm.

Table 1 Parameters for determining the suitability of Langmuir and Freundlich isotherms for describing K^+ adsorption behavior.

Treatment	**Langmuir isotherm**			
	Regression equation	**R^2**	**χ^2**	**RSME**
C0+S0	y=6.926x + 0.021	0.9595	3.98×10^{-3}	0.02148
C100	y=0.695x + 0.008	0.2854	1.88×10^{-3}	0.00303
S150	y=1.060x + 0.008	0.5255	6.99×10^{-3}	0.00257
C100+S150	y=1.482x + 0.005	0.2735	6.82×10^{-3}	0.00610
Treatment	**Freundlich isotherm**			
	Regression equation	**R^2**	**χ^2**	**RSME**
C0+S0	y=0.447x + 0.230	0.9879	3.69×10^{-4}	0.01633
C100	y=0.281x + 1.264	0.4892	0.012	0.10993
S150	y=0.369x + 1.008	0.6804	8.73×10^{-3}	0.09333
C100+S150	y=0.796x + 0.043	0.4847	0.070	0.27378

CONCLUSION

Calciprill and sodium silicate improved the K^+ adsorption in Bekenu series because of increased soil pH, impaired Al^{3+} and Fe^{3+} hydrolysis, and improved CEC. In terms of K^+ desorption in Bekenu series, Calciprill can retain K^+ and prevent leaching, whereas sodium silicate can rapidly release K^+ for crop uptake. It was observed that the inclusion of amendments can alter the K^+ adsorption where the K^+ adsorption in C0+S0 followed the assumptions of Freundlich isotherm, whereas K^+ adsorption in the soils with amendments (C100, S150, and C100+S150) followed the assumptions of Langmuir isotherm.

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SCREENING OF CELLULOLYTIC SOIL ACTINOMYCETES FOR PLANT GROWTH-PROMOTING TRAITS

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INTRODUCTION

Current agricultural practices rely heavily on the application of chemical fertilisers and pesticides to increase plant nutrition and ensure crop protection. However, the prolonged use of these chemical fertilisers can have negative impacts on soil structure and environmental health (Fatmawati *et al.*, 2019). One of the possible alternatives to reduce the use of chemical fertilisers involves the use of plant growth-promoting microorganisms (PGPM) as biofertilisers. Biofertilisers have a combination of beneficial microbes that have the potential to enhance plant growth and offer enormous promise for sustainable agriculture, particularly in the face of climate change (Boubekri *et al.*, 2022). Recent studies have further demonstrated that multifunctional PGPM capable of simultaneously fixing nitrogen, solubilizing phosphate and producing siderophores, represent a sustainable strategy for enhancing crop productivity and soil fertility (Laishram *et al.*, 2024). The plant growth-promoting potential of rhizosphere actinomycetes, including *Streptomyces* spp., has also been validated at the genomic level, with genes encoding key PGP pathways confirmed in recently characterized strains (Xu *et al.*, 2025). Actinomycetes are Gram-positive bacteria with a complex multicellular structure similar to the mycelium of filamentous fungi (Boukhatem *et al.*, 2022). Many reports have shown that actinomycetes have the abilities to colonize plant rhizospheres and promote growth directly through phytohormone production, siderophore secretion, and nutrient solubilization, or indirectly via biocontrol of soil-borne pathogens such as *Fusarium oxysporum* f.sp. *cubense* (Sousa and Olivares, 2016; Getha *et al.*, 2005). Further, this group of organisms has been recognized as cellulase producer that can act synergistically for rapid decomposition of crop residues (Abdulla, 2007). Previous screening of the FRIM Microbial Culture Collection (FRIM-MCC) identified 18 actinomycetes isolates with strong cellulase and hemicellulase activities (Lili Sahira *et al.*, 2025). Although these isolates have been characterized for their strong cellulolytic and hemicellulolytic activities, their PGP potential remains unexplored. This represents a critical research gap in understanding their full agricultural utility, which the present study aims to address. Thus, the current study extends this work by evaluating the phytotoxicity and plant growth-promoting (PGP) activities of these cellulolytic isolates, providing a foundation for developing microbial consortium as agricultural biofertilizers.

MATERIALS AND METHODS

Actinomycetes Isolates

Eighteen potential cellulase-producing actinomycetes previously isolated from forest soil at the FRIM Kepong campus were obtained from FRIM-MCC. Spore suspension stock cultures were maintained in 20% glycerol at -80°C. The isolates were thawed and inoculated onto fresh yeast extract-malt extract agar (ISP2) and incubated at 28°C for seven to ten days.

Phytotoxicity and Seed Germination Assay

The phytotoxicity of the 18 isolates was evaluated using the ragdoll method (Fatmawati *et al.* 2019) on mung bean and lima bean seeds. Surface-sterilized seeds were soaked in actinomycetes culture broth for 60 minutes, placed on wet paper towels, rolled, and incubated for three to five days. The Relative Seed Germination (RSG), Relative Root Growth (RRG), and Germination Index (GI) were calculated. Uninoculated ISP2 medium and sodium hypochlorite served as positive and negative controls, respectively.

Evaluation of Plant Growth-Promoting (PGP) Activities

Screening of Nitrogen-Fixing ability

Qualitative nitrogen fixation ability was assessed by culturing each isolate on nitrogen-free medium (containing K_2HPO_4, KH_2PO_4, $MgSO_4$, $CaCl_2$, dextrose, trace minerals, and agar) for seven to ten days at 28°C, with ISP2 medium as a positive growth control.

Screening for siderophore production

The Chrome Azurol Sulfonate (CAS) agar method was used to screen for siderophore production. Isolates were inoculated on CAS agar plates and incubated at 28°C for five days. Siderophore production was categorized as strong (halo zone ≥ 2 mm) or weak (halo zone < 2 mm) based on formation of an orange/yellow-orange halo around colonies.

Screening for phosphate solubilization test

A 5 mm agar plug from 7 to 10-day-old cultures in ISP2 media was placed upside down on Pikovskaya's (PVK) agar medium and incubated for seven days at 28 °C. Halo zone formation indicates phosphate solubilising activity. The Solubilization Index (SI) was calculated as: total diameter (colony + halo zone) ÷ colony diameter.

RESULTS AND DISCUSSION

Phytotoxicity of 18 cellulolytic isolates was evaluated on mung bean and lima bean seeds using the ragdoll method. Three isolates (TY034-077, TY048-069, and TY030-054) were highly phytotoxic (GI < 50%), with TY030-054 showing the most severe inhibition (GI 18.4% for mung beans; 7% for lima beans). The remaining 15 isolates (GI ≥ 50%) were advanced for PGP evaluation. Isolates TY035-056 and TY031-080 recorded GI > 100%, indicating direct growth-stimulating effects. This is consistent with Faddetta *et al.* (2023), who reported that actinobacterial cultures of *Streptomyces violaceoruber* improved tomato germination indices, attributable to the production of bioactive volatile organic compounds and secondary metabolites.

Plant Growth-Promoting (PGP) Traits

Plants frequently struggle to access soil nutrients in unusable forms; PGP actinomycetes resolve this by converting them into bioavailable states. Timofeeva *et al.* (2023) demonstrated that rhizosphere bacteria capable of nitrogen fixation, phosphate solubilization, and siderophore secretion collectively support sustainable agricultural development by improving soil fertility and crop yields.

Nitrogen Fixation: Ten out of the 15 isolates (67%) exhibited growth on the N-free medium, demonstrating their ability to utilize the nitrogenase enzyme to convert atmospheric nitrogen gas into ammonia. Isolates TY035-056, TY034-058, TY045-031, TY035-043, TY022-029 and TY049-057 showed moderate nitrogen fixation abilities (Table 1). This proportion aligns with Timofeeva *et al.* (2023), who established nitrogen-fixing rhizobacteria as key contributors to soil nitrogen bioavailability.

Siderophore Production: Thirteen isolates (87%) produced siderophores, chelating insoluble Fe^{3+} into plant-absorbable Fe^{2+}. Six isolates (TY035-056, TY031-080, TY031-015, TY032-

025, TY018-044, and TY032-061) were strong producers (halo zone ≥ 2 mm) on CAS agar (Table 1). The CAS colour change from blue to orange upon Fe^{3+} chelation is a well-validated qualitative indicator of siderophore activity (Timofeeva *et al.*, 2023) consistent with Boukhatem *et al.* (2022), who highlighted siderophore production as a primary mechanism by which actinobacteria improve plant iron nutrition and suppress soil-borne pathogens.

Phosphate Solubilization: Nine isolates (60%) produced clear halo zones on PVK agar, indicating their capability to release organic acids that dissolve insoluble tri-calcium phosphate (Figure 1). Isolates were categorized as High Efficiency (SI > 2.50), Moderate Efficiency (2.10 < SI < 2.50) and Non-Solubilisers (ND). Isolate TY035-051 demonstrated the highest efficiency with a Solubilization Index (SI) of 3.53, followed by TY035-043 (SI 2.57) and TY032-061 (SI 2.53) (Table 1). These values notably exceed those reported for *Streptomyces* strains from phosphate-rich soils, where solubilization was tightly coupled with siderophore co-production (Boubekri *et al.*, 2022). The synergistic relationship between phosphate solubilization and siderophore activity in several isolates supports Timofeeva *et al.* (2023), who showed that multi-trait bacteria produce stronger plant growth responses than single-trait isolates.

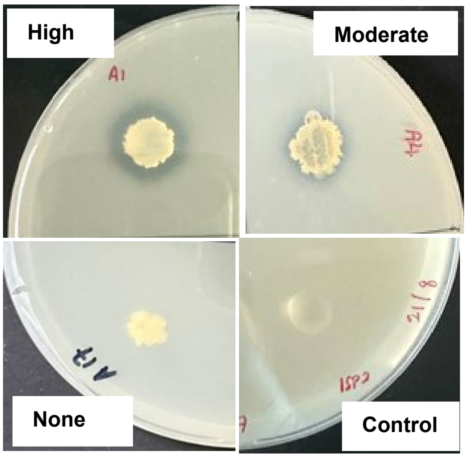

Figure 1 Qualitative screening of phosphate solubilizing activity on PVK agar. The presence of clear halo zones around the colonies indicates the successful dissolution of inorganic tri-calcium phosphate.

When integrating all PGP parameters, five isolates (TY035-056, TY034-058, TY035-051, TY049-057, and TY022-029) synergistically possessed all three PGP activities (nitrogen fixation, siderophore production, and phosphate solubilization). These multifunctional strains are primary candidates for microbial consortium development. Timofeeva *et al.* (2023) demonstrated that introducing a consortium with multiple simultaneous PGP activities produces synergistic plant growth stimulation beyond what single-isolate applications achieve.

Table 1 Siderophore production, N-fixation and phosphate solubilization of the 15 actinomycetes isolates.

No	Actinomycetes Isolates	Siderophore production category	Growth on N-free medium	Growth on PVK agar P-Solubilising Index
1.	TY035-056	Strong	++	2.38
2.	TY031-080	Strong	+	-
3.	TY031-015	Strong	-	-
4.	TY032-025	Strong	+	-
5.	TY034-058	Weak	++	2.13
6.	TY025-073	Weak	-	-
7.	TY045-031	Weak	++	-
8.	TY033-024	Weak	-	2.36
9.	TY018-044	Strong	-	2.31
10.	TY035-043	None	++	2.57
11.	TY022-029	Weak	++	2.23
12.	TY019-059	None	+	-
13.	TY035-051	Weak	+	3.53
14.	TY032-061	Strong	-	2.53
15.	TY049-057	Weak	++	2.27

CONCLUSION

This study demonstrates that selected cellulolytic soil actinomycetes from FRIM-MCC showed multiple PGP traits alongside low phytotoxicity, suggesting their potential as candidates for microbial consortium development. Five isolates (TY035-056, TY034-058, TY035-051, TY049-057, and TY022-029) exhibited synergistic PGP activities through nitrogen fixation, siderophore production, and phosphate solubilization, indicating their capability to simultaneously support plant nutrient availability. However, as these findings are based solely on *in vitro* screening, further validation through quantitative PGP assays (such as IAA production) and *in vivo* greenhouse and field trials remain essential before any practical biofertiliser application can be recommended. These isolates nonetheless represent a promising foundation for exploring the development of a stable microbial consortium inoculant.

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BIOREMEDIATION OF USED AUTOMOBILE OIL-CONTAMINATED SOIL USING *Lactobacillus* spp.: A LABORATORY-SCALE INVESTIGATION

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INTRODUCTION

The pollution caused by hydrocarbons poses a significant threat to the environment, primarily because of the presence of petroleum, pesticides, and organic chemicals that are toxic to living organisms (Kanungo *et al.*, 2024). It is common practice to choose bioremediation in addition to chemical and physical remediation techniques as the microbes break down complex organic compounds into simpler metabolites and nutrients that can be incorporated into the soil and further broken down by other microorganisms.

In a number of oil spill scenarios, bioremediation has been shown to be successful in reducing the environmental harm caused by petroleum toxins (Hazaimeh *et al.*, 2021). For instance, a study on the bioremediation of crude oil-soaked soils showed that more than half of the oil (53-63%) could be removed in just six months (Lisichkin *et al.*, 2022). In this study, *Lactobacillus spp.* which was isolated from a wetland area in Port Dickson, known for shipping routes in the Straits of Malacca was used to treat the contaminated soil with oil. This work is a part of a component that focusing on how specific indigenous microorganisms can be utilized for bioremediation.

MATERIALS AND METHODS

Preparation of *Lactobacillus* broth

A total of 120 ml of casein and 80 ml of bromelain extracts were combined and placed in a flask to obtain a final volume of 200 ml of broth. The *Lactobacillus* spp. bacteria, cultured at a temperature of 30 °C. The flask was placed inside the shaker and left overnight at a speed of 180 revolutions per minute at 30 °C**.**

Preparation of contaminated soil model and bioremediation study

2 kg of entisol soil collected from Pusu river flood plain, Gombak, Selangor to autoclaving. In addition, 2 kg of soil that had not been subjected to autoclaving was also prepared as control. Subsequently, the soil was subjected to drying out in a dryer at a temperature of 40 °C for overnight. For each test, 200ml of used automobile oil collected at the workshop in Sri Gombak was added into the 500 g of entisol for bioremediation studies. The mixtures were mixed well prior treatment and added with 10 ml of prepared *Lactobacillus* inoculation. All samples were kept in a shaker incubator at 37ºC up to 10 days.

Analysis on the response of the procedure

pH test and Measurement of hydrocarbons in soil using FTIR.

The soil sample was weighed at 10 g and placed in a 50 mL centrifuge tube. 20 mL of distilled water was added to the centrifuge tube, and the sample was shaken for 30 seconds. The sample was left for 15 minutes before being tested using a pH meter. The shaking extraction method for hydrocarbons in soil began by weighing 1 g of contaminated soil and placing it in a 10 ml centrifuge tube. 10 ml of acetone aliquots were placed into the centrifuge tube and agitated for at least 15 seconds. Then the soil sample is dried and measured using FTIR (ATR) (Perkin Elmer, USA).

RESULTS AND DISCUSSION

Effectiveness of *Lactobacillus* on degrading hydrocarbon content in contaminated soil with oil

Determination of pH by using pH meter for every samples

The samples were separated into two categories: soil that had been autoclaved and soil that had not. This distinction was created in order to determine if the microbial presence in the soil would affect the outcome of the experiment.

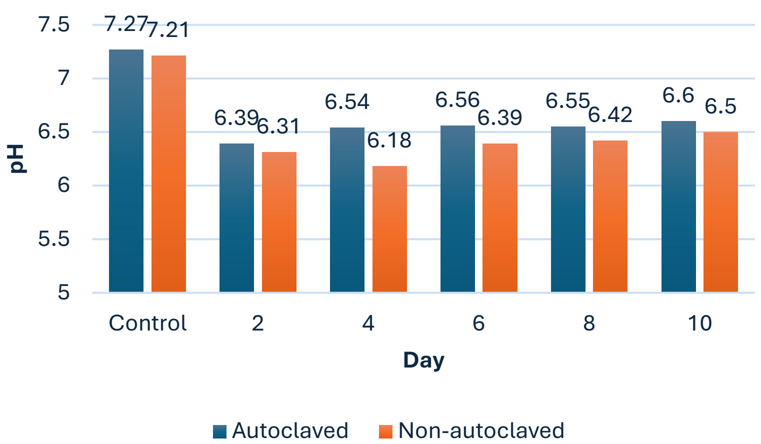

Figure 1 Bar graph of result of pH for 200 ml of oil with 10 ml of *Lactobacillus* spp on autoclaved and non-autoclaved contaminated soil. The control samples were without *Lactobacillus* spp.

Based on the results, the pH of all the samples, including the controls were acidic in relation to the quantity of oil pollution in the soils. The pH value of the oil decreased consistently from day 2 to day 10 indicating microorganisms role in the metabolic activities and breakdown of contaminants. Specific pH ranges significantly impacted the efficiency of certain enzymes, hence influencing the degradation of organic materials and heavy metals (Naz *et al.*, 2022).

FTIR analysis

The absorbance spectra were collected within the range of 4000-1300 cm^{-1} using 100 scans at a resolution of 4 cm^{-1}. The FTIR spectrum provides information about the functional groups located within 1 µm of the surface of an internal reflection element. In addition, it has the capability to acquire accurate spectra of any samples even in the presence of water (I. Eldos *et al.*, 2020). In Figure 2, the FTIR analysis reveals that there is an increase in transmittance for certain peaks at 3004 cm^{-1} in the control sample, as compared to samples (a) and (b) which shifted to a broader peaks at 2924 and 2856 cm^{-1}, indicating the addition of *Lactobacillus* significantly metabolized the hydrocarbon chain into fragments of smaller hydrocarbons.

However, for the peaks at 1710 cm^{-1}, the control sample exhibits a decrease in transmittance compared to samples (a) and (b) showing the break down of C=O group into the simple compound, C-H.

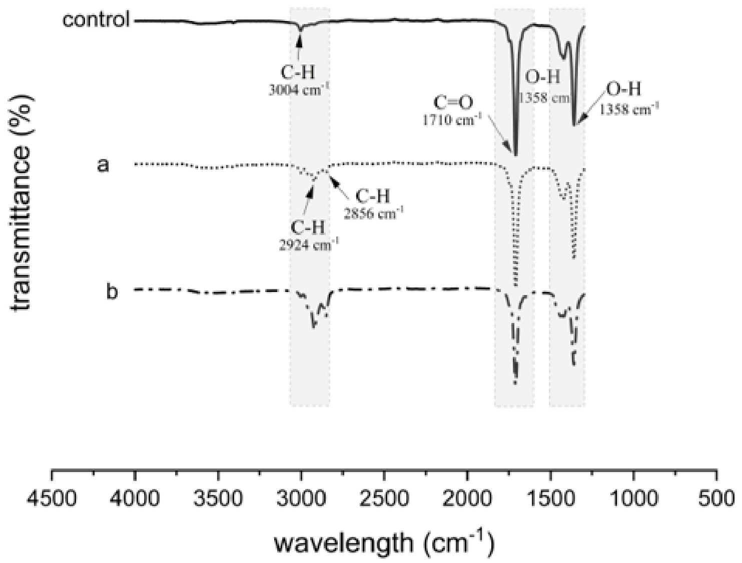

Figure 2 Comparison of FTIR spectra for contaminated soil with 200 ml of oil and 10 ml of *Lactobacillus* spp on (a) day 2 and (b) day 10. The control sample was one without any *Lactobacillus* spp.

FTIR analysis in the optimization of *Lactobacillus* bioremediation effects on contaminated soil

To enhance the efficiency of bioremediation, the same experimental setup was established to track the breakdown of hydrocarbons in each sample. Figure 3 showed that the control sample has a higher peak at 3004 cm^{-1} compared to the samples with volumes of 2 ml, 3 ml, 4 ml, and 5 ml. The transmittance of the C-H bond in the complex compound steadily increases, indicating the degradation of the complicated compound into a simpler form.

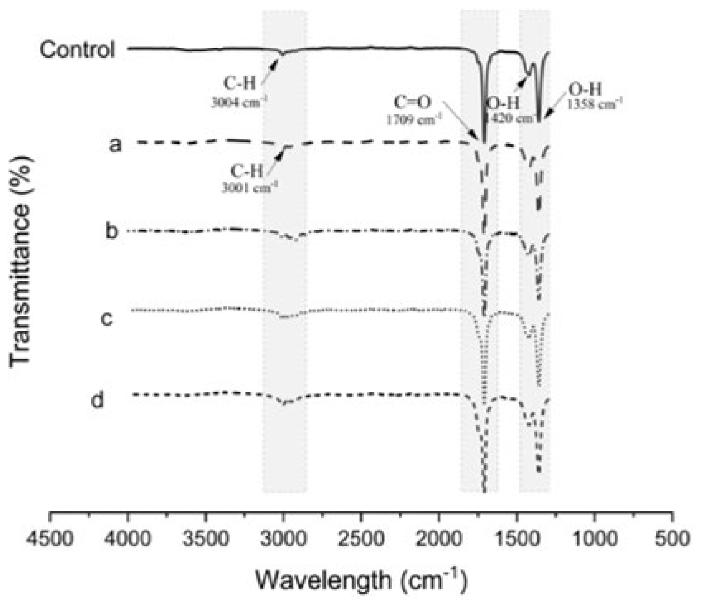

Figure 3 Comparison of FTIR spectra on day 2 for (a) 20 (b) 30, (c) 40 ml and (d) 50 ml of *Lactobacillus* spp

CONCLUSION

In conclusion, the degradation of hydrocarbon content indicates that the bioremediation of oil spill-contaminated soil employing *Lactobacillus* has proven to be successful. The findings demonstrated a considerable decrease in the concentration of hydrocarbons, confirming *Lactobacillus*'s ability to convert complicated hydrocarbons into less hazardous, simpler molecules. Fourier Transform Infrared (FTIR) spectroscopy offered a dependable analytical technique to confirm the hydrocarbons' degradation, providing comprehensive information about the alterations in the soil chemical composition both before and after treatment.

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EFFECTS OF SOIL SOLARIZATION AND FARMYARD MANURE ON THE GROWTH OF IRRIGATED RICE IN THE SAHEL SAVANNA OF NIGERIA

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INTRODUCTION

Rice (*Oryza sativa* L.) is a major staple food crop and a vital source of livelihood for millions of people in sub-Saharan Africa. Despite its significance, rice productivity in the Sahel Savanna zone of Nigeria remains below its potential due to poor soil fertility, high weed pressure, and limited soil moisture retention. Sustainable soil management practices are therefore essential for improving yield and maintaining soil health in these semi-arid environments. Soil solarization, which involves covering moist soil with polyethylene sheets to trap solar radiation, is an environmentally friendly practice that suppresses soil-borne pathogens and weeds while improving soil physicochemical properties and nutrient availability (Cucu *et al.*, 2025). Similarly, farmyard manure (FYM) enhances soil structure, microbial activity, nutrient cycling, and crop productivity (Hussain *et al.*, 2024). Although the individual benefits of soil solarization and FYM are well documented, information on their combined effects under the irrigated conditions of the Nigerian Sahel is scarce. Given the region's high solar irradiance and inherently low-fertility soils, understanding the interaction between these practices is essential for developing sustainable rice production strategies. Therefore, this study evaluated the effects of soil solarization and FYM application on the productivity of irrigated rice in Gashua, Sahel Savanna, Nigeria.

MATERIALS AND METHODS

The experiment comprised two factors: soil solarization and farmyard manure (FYM) application. Soil solarization consisted of three levels, namely uncovered soil (control), single-layer polyethylene cover, and double-layer polyethylene cover. Transparent polyethylene sheets with a thickness of 30 µm (0.03 mm) were tightly laid over the prepared plots, with the edges securely buried to minimize heat loss, and maintained in place for six weeks before transplanting to increase soil temperature and suppress soil-borne pathogens, pests, and weed propagules. At the end of the solarization period, the polyethylene sheets were removed, and FYM was incorporated into the soil at rates of 0, 15, and 30 t ha^{-1} according to the treatment combinations before transplanting the tomato seedlings. The FYM was obtained from the Livestock Production Unit of the Federal University Gashua Teaching and Research Farm and consisted of a well-decomposed mixture of cattle dung, urine, bedding materials, and feed residues. Prior to application, representative samples of the FYM were analyzed at the Soil and Water Laboratory, Faculty of Agriculture, Federal University Gashua, for selected physicochemical properties. The manure had a pH of 6.70, organic carbon content of 15.1 g kg^{-1}, available phosphorus of 0.83 mg kg^{-1}, total nitrogen of 0.36 g kg^{-1}, bulk density of 1.29 g cm^{-3}, and exchangeable Mg, K, Ca, and Na concentrations of 0.86, 1.31, 2.41, and 0.98 cmol kg^{-1}, respectively. The treatments were arranged in a split-plot design with three replications, resulting in a total of 27 experimental units. Soil solarization treatments were assigned to the main plots, whereas FYM application rates were allocated to the subplots. Each experimental plot measured 3 × 2 m (6 m^2) and was separated by ridges to prevent nutrient movement, with 1.0 m and 0.5 m spacing maintained between main plots and subplots, respectively, resulting in a total experimental area of approximately 10 × 23 m. The experimental field was ploughed, harrowed, leveled, and laid out into three blocks, each comprising nine subplots representing the combinations of soil solarization and farmyard manure (FYM) treatments. Before solarization, the field was irrigated to near field capacity to enhance heat transfer within the soil profile, after which the polyethylene sheets were installed according to the treatment specifications. Following the six-week solarization period, the sheets were removed, FYM was incorporated at the designated rates, and three-week-old rice seedlings were transplanted in the evening at a spacing of 20 × 20 cm to minimize transplanting shock. The field was irrigated immediately after transplanting, with subsequent irrigation applied at three-day intervals until panicle initiation and every two days thereafter to maintain adequate soil moisture for crop growth and grain filling. Five plants were randomly tagged in each plot for growth parameters.

Data Collection and Analysis

Data on growth attributes included plant height, measured from the base of the plant to the tip of the panicle at 6 and 9 weeks after transplanting (WAT), and number of tillers per plant, obtained by counting all tillers from the tagged plants and averaging per plot. Generated data were subjected to analysis of variance (ANOVA) appropriate for the split-plot design using STAR 2.2 edition. Treatment means were compared using Student-Newman-Keuls -test (SNK) at a 5% level of significance.

RESULTS AND DISCUSSION

Effect of solarization and farmyard manure on vegetative growth attributes of irrigated rice

Table 1 presents the effect of solarization and farmyard manure on vegetative growth of irrigated rice. Result reveals that soil solarization and farmyard manure (FYM) application significantly influenced the vegetative growth of rice during the 2019 and 2020 dry seasons. Result reveals that plant height did not vary significantly ($p > 0.05$) among solarization treatments across the seasons. Conversely, the number of tillers per square meter (m^2) showed a marked response to solarization, with double and single-layer polyethylene covers producing significantly ($p < 0.05$) higher tiller numbers (203.22 and 202.11 m^{-2} in 2019; 202.67 and 202.00 m^{-2} in 2020, respectively) compared to the unsolarized control (198 m^{-2}). The greater tiller production observed under the solarized treatments was consistent with the increased soil temperature recorded in the study, indicating that soil solarization created a more favorable environment for rice vegetative growth. Similar improvements in crop growth following soil solarization have been attributed to enhanced soil conditions and greater nutrient availability (Cucu *et al.*, 2025; Hussain *et al.*, 2024). Similar observations were reported by Urmi *et al.* (2022), who found that elevated soil temperatures during solarization improved soil microbial activity and nutrient cycling.

FYM application further enhanced rice performance, particularly in tiller production. The 15 t ha^{-1} FYM rate significantly increased the number of tillers (209 m^{-2} in 2019; 208.33 m^{-2} in 2020) and plant height (80.0 cm and 80.33 cm, respectively), outperforming both the control (0 t ha^{-1}) and higher FYM rate (30 t ha^{-1}). The superior performance observed with 15 t ha^{-1} FYM indicates that a moderate rate of organic amendment was sufficient to enhance rice growth under the prevailing experimental conditions. Similar responses have been reported in previous studies, where moderate rates of farmyard manure promoted crop growth more effectively than higher application rates (Hussain *et al.*, 2024).

The positive influence of FYM aligns with the findings of Hussain *et al.* (2024), who demonstrated that organic amendments improve soil organic carbon, cation exchange capacity (CEC), and microbial biomass, enhancing rice tillering and canopy growth in semi-arid soils.

Table 1 Effects of Soil Solarization and FYM on Plant height (cm) and Number of Tillers m-^{2} during the Dry seasons of 2019 and 2020.

Treatment	2019		2020	
	Plant height (cm)	Number of tillers (m^{-2})	Plant height (cm)	Number of tillers (m^{-2})
Solarization (S)				
Uncover	78.33	198.00^{b}	77.33	198.11^{b}
Single polythene sheet	78.33	202.11^{a}	77.00	202.00^{a}
Double polythene sheet	80.33	203.22^{a}	78.33	202.67^{a}
Pr >F	0.1479	0.0366	0.4800	0.0127
SE±	0.839	1.376	0.793	1.038
FYM (t ha^{-1})				
0	78.66	194.11^{c}	76.00^{b}	196.11^{b}
15	80.00	209.00^{a}	80.33^{a}	208.33^{a}
30	78.11	200.22^{b}	76.33^{b}	198.88^{b}
SE±	0.839	1.376	0.793	1.038
Pr >F	0.2869	0.0420	0.0017	0.0007
Interaction				
S x FYM	0.0070	0.2151	0.0804	1.000

Means followed by the same letter in a column are not significantly different at p ‹ 0.05 using Student Newman Keuls (SNK). SE= Standard error of means.

The interaction of soil solarization on plant height during the 2019 dry season is significant as shown in Figure 1. The tallest plants (82.0 cm) were obtained with double-layer soil solarization combined with 15 t ha^{-1} FYM, although this treatment was statistically comparable to no solarization + 15 t ha^{-1} FYM (79.0 cm), single-layer solarization + 15 t ha^{-1} FYM (80.0 cm), and single-layer solarization + 30 t ha^{-1} FYM (79.0 cm). In contrast, the shortest plants (72.0 cm) were recorded under single-layer solarization without FYM application. The superior performance of the combined solarization and moderate FYM treatment suggests that improved soil warming enhanced the mineralization of organic nutrients, thereby increasing nutrient availability and promoting vigorous vegetative growth. Soil solarization is known to suppress weeds and soil-borne pathogens while stimulating nutrient mineralization, whereas FYM improves soil structure, microbial activity, and nutrient cycling, resulting in greater nutrient uptake and crop growth (Li *et al.*, 2025; Nwe Htwe *et al.*, 2025). The absence of further improvement at 30 t ha^{-1} FYM indicates that increasing manure beyond the moderate rate did not confer additional benefits to plant height, suggesting that 15 t ha^{-1} FYM was sufficient to optimize vegetative growth under the prevailing soil and climatic conditions. Similar findings have been reported by recent studies, which demonstrated that integrating organic amendments with appropriate soil management practices enhances rice growth more effectively than the application of either practice alone (Riddech *et al.*, 2025).

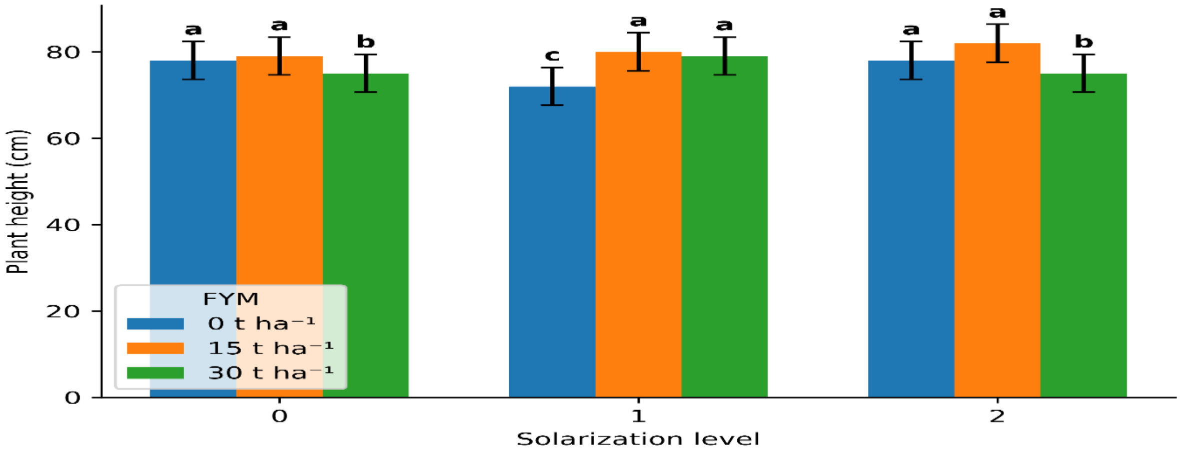

Figure 1 Interaction of Soil Solarization and FYM on plant height of Rice at FUGA during the 2019 dry season.

CONCLUSION

The study demonstrated that soil solarization and farmyard manure (FYM) significantly influenced the growth of irrigated rice under the Sahel Savanna conditions of Nigeria. The combination of double-layer soil solarization and 15 t ha^{-1} FYM produced superior plant height and tiller production, indicating that integrating soil solarization with a moderate rate of FYM can effectively enhance early rice growth. These findings suggest that this integrated soil management practice has the potential to improve rice establishment and crop vigor under irrigated conditions in the Sahel Savanna and warrants further evaluation for its effects on yield and long-term soil health.

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COMMUNITY-SCALE BIOMASS DECOMPOSITION: RESULTS OF ANALYSIS AND USES

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INTRODUCTION

Many residential neighbourhoods are blessed with trees, gardens, and lawns. All vegetative parts of these are made up of carbon and various other chemical elements brought up from the soil to the plant by the roots. Even when these plant parts were cut and left on the soil surface, they still retain those elements. This is one of nature's ways of conserving and recycling nutrients. Plant parts are composed of chemical compounds that lock up elements such as N, P, K, S, Mg, etc. in complex structures that are difficult to dismantle (Fant & Ghedini, 2024). Products of decomposition of vegetative matter collected from a diverse community have been studied, and some results are discussed in this paper.

METHODOLOGY

Most often, crop residues, grass trimmings, cut branches and fallen leaves are left by the roadside for collection by the local council. KATURA or Kampung Tunku Residents' Association, recognising the wealth of plant nutrients and organic matter in these materials, organised regular collection of this biomass, nicely tied-up and placed in specially-designed boxes sited at strategic points in the neighbourhood. The biomass that was collected was brought to a designated processing centre. The biomass, which originated from plants and trees in a large area like Kampung Tunku, is multi-species. Each collection was spread out at the Centre above previous collections and exposed to the elements for a week or two or more. Some were shredded coarsely. Others were allowed to decompose *in-situ*. Several decomposition products were identified: (1) H, a fine, dark material observed at the bottom of a pile of biomass, sometimes up to 0.5 m thick. Earthworms, millipedes, and other soil fauna were present. It is identified as 'humus', often mentioned in the literature on pedology (2) C, "coarse subor" broken pieces of biomass, mostly unrecognisable as tree/plant leaves, fruits or branches (3) F, "fine subor", a fine, dark material developed after C was allowed to decompose over time, with or without mechanical shredding, containing various soil fauna. These three forms of decomposed biomass were sampled and sent for chemical analysis. In addition, surface soil that was mulched with C, for several weeks (M1, M2), at two sites, and surface soil, S, under a rambutan tree, were also sampled.

RESULTS AND DISCUSSION

A new term for community biomass

Plant biomass, especially in a multi-species context, is inherently rich in a large variety of plant nutrients. This quality is retained even when the plant parts were detached from the plant. With this quality, it is considered very valuable. Thus, it is very inappropriate to refer to the biomass as "waste", "rubbish" or "garbage". To ensure that biomass is recognised as something to be treasured, a new term "subor", combining two Malay words, "sumber" and "organik", was proposed.

Results of chemical analysis

Table 1 shows that the carbon content of biomass, being materials that make up plants, in all samples is high. Most samples have relatively high nitrogen (N) contents too, in keeping with the high quality of the vegetation and the species diversity of the biomass (Figure 1). The ratio of carbon to nitrogen (C:N) is highlighted in these results. C:N has been studied widely in the context of predicting or evaluating the quality of soil conditioners. The three products mentioned above demonstrated their superior quality through the presence of abundant soil fauna. When applied to the soil, their effects on plant performance were notable.

Species diversity is reflected in this picture. Besides normal leaves of various shapes, colours and sizes, there were palm fronds and other plant parts from vegetable and flower gardens. Decomposition has progressed significantly and most of the plant parts cannot be easily recognised

Figure 1 Species diversity in a community biomass

The ratio of carbon to nitrogen in vegetative matter

The C:N is often used as an indicator of effectiveness in developing vegetative or animal matter to be soil conditioners. Low C:N is associated with a conditioner that is effective in providing nutrients that are easily available to plants. High C:N, even with high nutrient contents in the conditioner, does not facilitate the uptake of the desired nutrients by plants as the nutrients are tied up in organic compounds. As an example, in oil palm holdings, the trunks and fronds do not become good soil conditioners because of their high carbon contents, and therefore high C:N. To help obtain a soil conditioner with an acceptable C:N, the trunks, fronds and empty fruit bunches (EFB) are often mixed with Palm Oil Mill Effluent (POME). POME is known to be richer in nutrients than the three palm components mentioned earlier (Raymond *et al.*, 2024).

In Table 1, the C:N for products, H,F,M1 and M2 are 14, 15 . 15 and 21, respectively. These low C:N values show that these products are able to supply nutrients in the forms that are easily available to plant roots. The C:N for S and C are at a higher range, indicating lower ability to supply plant-available nutrients.

Table 1 Results of chemical analysis of decomposition products and surface soils

Sample description	Carbon (%)	Nitrogen (%)	C:N	P_2O_5 (%)	K_2O (%)
Humus (H)	28.89	2.04	14.16	0.61	0.19
Fine subor (F)	23.20	1.59	14.59	0.51	0.18
Surface soil under coarse subor (M1)	28.22	1.91	14.77	0.34	0.13
Surface soil under coarse subor (M2)	10.77	0.52	20.71	0.22	0.10
Unmulched surface soil, near rambutan tree (S)	5.83	0.13	44.88	0.04	0.05
Coarse subor (C)	43.40	1.61	26.96	0.26	0.89

Current uses
Coarse subor has been used as a mulch in many instances. Practitioners of mulching confirmed its effectiveness in eradicating weeds. In patches where a weed like *Imperata cylindrica* survived, their rhizomes could not spread far to spots where the mulch was thick. Fine subor was used as a component of several growth media. Germination of maize, okra and French beans were found to be highest in media which was made up of more than 50% fine subor. Fine subor has also helped to increase crop yields in the field when applied to the soil.

Potential utilisation of decomposition products
Based on the generally high nutrient contents, favourable C:N ratios and encouraging positive effects of mulching, the decomposition products have the potential to be used as components that contribute to several possible development activities/projects, as follows:

1. Rehabilitation of degraded land in areas where surface soil has been severely disturbed and degraded. Coarse subor is very suitable to be used as a mulch to suppress weeds. Enriched fine subor can be used to improve soil quality for planting groundnuts or other leguminous plants. The biomass of these legumes can then be returned to the soil to improve soil conditions further for food-crop production.
2. Creation of chemical-free gardens for vegetable production, where small plots of flat land are available for farming. Coarse subor can be used to suppress weeds, and fine subor (Figure 2) to increase soil quality.
3. Production of a good-quality potting medium. Fine subor mixed with other materials such as cocopeat or other materials commonly used in potting media.
4. Development of mulching materials for weed control in gardens and lawns. Use coarse subor as a mulch in patches where weeds dominate. Coarse subor in large quantities can also help water retention during drier periods.
5. Creation of compost as a soil conditioner to improve fertility and soil physical properties. Fine subor can be mixed with animal biomass such as goat manure to produce a good compost.

Figure 2 A pile of fine subor with earthworms and other soil fauna

CONCLUSION

Apart from the social benefits associated with working with a community, gathering biomass from a large area, such as a residential neighbourhood like Kampung Tunku, provides a number of advantages. One of these is diversity in the vegetative matter due to the large range of species available in the area. The chances of the biomass containing a wide range of nutrients is greater. Involving more homes and gardens reduced the amount of vegetative matter discarded and not recycled. Useful products with desirable properties were obtained from systematically gathering biomass and allowing decomposition to take place. These products can be gainfully applied in soil quality improvement for sustainable crop production.

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ASSESSING AGRICULTURAL LAND-USE IMPACTS ON EROSION AND SEDIMENTATION IN CAMERON HIGHLANDS USING AN INTEGRATED SCENARIO MODELLING APPROACH

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INTRODUCTION

In 2024, Cameron Highlands produced 538,102.87 tonnes of vegetables, accounting for approximately 90% of total vegetable production in Pahang, highlighting its critical role in regional food production (Jabatan Pertanian Malaysia, 2024). However, decades of intensive farming on steep slopes have contributed to severe environmental degradation, with 22.4% of farmland located on slopes exceeding 25° (How *et al.*, 2021). Sedimentation has significantly reduced the storage capacity of the Sultan Abu Bakar Hydroelectric Dam (Ringlet Reservoir), while agricultural runoff continues to degrade water quality in the Telom, Bertam, and Lemoi river systems through elevated total suspended solids (TSS) (Khalik *et al.*, 2013; Gasim *et al.*, 2009; Rasul *et al.*, 2015).

The Malaysian Good Agricultural Practices (MyGAP) certification scheme was introduced to encourage more sustainable farming practices. Beyond reducing pesticide use, MyGAP promotes better land management practices, including land-use risk assessment, restrictions on cultivation in environmentally sensitive areas such as steep slopes (≥25°), and implementation of appropriate soil and water conservation measures to minimise environmental impacts. These practices have the potential to indirectly reduce soil erosion and sediment generation by limiting excessive soil disturbance, improving slope management, and reducing surface runoff. Although implementation cost remains a challenge to farmers (MARDI, 2023), MyGAP provides an important framework for improving farm-level management practices. Within this context, this study evaluates erosion and sedimentation responses under different land-use and policy scenarios, including MyGAP adoption, using an integrated modelling framework. .

MATERIALS AND METHODS

The study was conducted across five sub-basins in Cameron Highlands: Sungai Terla (Sub-basin 1), Sungai Telum Upper (Sub-basin 2), Sungai Telum Middle (Sub-basin 3), Sungai Mensun (Sub-basin 4), and Sungai Bertam (Sub-basin 5). Land-use data were derived from a combination of high-resolution Pleiades satellite imagery (50 cm archive), Digital Elevation

Model (DEM) data acquired from the Shuttle Radar Topography Mission (SRTM, 1-arc second resolution; NASA JPL, 2013), and digital land-use maps provided by the Department of Agriculture, Pahang State. Terrain analysis including slope classification, aspect, hill shade, and contour mapping was performed using ArcGIS version 10.8. Slope classes were categorised following Buku Garis Panduan Pembangunan Pertanian di Tanah Bercerun (Jabatan Pertanian Malaysia, 2020), ranging from flat (0–2°) to very steep (>30°).

Sedimentation and Erosion Assessment

Primary sediment data were collected by measuring river discharge (Q) and sediment yield (SY) using a Pulsar Stingray 2.0 Portable Level Velocity Logger, combined with suspended solids analysis. Secondary sedimentation data for the Sultan Abu Bakar Hydroelectric Dam were sourced from government agencies, published journals, and modelling outputs from the Soil and Water Assessment Tool (SWAT). Soil loss estimation from open and covered farming systems was based on field measurements at selected MyGAP and non-MyGAP farms. Soil erosion risk was also assessed using Interferometric Synthetic Aperture Radar (InSAR) data and validated against previous risk maps from the Department of Agriculture-2015, PLANMalaysia-2018, and REDAC USM-2020 which was extracted from Zainal Abidin *et al.* (2023).

Scenario Development and System Dynamics Modelling

An integrated modelling approach combining System Dynamics (SD) and land-use scenario analysis was developed to simulate interactions between land-use change, agricultural practices, and erosion-sedimentation dynamics. System Dynamics, introduced by Forrester (1961) and operationalised using Vensim software, models complex non-linear feedback interactions among environmental and socioeconomic variables over time. The erosion-sedimentation component was parameterised using field data, secondary records from the Department of Environment (DOE) Water Quality Index monitoring programme (2016–2022), and SWAT model outputs.

Two independent sets of simulations were conducted against a business-as-usual (BAU) baseline from 2026–2050 to evaluate erosion–sedimentation responses under different management and land-use conditions. The first set comprised policy-driven simulations assessing the influence of agricultural management interventions. Policy 1 expanded MyGAP adoption, Policy 2 added pesticide reduction, Policy 3 incorporated slope erosion mitigation, and Policy 4 introduced pesticide-free certification.

The second set comprised land-use zoning simulations evaluating the influence of land-use regulation on sedimentation dynamics. Scenario 1 represented the BAU baseline condition, reflecting unmanaged agricultural expansion, Scenario 2 restricted farming on slopes above 25°, Scenario 3 applied mitigation on existing steep farms, and Scenario 4 expanded MyGAP and pesticide-free cultivation. These simulations were used to evaluate the effects of agricultural management and land-use regulation on sedimentation dynamics in Cameron Highlands.

RESULTS AND DISCUSSION

Baseline land-cover analysis across the five sub-basins showed that 6.7% of the 32,627 ha study area is covered by plastic rain shelters, concentrated mainly in Sub-basins 2 and 4 where MyGAP farm density is highest. Terrain analysis further indicated that 59.7% of Cameron Highlands consists of steep slopes exceeding 20°, where agricultural activities are widely practiced despite recommended slope limitations. These steep agricultural areas are major contributors to erosion and downstream sediment delivery (Luis *et al.*, 2011; Noh *et al.*, 2019; How *et al.*, 2021; Zainal Abidin *et al.*, 2023). Previous studies reported soil loss rates of 24–80 t/ha/year in open vegetable farms, whereas covered rain-shelter systems reduced losses to approximately 1–1.3 t/ha/year, highlighting the importance of surface protection in erosion control (Wan Abdullah *et al.*, 2001; Midmore *et al.*, 1996). In contrast, field measurements from micro runoff plots from another study by MARDI, recorded as average soil loss per rainfall event under wet and dry rainfall conditions, showed that rain shelters and mulching reduced soil loss from 0.15 to 0.01 t/ha. While these values are not directly comparable due to differences in temporal scale and methodology, both findings consistently demonstrate the importance of surface protection in reducing soil erosion. However, long-term land-use change has contributed to increasing sedimentation in the Ringlet Reservoir, with storage capacity declining by 56% by 2008. Water Quality Index (WQI) trends from DOE monitoring stations also indicated that high total suspended solids (TSS), particularly during rainy periods, remain a persistent non-point source pollution issue.

All policy interventions and land-use scenarios reduced dam sedimentation relative to the BAU trajectory in scenario modelling (2026–2050). Policy 3 reduced the most (28%), followed by Policy 4 (18.9%), Policy 2 (11.9%), and Policy 1 (5.5%) (Table 1). Restricting agricultural expansion on slopes over 25° (Scenario 2) reduced sedimentation the most (13.2%), while farm-level mitigation alone (Scenario 3) improved only 1.4% (Table 2).

Table 1 Predicted sedimentation reduction under policy intervention scenarios (2026–2050)

Policy Intervention	**Sedimentation Reduction (%)**	**Interpretation**
Policy 1	5.5	Small reduction through MyGAP adoption
Policy 2	11.9	Improved reduction with pesticide control
Policy 3	28.0	Highest reduction with integrated erosion control
Policy 4	18.9	Greater reduction due to broader environmental controls

Table 2. Predicted sedimentation reduction under land-use scenarios (2026–2050)

Land-use Scenario	**Sedimentation Reduction (%)**	**Interpretation**
Scenario 1	0.0	Baseline condition (BAU)
Scenario 2	13.2	Highest reduction by limiting farming on steep slopes
Scenario 4	4.3	Moderate reduction through improved farming practices
Scenario 3	1.4	Limited reduction without land-use restriction

The results showed that erosion in Cameron Highlands is strongly influenced by agricultural management practices. Rain shelters and mulching reduced soil loss from 0.15 to 0.01 t/ha, highlighting the importance of surface protection. However, long-term use of plastic rain shelters may alter runoff dynamics by intercepting and concentrating rainfall into localised discharge points, increasing surface runoff and flow concentration along drainage paths and farm edges. This process may reduce infiltration and increase the risk of localised erosion and sediment transport, particularly on steep terrain. Therefore, while rain shelters provide short-term erosion protection, complementary measures such as proper drainage systems, contour-based runoff diversion, mulching, vegetative ground cover, and slope stabilisation practices are necessary to minimise concentrated runoff and improve long-term soil and water conservation. These findings suggest that farm-scale mitigation alone is insufficient without broader land-use regulation and more sustainable erosion control strategies.

CONCLUSION

This study demonstrates that agricultural land-use practices strongly influence erosion and sedimentation in Cameron Highlands. Integrated interventions combining MyGAP adoption, slope regulation, and erosion mitigation reduced reservoir sedimentation by up to 28%, compared to only 5.5% under certification alone. Restricting agriculture on slopes above 25° achieved a 13.2% reduction, highlighting the importance of land-use control. These findings indicate that voluntary certification alone is insufficient without effective implementation of slope regulation and soil conservation measures, and suggest that maximising the effectiveness of existing MyGAP requirements through stronger compliance monitoring and consistent application of slope management and soil conservation practices on steep agricultural land (>25°) could substantially enhance sediment reduction outcomes in Cameron Highlands. Future studies should incorporate climate change projections and explore environmentally sustainable alternatives to plastic rain shelters.

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QUANTIFYING SAMPLING BIAS IN SOIL CO_2 FLUX MEASUREMENT IN OIL PALM PEAT PLANTATIONS

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INTRODUCTION

Tropical peatlands are important global carbon reservoirs but have become major sources of greenhouse gas emissions following conversion to agricultural plantations, particularly oil palm cultivation. Drainage and land management practices accelerate peat decomposition, resulting in increased carbon dioxide (CO_2) emissions from soil respiration processes. Reliable quantification of soil CO_2 fluxes is therefore essential for improving carbon accounting and developing sustainable management strategies.

Manual chamber techniques are widely used to estimate soil CO_2 emissions because they are relatively simple and cost-effective. However, these measurements are often conducted at a single time point during the day, assuming that the observed flux represents the daily average. In reality, soil CO_2 fluxes fluctuate considerably throughout the day due to changes in environmental conditions such as soil temperature and moisture.

MATERIALS AND METHODS

The study was conducted in a mature oil palm plantation established on tropical peat soil in Malaysia. Four plantation microforms were evaluated, namely harvest path (HP), palm base (PB), inter-row (IR), and frond pile (FP). Automated chamber systems were installed to continuously monitor soil CO_2 fluxes and environmental variables including soil temperature and soil moisture.

Manual chamber measurements representing conventional field sampling approaches were also conducted and compared against automated chamber data. Sampling bias was calculated using:

$$Bh = 100 \times (Fh - Fd) / Fd$$

where Bh represents sampling bias (%), Fh is the flux measured at a specific hour, and Fd is the daily mean flux.

Corrected fluxes were estimated using:

$$Fe = (100Fh) / (100 + Bh)$$

where Fe represents corrected flux estimates.

RESULTS AND DISCUSSION

Distinct diurnal patterns of soil CO_2 fluxes were observed across all plantation microforms. Flux variations were closely associated with fluctuations in soil temperature and soil moisture throughout the day. Bias analysis demonstrated that single-time-point measurements may substantially misrepresent daily mean fluxes.

Depending on the microform and sampling time, biases ranged between -18% and +24%. Measurements conducted during peak flux periods tended to overestimate daily emissions, whereas measurements during low flux periods underestimated actual fluxes. The harvest path microform showed particularly high variability due to soil compaction and changing moisture conditions associated with field operations.

Using the correction equation developed in this study, annual plantation-scale emissions over a six-year period were recalculated. Corrected estimates ranged from 36 to 53 Mg CO_2 ha^{-1} yr^{-1}, indicating that accounting for diurnal variability can substantially improve the reliability of emission inventories.

CONCLUSION

This study demonstrated that single-time-point soil CO_2 flux measurements can introduce substantial sampling bias in tropical peat oil palm plantations. Diurnal fluctuations differed considerably among plantation microforms and were strongly influenced by environmental variables such as soil temperature and moisture. Sampling bias ranged from –18% to +24%, indicating that conventional manual chamber measurements may either overestimate or underestimate long-term emissions depending on sampling time.

The correction equation developed from automated chamber observations successfully improved annual emission estimates, producing corrected plantation-scale emissions ranging from 36 to 53 Mg CO_2 ha^{-1} yr^{-1}. Incorporating diurnal correction factors into greenhouse gas monitoring frameworks is therefore essential for achieving more accurate carbon accounting in tropical peatland ecosystems.

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SURFACE-OXIDIZED BIOCHAR ENHANCES SOIL NUTRIENT RETENTION AND FERTILIZER USE EFFICIENCY IN TROPICAL ULTISOL CULTIVATED WITH *Elaeis guineensis* SEEDLINGS

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INTRODUCTION

Highly weathered tropical Ultisols are characterized by strong acidity, low nutrient retention, and high susceptibility to leaching, which collectively limit fertilizer-use efficiency and sustainable crop production (Fatai *et al.*, 2017). These constraints are particularly critical for oil palm (*Elaeis guineensis*), where productivity often falls below its genetic potential due to poor soil fertility (Cristancho *et al.*, 2011). Conventional reliance on high fertilizer inputs is not only economically costly but also environmentally unsustainable (Wang *et al.*, 2022). Biochar has been widely explored as a soil amendment due to its porous structure and ability to improve soil physicochemical properties. However, pristine biochar often exhibits limited surface functionality, restricting its nutrient retention capacity (Jiao *et al.*, 2025). Recent studies have demonstrated that chemical modification, particularly oxidation, can enhance biochar performance by introducing oxygen-containing functional groups that improve cation exchange capacity and adsorption behavior (Günal *et al.*, 2018). In this context, the present study evaluates hydrogen peroxide (H_2O_2)-modified palm kernel shell biochar (OxyAChar) as a functional soil amendment. The study aims to (i) enhance biochar surface properties through controlled oxidation, and (ii) assess its effectiveness in improving soil nutrient retention, plant growth, nutrient uptake efficiency, plant physiology and fertilizer-use efficiency in Ultisol under reduced fertilizer input.

MATERIALS AND METHODS

Biochar Preparation and Modification

Palm kernel shell (PKS) biochar was produced via slow pyrolysis at 400 °C for 2 h under oxygen-limited conditions (Hwong *et al.*, 2022). Surface oxidation was performed using hydrogen peroxide (H_2O_2) solutions at concentrations of 1%, 3%, 10%, 20%, and 30% (v/v) at a solid-to-liquid ratio of 1:20 (w/v) following established methods with minor modifications (Chemerys *et al.*, 2020; Huff & Lee, 2016) with minor modifications. The mixtures were agitated at 110 rpm for 2 h. The samples were then filtered, washed with distilled water until neutral pH was achieved, oven-dried at 105 °C, and stored for subsequent analysis.

Characterization of OxyAChar

The physicochemical properties of pristine and oxidized biochar (OxyAChar) were characterized using field emission scanning electron microscopy (FESEM) at 5000× magnification to observe surface morphology. Surface area and pore characteristics, including micropore surface area, mesopore surface area, and total pore volume, were determined using Brunauer–Emmett–Teller (BET) analysis.

Soil Description

The soil used in this study was classified as Ultisol (Serdang Series), specifically Typic Kandiudults according to USDA Soil Taxanomy (USDA, 2014). Soil samples were collected from the Universiti Malaya AgroScience field, Gemas, Negeri Sembilan, Malaysia. The soil was air-dried, gently crushed, and sieved through a 2 mm mesh prior to use. Initial soil analysis indicated a strongly acidic pH (3.83), low total nitrogen (0.10%), moderate available phosphorus (25.99 mg kg^{-1}), and exchangeable potassium (358.33 mg kg^{-1}), consistent with the characteristics of highly weathered tropical Ultisols (Ajeng *et al.*, 2020).

Glasshouse Experiment

A six-month glasshouse experiment (November 2024–May 2025) was conducted at the Rimba Ilmu Botanical Garden, Universiti Malaya, Kuala Lumpur, Malaysia. The study followed a randomized complete block design (RCBD) with six treatments and eight replicates to minimize potential environmental variation within the glasshouse, including differences in light intensity and temperature across bench positions. The treatments consisted of: (i) control (Ultisol only), (ii) F100 (100% recommended fertilizer rate), (iii) Biochar (BC; unmodified palm kernel shell biochar), (iv) OxyAChar (OAC; oxidized palm kernel shell biochar), (v) BC + F70 (biochar with 70% recommended fertilizer rate), and (vi) OAC + F70 (OxyAChar with 70% recommended fertilizer rate). Based on the physicochemical characterization results, biochar oxidized with 3% H_2O_2 exhibited the most favorable properties and was selected for the glasshouse experiment as OxyAChar (OAC). The 30% reduction in fertilizer input was selected based on previous findings demonstrating that biochar application can reduce synthetic fertilizer requirements by up to 34.85% while maintaining crop performance (Yusuf *et al.*, 2025). Fertilization was conducted using NPK compound fertilizer (14:13:9:2.5) supplemented with kieserite (Ks), following standard oil palm nursery practices. Three-month-old oil palm (*Elaeis guineensis*) seedlings were used. Soil properties (organic carbon, total N, available P, exchangeable K), plant growth (chlorophyll content, leaf area, plant height, stem girth, biomass), and nutrient uptake (N, P, K) were measured. Physiological assessments included photosynthetic pigments, oxidative stress markers (H_2O_2, MDA), antioxidant systems (enzymatic and non-enzymatic), and antioxidant capacity (DPPH, FRAP).

Statistical Analysis

All data were analyzed using IBM SPSS Statistics (version 21.0; IBM Corp., Armonk, NY, USA). One-way analysis of variance (ANOVA) was performed to evaluate treatment effects. When significant differences were observed ($p < 0.05$), Duncan's Multiple Range Test (DMRT) was used for mean separation. Results are presented as mean ± standard error (SE).

RESULTS AND DISCUSSION

OxyAChar Optimization

H_2O_2 oxidation significantly modified the surface morphology and pore structure of PKS biochar. FESEM observations (**Figure 1**) showed a more developed and heterogeneous porous structure in oxidized biochar compared to pristine biochar, indicating the formation of additional pore channels following oxidation. BET analysis confirmed enhanced pore development, with increases in micropore and mesopore surface areas and total pore volume. The 3% H_2O_2 treatment achieved optimal performance, increasing micropore surface area by 35.4%, mesopore surface area by 28.8%, and total pore volume by 22.1% relative to pristine biochar. In contrast, higher concentrations (≥10%) caused structural deterioration, likely due to pore collapse from excessive oxidation. Therefore, biochar oxidized with 3% H_2O_2 was selected for subsequent application in the glasshouse study as OxyAChar (OAC).

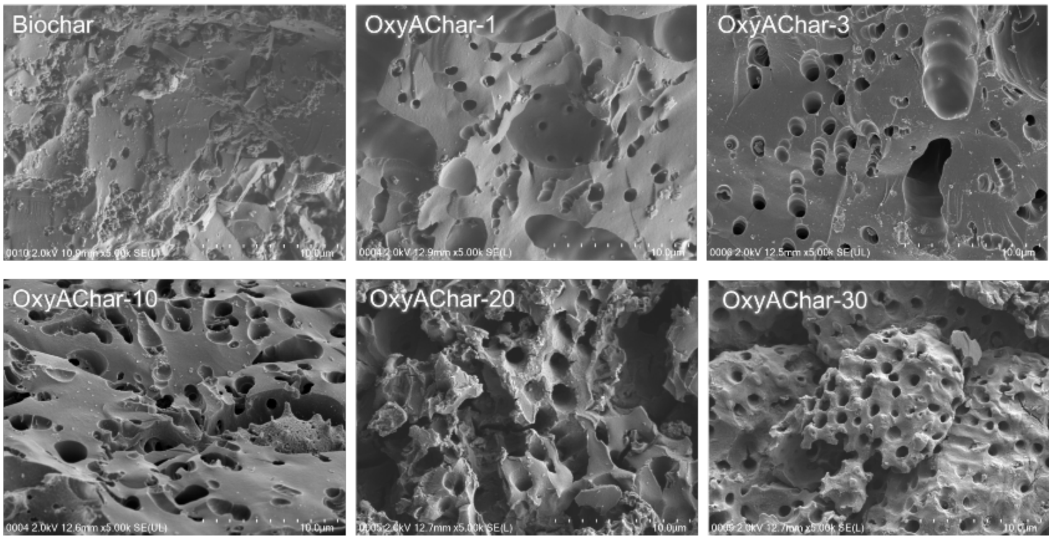

Figure 1 FESEM micrographs (5000× magnification) of pristine and H_2O_2-modified palm kernel shell (PKS) biochar (OxyAChar), illustrating changes in surface morphology and pore structure following oxidation

Growth Performance and Nutrient Uptake

Application of 100% fertilizer (F100) significantly improved plant growth compared to the control, confirming nutrient limitation in Ultisol. Biochar-only treatments (BC and OAC) showed moderate improvements, indicating partial enhancement of soil conditions but insufficient nutrient supply for optimal growth. In contrast, combining biochar with reduced fertilizer (F70) markedly enhanced plant performance. Both BC + F70 and OAC + F70 achieved growth comparable to or exceeding F100, demonstrating a clear synergistic effect. Among all treatments, OAC + F70 produced the highest biomass and overall growth, indicating that surface oxidation further improves biochar functionality (**Figure 2**).

Figure 2 Visual comparison of oil palm seedling height under six treatments after six months in the glasshouse. Oil palm (*Elaeis guineensis*) seedlings are arranged from left to right as follows: OAC + F70 (OxyAChar + 70% fertilizer), F100 (100% chemical fertilizer), BC + F70 (biochar + 70% fertilizer), OAC (OxyAChar), BC (biochar), and C (control)

Nutrient uptake patterns were consistent with growth responses. Nitrogen uptake under BC + F70 and OAC + F70 was comparable to F100, indicating efficient nutrient utilization under reduced fertilizer input (**Figure 3**). Phosphorus uptake was highest in biochar-amended treatments, particularly OAC + F70, suggesting improved phosphorus availability in acidic Ultisol. Potassium uptake followed a similar trend, with biochar–fertilizer combinations achieving values comparable to full fertilization. Overall, the combined application of biochar and reduced fertilizer improved nutrient uptake efficiency, with OxyAChar showing superior performance, likely due to enhanced nutrient retention and reduced leaching.

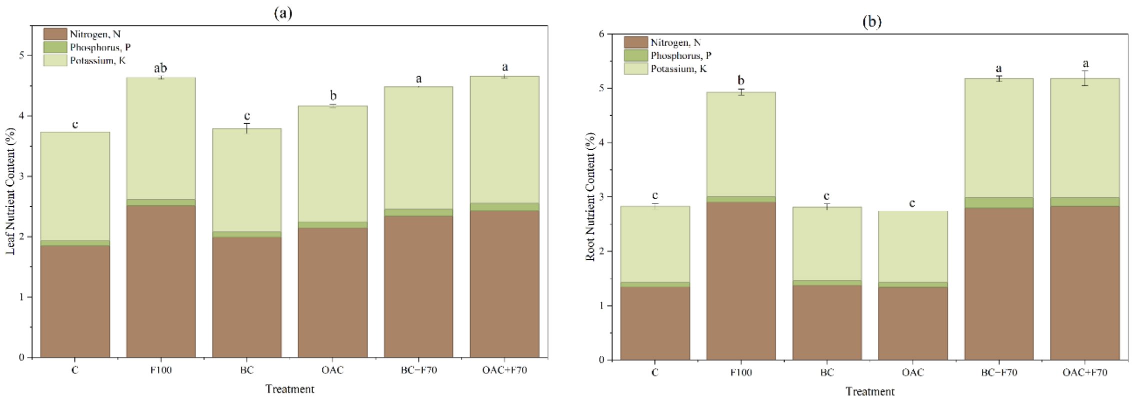

Figure 3 Effects of treatments on nutrient uptake (N, P, K) in oil palm seedlings

Soil Chemical Properties

Application of OxyAChar significantly improved soil chemical properties, including organic carbon, total nitrogen, available phosphorus, and exchangeable potassium, indicating enhanced soil fertility in Ultisol (**Figure 4**). Soil organic carbon increased markedly under OAC and OAC + F70, showing improvements of approximately 36–41% compared to the control. Total nitrogen was also higher in combined treatments (BC + F70 and OAC + F70), reflecting improved nutrient retention. A notable effect was observed for phosphorus, where OAC + F70 recorded the highest available P, nearly threefold higher than F100, indicating reduced phosphorus fixation in acidic soil. Similar trends were observed for exchangeable potassium, with biochar–fertilizer treatments maintaining higher K availability.

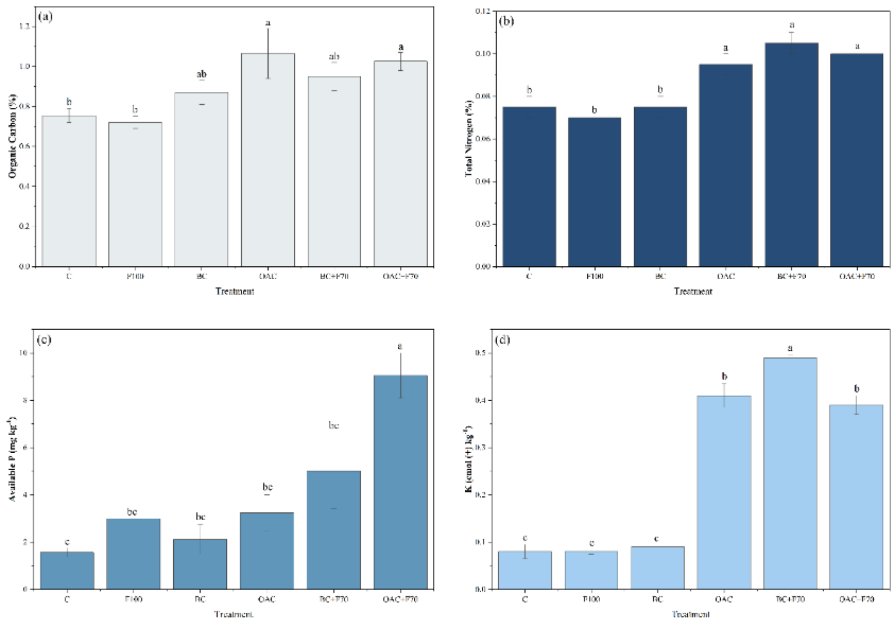

Figure 4 Effects of soil amendment treatments on soil nutrient properties after six months of glasshouse cultivation: (a) organic carbon, (b) total nitrogen, (c) available phosphorus, and (d) exchangeable potassium

Physiological Performance

OxyAChar significantly enhanced physiological performance and alleviated oxidative stress in oil palm seedlings. The OAC + F70 treatment recorded the highest total chlorophyll content (1.28 mg g^{-1} FW), representing a 103% increase relative to the control, indicating improved photosynthetic capacity under reduced fertilizer input. Oxidative stress markers showed a clear decline across treatments. The control exhibited the highest levels of H_2O_2 and MDA, while OAC + F70 reduced H_2O_2 by 67.1% and MDA by 63.2%, indicating effective mitigation of oxidative damage. Non-enzymatic antioxidants were markedly enhanced under OAC + F70, with total flavonoid content increasing by 283.6% and total phenolic content by 424.1% compared to the control. This enhancement was supported by antioxidant assays, where OAC + F70 showed the lowest IC_{50} values (0.55 mg mL^{-1} in leaves) and the highest FRAP activity (4.95 µmol Fe^{2+} g^{-1}), indicating strong radical scavenging capacity. In contrast, enzymatic antioxidant activities (APX, CAT, DHAR, and SOD) were highest in the control and decreased under OAC + F70 (e.g., SOD reduced by 73.9%), reflecting lower oxidative stress and reduced demand for enzymatic defense.

CONCLUSION

This study demonstrated that oxidation with 3% H_2O_2 effectively optimized palm kernel shell biochar, producing OxyAChar with enhanced physicochemical properties. Based on these results, the 3% H_2O_2-oxidized biochar was selected for application in the glasshouse experiment. Its application significantly improved soil chemical properties and nutrient retention in highly weathered Ultisols, leading to enhanced fertilizer-use efficiency. Consequently, oil palm (*Elaeis guineensis*) seedlings exhibited improved growth performance and physiological status, as reflected by increased chlorophyll content, enhanced non-enzymatic antioxidant activity, and reduced oxidative stress. Overall, the integration of OxyAChar with reduced fertilizer input (OAC + F70) represents a sustainable strategy for improving soil fertility and maintaining plant productivity while reducing reliance on chemical fertilizers.

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MAXIMIZING QUALITY OF SOIL-GROWN GOLDEN MELON: THE ROLE OF VARYING FERTILIZER RATES AND CALCIUM FOLIAR APPLICATION

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INTRODUCTION

The Golden melon (*Cucumis melo* L.), a premium cultivar of Inodorus melon group, has garnered significant attention in the global agricultural sector due to its distinctively vibrant yellow rind, crisp flesh texture, and high soluble solid content. As consumer demand for nutrient-dense fruits continues to surge, its rich nutritional profile comprising essential vitamins and antioxidants solidifies its position as a high-value cash crop (Gomez *et al.*, 2020). Consequently, optimizing both the quantitative yield and the qualitative traits of this fruit has emerged as a primary focus for modern agricultural research.

Conventionally, the commercial production of Golden melon in tropical regions has been heavily reliant on rain shelter structures that integrated with soilless fertigation systems. While this method offers meticulous control over nutrient delivery, it is fraught with substantial limitations. Foremost among these is the exorbitant initial capital expenditure required for the construction of rain shelter structure, which significantly restricts the capacity of small-scale growers (Nor *et al.*, 2022). Furthermore, agronomic observations indicate a critical physiological issue associated with soilless fertigation. Golden melons are highly susceptible to fruit cracking. This defect is often triggered by rapid fluctuations in moisture levels and nutrient imbalances that occur in fast-draining soilless media, leading to substantial post-harvest economic losses (Maryomana and Beevy, 2023). In light of these constraints, transitioning towards conventional soil-based cultivation presents a promising and economically sustainable alternative. Soil-based cultivation refers to the direct planting of Golden melon in mineral soil under open-field conditions, where nutrients are supplied through conventional soil fertilization practices and plants are maintained using standard field management techniques, including drip irrigation. As compared with soilless fertigation systems, this cultivation approach requires lower initial investment and is more accessible to smallholder growers. Cultivating Golden melons directly on soil possesses the potential to increase overall yield by allowing for extensive scalability. Unlike rain shelter systems, soil-based farming allows growers to maximize vast tracts of arable land without being confined by high structural costs. Moreover, the natural buffering capacity of soil provides a more stable microenvironment, which may mitigate the physiological stress factors contributing to fruit cracking (Madumane *et al.*, 2024). To date, there is a critical void in scientific literature regarding a standardized, comprehensive planting package for soil-based Golden melon.

To bridge this knowledge gap, a systematic investigation is imperative. The aspect of fertilization constitutes the foundational basis of research required to fulfill the development of a holistic planting package. Therefore, this study aimed to determine the effects of varying fertilizer rates and foliar calcium application on the growth, yield and fruit quality performances of soil-grown Golden melon.

MATERIALS AND METHODS

The experiment was conducted at rainshelter in MARDI Sintok, Kedah. During the experiment, average maximum temperature was recorded once a day at 2.00 pm as recorded 35.1 (±5) ºC with average relative humidity (RH) at 62.4 (±10) % under natural photoperiod conditions (12 hours light/ 12 hours dark). The planting material used in this study was Golden melon (cv. Golden Sweet Sea) seeds purchased from Crop Power Seed Company. The experiment comprised two main factors: fertilizer rates and foliar calcium application. The fertilizer treatments consisted of five rates: 33.3% less, 0% (control), 33.3% more, 66.7% more, and 100% more relative to the standard rate. The range of fertilizer rates was determined based on a previous study on the effects of fertilizer rates on watermelon conducted by Hassan *et al.* (2022). The specific nutrient amounts for each treatment were calculated based on the control treatment (118.33 kg/ha N, 118.33 kg/ha P_2O_5, and 145.23 kg/ha K_2O) using two types of NPK fertilizer as 15:15:15 and 12:12:17:2. Furthermore, the foliar calcium treatments consisted of two levels: 0% (without application) and 0.3% $CaCl_2$ foliar spray. The foliar $CaCl_2$ (0.3%) treatment was selected based on its establishment usage in previous studies conducted on litchi (Guo *et al.* 2023). The factorial treatment combinations were arranged in a Randomized Complete Block Design (RCBD) with six replications and four plants per replication, totalling 240 plants.

Plant maintenances and treatment applications

Germinated Golden melon seedlings, initially grown in a peat moss medium, were transplanted 14 days after sowing into 16 × 16 inch (4 L) in white polyethylene bags filled with soil. This study used Kuah series soil, which is the dominant soil series composition at MARDI Sintok. The soil chemical properties were recorded, including initial soil pH and electrical conductivity (EC) prior to the fertilizer rate treatments, where the pH was 5.78 and the EC was 0.18 ms/cm. The fertilizer treatments were applied at 3, 15, 30, and 45 days after transplanting (DAT), with the specific fertilizer rates treatments presented in Table 1. The fertilizer was applied manually by placing it directly onto the soil near the base of the plant. Meanwhile, the foliar calcium was applied using a knapsack sprayer at a concentration of 0.3% at 30, 40, and 50 DAT. Approximately 200 mL of $CaCl_2$ was mist-sprayed onto the foliage of each plant. The plants were irrigated to maintain soil moisture at field capacity according to three growth stages. Water was supplied at a rate of 1–2 L plant/ day during the early vegetative stage, increased to 2–3 L plant/ day from the vegetative to reproductive stage, and further increased to 3–4 L plant/ day during the reproductive to fruiting stage using a drip irrigation system. This irrigation approach-maintained soil moisture at field capacity, thereby minimizing the potential for nutrient leaching. Pest and disease management was carried out as needed, depending on the growing stage of the plants. At 60 DAT, all fruits were carefully harvested for data collection.

Table 1 Amount of fertilizer application for each fertilizer rate per plant

Fertilizer rates	**NPK Green (15:15:15)**	**NPK Blue (12:12:17)**		
	3 DAT	**15 DAT**	**30 DAT**	**45 DAT**
T1 – 33.3% less	7g	10g	10g	10g
T2 – 0% (Control)	10g	15g	15g	15g
T3 – 33.3% more	13g	20g	20g	20g
T4 – 66.7% more	17g	25g	25g	25g
T5 – 100% more	20g	30g	30g	30g

Data collections and analysis

At 40 DAT, plants were randomly selected from each treatment plot for leaf chlorophyll content measurement. It was determined using a leaf chlorophyll meter (SPAD-502 Plus, Konica Minolta). The fruit weight was measured and recorded at harvest, which was at 60 DAT, using digital analytical balance. Fruit quality was quantified post-harvest based on four parameters: fruit length, fruit width, flesh thickness, and total soluble solids (TSS). Fruit length, width, and thickness were measured using a digital caliper (Mitutoyo Series No. 500), while TSS was determined using a digital refractometer (Atago Co., Ltd.), with readings recorded in degrees Brix (°Brix). All collected data were analyzed using Statistical Analysis Software (SAS) version 9.4 (SAS Institute Inc., Cary, NC). The General Linear Model (GLM) procedure was used to perform the Analysis of Variance (ANOVA), and mean comparisons were calculated using the Least Significant Difference (LSD) test at P≤0.05.

RESULTS AND DISCUSSION

The results indicated that varying fertilizer rates had a highly significant effect on leaf SPAD (P≤0.01) and no significant effect was observed in fruit weight parameter. Specifically, the application of fertilizer at a rate of 66.7% higher than the standard resulted in the maximum leaf SPAD, which was 7.56% greater compared to the control (0%). The elevated leaf SPAD values associated with higher fertilizer rates suggest an improvement in leaf chlorophyll concentration and nitrogen uptake, which are vital for maintaining high photosynthetic efficiency.

Table 2 Effect of fertilizer rates and foliar calcium application on growth, yield and fruit quality parameters of Golden melon (Mean ± SE; n=6)

Factor	Levels	Leaf SPAD	Fruit weight (kg)	Fruit length (cm)	Fruit width (cm)	Flesh thickness (cm)	TSS
Fertilizer rates	33.3% less	43.4cd±1.5	1.1±0.8	14.0±2.6	12.5±1.3	3.2±3.0	15.6a±2.6
	0%	42.8d±2.2	0.9±4.2	13.3±1.9	12.0±2.9	2.7±4.2	15.6a±0.5
	33.3% more	44.6bc±2.6	1.2±1.1	14.5±2.6	13.5±4.1	2.7±2.7	14.6b±1.1
	66.7% more	46.3a±2.8	1.0±2.0	14.6±3.9	13.2±3.5	2.7±2.3	14.6b±2.2
	100% more	45.9ab±2.2	1.1±4.4	12.0±1.5	12.5±1.6	2.7±2.2	14.7b±0.1
Foliar calcium	None	45.4±1.5	1.1±3.9	13.1b±1.2	12.4b±0.7	2.7b±1.0	15.5±2.6
	Spray	45.7±1.4	1.0±2.4	13.5a±2.0	12.7a±1.7	2.9a±1.5	15.7±1.6
		F-Test (Significant level)					
Fertilizer rates		**	ns	ns	ns	ns	**
Foliar calcium		Ns	ns	*	*	*	ns
Fert. rates X Calcium		Ns	ns	ns	ns	ns	**

**Significant at P≤0.01, *Significant at P≤0.05
Means with the different letters in each column indicate significant differences at P≤0.05 level according to LSD.

This observation aligns with the findings of Muhamad Hassan *et al.* (2024), who reported that increased NPK fertilization rates (125–150% of standard) positively influence the SPAD index by optimizing nutrient supply during vegetative stage. Regarding the foliar calcium treatments, fruit length, fruit width, and flesh thickness were significantly affected (P≤0.05). The results demonstrated that the application of foliar calcium spray significantly increased fruit length, fruit width, and flesh thickness by 3.05%, 2.42%, and 7.41%, respectively compared to control. This improvement in fruit length, width, and flesh thickness aligns with Khomphet *et al.* (2023), who showed that foliar calcium-boron sprays enhance cell division and elongation in melon fruits by strengthening cell walls via calcium pectate formation and overcoming phloem immobility through direct application.

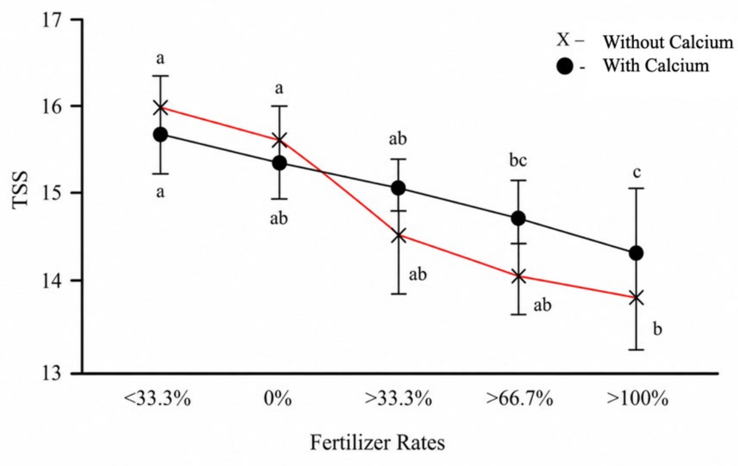

Figure 1 Effect of fertilizer rates on TSS of Golden melon with and without foliar calcium application (Mean ± SE; n=6)

Moreover, a significant interaction was observed for TSS ($P \leq 0.01$). Specifically, for plants without calcium application, a significant reduction in TSS was only evident when the fertilizer rate reached the highest level (>100%) compared to the lower rates (<33.3% and 0%). Similarly, under calcium application, TSS significantly decreased at higher fertilizer rates (>66.7% and >100%) compared to the lowest rate (<33.3%), while the intermediate rates showed a gradual, non-significant decline. This suggests that excessive fertilizer may have shifted assimilate allocation toward vegetative growth rather than sugar accumulation in the fruit, leading to lower soluble solids, which is consistent with previous melon fertilization studies (Moreira *et al.*, 2022).

CONCLUSION

In conclusion, higher fertilizer rates improved growth, particularly leaf SPAD, but had no significant effect on fruit weight. Foliar calcium application enhanced fruit physical quality, including fruit length, width, and flesh thickness. However, increasing fertilizer rates reduced total soluble solids (TSS), indicating a negative effect on fruit sweetness regardless of calcium application. A 33.3% reduction in fertilizer rate showed relatively higher TSS under the conditions of this study, while foliar application of 0.3% $CaCl_2$ improved fruit physical characteristics. Overall, the results highlight the need to balance fertilizer input to optimize growth, yield and fruit quality in Golden melon production.

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EFFECTS OF LIQUID ORGANIC FERTILIZER DERIVED FROM PINEAPPLE RESIDUES AT DIFFERENT FERMENTATION PERIODS ON VEGETATIVE GROWTH OF MD2 PINEAPPLE

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INTRODUCTION

MD2 pineapple is currently the most popular pineapple variety in Malaysia because of its high sweetness, low acidity, attractive appearance, and longer shelf life. Its strong consumer demand and high export value have driven the rapid expansion of MD2 cultivation, making it a key contributor to the Malaysian pineapple industry. Pineapple's cultivation generates substantial quantities of agricultural residues, particularly leaves and rejected fruits, which are often underutilized. Improper disposal of these residues contributes to environmental pollution, greenhouse gas emissions, and loss of valuable nutrients, while excessive reliance on inorganic fertilizers may gradually degrade soil structure, reduce microbial diversity, and lower long-term soil fertility. The transformation of pineapple residues into liquid organic fertilizer (LOF) offers a sustainable solution by recycling nutrients back into the production system, thereby supporting circular agriculture and reducing dependency on synthetic inputs (Diacono & Montemurro, 2010; Lazcano & Domínguez, 2011).

Fermentation-based LOF production enhances nutrient availability through microbial decomposition, mineralization, enzymatic activity, and organic acid formation. During fermentation, beneficial microorganisms convert complex organic compounds into simpler plant-available forms such as nitrate, ammonium, soluble phosphorus, and exchangeable potassium. The production of phyto-hormones and bioactive compounds during fermentation may further stimulate root growth, nutrient uptake, and overall plant vigor (Calvo *et al.*, 2014; Sharma *et al.*, 2017). However, nutrient release efficiency is highly influenced by substrate composition, carbon-to-nitrogen ratio, moisture content, and fermentation duration, all of which affect microbial activity and nutrient solubilization processes (Bernal *et al.*, 2009).

Previous studies have demonstrated that organic fertilizers derived from agricultural wastes can improve soil physicochemical properties, enhance microbial biomass, and promote sustainable crop production systems (Agegnehu *et al.*, 2017). For pineapple cultivation, balanced nutrient supply during the vegetative stage is particularly important because leaf development directly influences photosynthetic capacity and assimilate accumulation required for fruit formation (Bartholomew *et al.*, 2003). Optimizing LOF formulation based on appropriate ratios of pineapple residues and fermentation periods may therefore enhance nutrient availability while maintaining environmental sustainability.

Therefore, this study aimed to evaluate the effects of residue ratio and fermentation period on the nutrient composition of pineapple-based LOF and to assess its agronomic relevance for pineapple growth performance. The findings are expected to provide scientific evidence supporting the utilization of pineapple waste as value-added organic fertilizer, contributing to improved nutrient recycling efficiency, reduced environmental impact, and sustainable intensification of pineapple production systems.

MATERIALS AND METHODS

The experiment was conducted at the AgroFarm research area, Universiti Utara Malaysia (UUM), Kedah, Malaysia, under tropical open-field conditions using polybag cultivation. Healthy and uniform MD2 pineapple (*Ananas comosus* L.) suckers were selected, cleaned, and trimmed before planting. Polybags (40 × 40 cm) were filled with 15–20 kg of growing medium consisting of topsoil and organic compost mixed at a 3:2 ratio. The experiment was arranged in a Completely Randomized Design (CRD) comprising seven treatments with ten replications. Liquid organic fertilizer (LOF) was produced from pineapple leaf and fruit residues mixed at three ratios (40:60, 60:40, and 20:80; leaf:fruit) and fermented anaerobically for either two weeks or three months, generating six LOF treatments (T1–T6). Treatment T7 served as the control without LOF application. Prior to application, the fermented LOF was filtered and diluted at 100 mL in 10 L of water. The diluted solution was first applied as a soil drench (100 mL per polybag) during the early vegetative stage, followed by monthly foliar sprays until leaf surfaces were thoroughly wetted. All plants received similar irrigation, weed control, and routine crop management practices throughout the study. Agronomic performance was evaluated seven months after planting by measuring plant height and the number of fully expanded healthy leaves per plant. Plant height was measured from the soil surface to the tip of the longest fully expanded leaf, while damaged or senescent leaves were excluded from leaf counts. Nutrient composition of the LOF, including nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), magnesium (MgO), and boron (B_2O_3), was determined by Makmal Kimia Pertanian, Felcra Plantation Services Sdn. Bhd. using standard laboratory analytical procedures. The collected data were analyzed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) based on the General Linear Model (GLM) procedure was performed to determine the effects of different LOF treatments on pineapple vegetative growth, and treatment means were compared at a significance level of $P \leq 0.05$.

RESULTS AND DISCUSSION

Nutrient Composition of Liquid Organic Fertilizer

The nutrient composition of liquid organic fertilizer (LOF) produced from pineapple (*Ananas comosus*) leaf and fruit residues varied depending on fermentation duration and substrate ratio (Table 1). Overall, nitrogen (N) and phosphorus (P_2O_5) concentrations increased markedly with longer fermentation periods, while potassium (K_2O), magnesium (MgO), and boron (B_2O_3) showed variable trends depending on the composition of residues.

Nitrogen concentrations increased substantially with longer fermentation duration. Treatments fermented for three months (T4–T6) recorded significantly higher nitrogen levels compared with those fermented for only two weeks (T1–T3). The highest nitrogen concentration was recorded in T6 (5966.57 ppm)**,** which consisted of a higher proportion of fruit residue (20:80 leaf-to-fruit ratio). Fruit residues typically contain higher levels of soluble organic compounds such as sugars and organic acids, which promote microbial activity during fermentation and accelerate nutrient mineralization. Prolonged microbial decomposition therefore contributes to the increased release of nitrogen into the liquid phase (Sarah *et al.*, 2023).

Table 1 Nutrients content of LOF across treatments.

Treatments	Fermentation Period	Ratio (Leaf:Fruit)	N	P_2O_5	K_2O	MgO	B_2O_3
			---------------------- ppm ----------------------				
T1	2 weeks	40:60	2064.37 e	178.03 d	0.29 c	370 d	17.66 d
T2	2 weeks	60:40	2618.30 d	209.33 c	0.25 d	422 c	26.27 b
T3	2 weeks	20:80	1760.53 f	422.30 b	0.35 b	549 a	28.12 a
T4	3 months	40:60	3982.37 c	223.70 c	0.27 c	489 b	24.18 c
T5	3 months	60:40	4608.20 b	165.40 d	0.28 c	561 a	24.79 c
T6	3 months	20:80	5966.57 a	528.13 a	0.42 a	330 e	16.40 d
C.V			3.21	3.92	3.44	3.09	3.58

Means followed by different letters within a column are significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test (DMRT); C.V = Coefficient of Variation; (n=3).

Phosphorus (P_2O_5) showed a similar trend, with the highest value recorded in T6 (528.13 ppm). Microbial fermentation can enhance phosphorus availability by producing organic acids that solubilize phosphate compounds present in plant residues. This process increases the concentration of soluble phosphorus in the final liquid organic fertilizer (Zhang *et al.*, 2025). Potassium (K_2O) values ranged between 0.25 and 0.42 ppm, with the highest level recorded in T6. Since potassium exists mainly in soluble ionic forms in plant tissues, it can be readily released during the decomposition process. Therefore, variations in potassium concentration are largely influenced by the chemical composition of the residues and fermentation duration. Magnesium (MgO) concentrations ranged from 330 to 561 ppm, with the highest value observed in T5 (561 ppm). Magnesium is an essential component of chlorophyll molecules and plays a critical role in photosynthetic processes. The relatively high MgO levels observed in treatments with higher leaf proportions may be attributed to the greater magnesium content typically present in plant leaves. Boron (B_2O_3) concentrations ranged between 16.40 and 28.12 ppm, with the highest value recorded in T3 (28.12 ppm). Unlike nitrogen and phosphorus, boron did not exhibit a consistent increase with fermentation duration. This may be due to the relatively low concentration of boron in plant tissues and its possible utilization by microorganisms during fermentation.

Effect of Liquid Organic Fertilizer on Pineapple Growth

The effects of pineapple-derived liquid organic fertilizer (LOF) on vegetative growth at 7 months after planting are presented in Table 2. Statistical analysis using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$ indicated significant differences among treatments for both plant height and number of leaves, demonstrating the influence of LOF nutrient composition on pineapple vegetative performance.

Table 2 Effect of LOF treatments on plant height and number of leaves at 7 months.

Treatment	Plant height	No. of Leaves
	---- cm ----	
T1	73.34 c	51 b
T2	90.48 ab	60 a
T3	93.98 a	56 ab
T4	82.97 b	55 ab
T5	91.69 ab	56 ab
T6	87.31 ab	54 ab
T7 Control	89.91 ab	57 ab
C.V	8.25	8.42

Means followed by different letters within a column are significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test (DMRT); C.V = Coefficient of Variation; (n=10).

Plant height

As shown in Table 2, plant height ranged from 73.34 cm to 93.98 cm. Treatment T3 produced the tallest plants **(**93.98 cm**)** and was significantly higher than T1 and T4, indicating that this LOF formulation provided a favorable nutrient balance for promoting vegetative growth. Treatments T2 (90.48 cm)**,** T5 (91.69 cm)**,** T6 (87.31 cm) and T7 Control (89.91 cm) were statistically comparable to T3, suggesting that several LOF formulations were capable of producing similar growth responses. Meanwhile, T1 recorded the lowest plant height (73.34 cm) and differed significantly from most treatments, indicating that nutrient availability from this formulation may not have been sufficient to support optimum plant development.

The increased plant height observed in T2, T3 and T5 may be associated with improved nitrogen supply from the fermented organic materials. Nitrogen is a key component of chlorophyll and amino acids, contributing to enhanced photosynthesis and cell division which promote plant elongation (Marschner, 2012; Taiz *et al.*, 2015). In addition, phosphorus supports root development and energy transfer, while potassium regulates enzyme activation and water balance, all of which contribute to improved vegetative growth (Havlin *et al.*, 2014).

Number of leaves

The number of leaves also differed significantly among treatments **(**Table 2**).** Treatment T2 produced the highest leaf number (60 leaves) and was significantly higher than T1. Treatments T3, T4, T5, T6 and T7 Control produced intermediate leaf numbers ranging from 54 to 57 leaves**,** which were not significantly different from T2. The lowest number of leaves was observed in T1 (51 leaves), indicating reduced vegetative vigor.

Leaf development is closely related to nitrogen availability because nitrogen promotes chlorophyll formation and photosynthetic capacity, which influence carbohydrate production for new tissue formation (Epstein & Bloom, 2005). Organic fertilizers such as LOF release nutrients gradually through microbial mineralization, providing a more sustained nutrient supply that supports continuous leaf formation (Diacono & Montemurro, 2010). The comparable performance between several LOF treatments and the control indicates that pineapple-based LOF has the potential to supplement or partially replace inorganic fertilizers without negatively affecting vegetative growth.

CONCLUSIONS

With an application volume of 100 mL per polybag, the estimated nutrient supply per polybag was approximately 1.76–5.97 mg N and 0.17–0.53 mg P_2O_5 per application, with only trace amounts of K_2O, MgO, and B_2O_3. When applied 7 times throughout the vegetative growth period, the cumulative nutrient input per plant was approximately 12.32–41.79 mg N and 1.19–3.71 mg P_2O_5. Despite the relatively low absolute nutrient quantities supplied per application, the repeated application strategy ensured a continuous and readily available nutrient supply in the rhizosphere and through foliar absorption pathways. Nitrogen plays a key role in chlorophyll formation, protein synthesis, and cell division, thereby directly influencing leaf initiation and expansion, which explains the significant increase observed in leaf number among LOF-treated plants. Similarly, adequate nitrogen availability promotes vegetative vigor, contributing to greater plant height through enhanced meristematic activity and internode elongation. Phosphorus, although present at lower concentrations, is essential for energy transfer (ATP), root development, and early plant establishment. The consistent supply of small amounts of P_2O_5 likely improved root growth and nutrient uptake efficiency, indirectly supporting plant height increment and leaf production. Even trace levels of K_2O, MgO, and B_2O_3 may have contributed synergistically to physiological functions such as stomatal regulation, chlorophyll formation, and cell wall development, which collectively support overall plant growth performance. The observed improvements in plant height and leaf number following seven LOF applications suggest that frequent low-dose fertilization enhances nutrient use efficiency compared with single high-dose application. This gradual nutrient release pattern is consistent with previous findings that liquid organic fertilizers improve nutrient availability, stimulate beneficial microbial activity, and enhance plant physiological performance, ultimately promoting sustained vegetative growth. Overall, T2, T3 and T5 demonstrated superior vegetative growth performance compared to other treatments, suggesting that the nutrient composition derived from pineapple waste fermentation can effectively enhance plant growth at the vegetative stage. The moderate performance of the control treatment indicates that LOF application is capable of producing comparable results to conventional fertilization practices. Improved vegetative growth, particularly increased plant height and leaf production, contributes to higher photosynthetic capacity, which is essential for assimilate accumulation and subsequent fruit development in pineapple (Bartholomew *et al.*, 2003). The vegetative growth data presented in Table 2 will be further compared with yield and fruit quality parameters to evaluate whether improved early growth performance translates into increased productivity and enhanced fruit characteristics. These findings highlight the potential of pineapple-based LOF as a sustainable nutrient management strategy that supports circular agriculture through recycling of agricultural waste into value-added fertilizer products.

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SOIL FERTILITY ASSESSMENT AND EARLY GROWTH PERFORMANCE OF A *Falcataria falcata* (BATAI) PROGENY TRIAL IN SELANDAR, MELAKA

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INTRODUCTION

Falcataria falcata (L.), known locally as batai, is a fast-growing Southeast Asian tree valued for its high biomass productivity and suitability for veneer and plywood. It can reach over 30 meters within a 7-to-10-year rotation, and its light, soft-textured wood serves as raw material for plywood, light construction timber, particleboard, and paper pulp. As a nitrogen-fixing legume, it also supports soil amelioration and carbon sequestration (Krisnawati *et al.*, 2011), making it a preferred species for rehabilitating degraded lands and advancing sustainable forest management in Malaysia.

Systematic genetic improvement of *F. falcata* plantations relies on progeny trials to evaluate the breeding value of parent trees. This study utilizes half-sib families, offspring sharing a single maternal parent (Zobel and Talbert, 1984), to distinguish genetic potential from environmental influences. Establishing a precise soil baseline is a statistical necessity to ensure spatial heterogeneity does not mask genetic superiority. By characterizing the trial site's physical and chemical properties, researchers can identify Genotype-by-Environment (GxE) interactions, ensuring selected progenies demonstrate genuine genetic robustness across the site.

This study aimed to characterize the physical and chemical properties of the progeny trial site, to evaluate early growth performance among *F. falcata* families, and to determine whether site variability influenced growth performance.

MATERIALS AND METHODS

Establishment of the progeny trial plot of *F. falcata*

The progeny trial plot of *F. falcata* is established in November 2025 at FRIM's Research Station in Selandar, Melaka, Malaysia. The trial consisted of 20 families with 400 saplings arranged in a randomized complete block design (RCBD), with five replicates at a spacing of 4 m × 3 m, covering an area of 0.48 ha.

Analysis of Chemical and Physical Characteristics of Soil Samples

Soil samples were collected before the establishment of the progeny plot from three replicates (Rep) (Rep 1, Rep 3, and Rep 5) at three distinct depths: 0–15 cm, 15–30 cm, and 30–50 cm. Parameters analysed included pH, available phosphorus (Av.P), total nitrogen (N), organic carbon (OC), exchangeable cations (Ca, Mg, K), Cation Exchange Capacity (CEC), and particle size distribution. Soil samples were analysed by the Soil Chemistry Laboratory, FRIM (the laboratory is accredited ISO/IEC 17025).

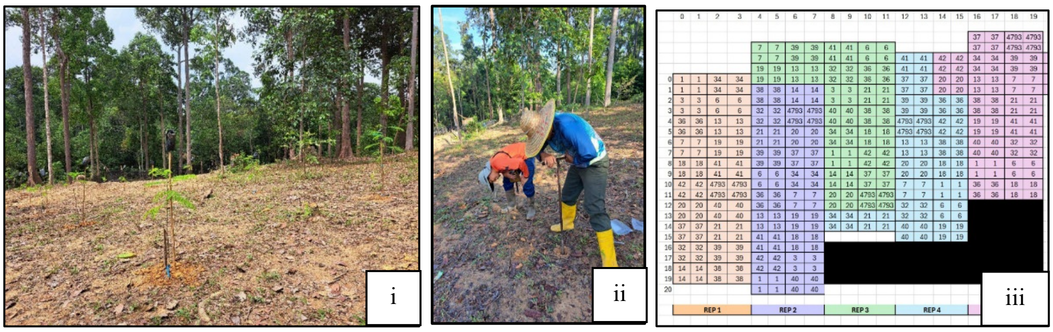

Figure 1 (i) The progeny trial plot of *F. falcata* in Selandar, Melaka, (ii) soil samples collection using a soil auger, and (iii) progeny trial plot layout design (RCBD) of *F. falcata* in Selandar, Melaka

Growth Data Collection and Statistical Analysis

Preliminary growth data were taken after the establishment of the progeny plot and two (2) months after planting. The growth parameter data taken were the survival rate (%) and height increment (cm). The measured growth parameters were analysed using IBM SPSS version 29 to assess the significant differences by analysis of variance (ANOVA) in the growth performance of *F. falcata*. Tukey's HSD post-hoc test was then performed to compare the height increment means. The height increment data were measured and compared based on the differences between families and replicates. Statistical significance was defined at = .05.

To assess the practical significance of the findings, partial eta squared (η2p) was calculated as a measure of effect size. Following the benchmarks proposed by Cohen (1988), values of .01, .06, and .14 were used to define small, medium, and large effects, respectively. This approach allows for an estimation of the proportion of variance accounted for by each factor while controlling for other variables in the model (Richardson, 2011; Lakens, 2013).

RESULTS AND DISCUSSION

Soil Physical and Chemical Characteristics at SPF Selandar Progeny Trial Plot

The soil analysis indicates that the study site is characterized by strongly acidic and nutrient-deficient conditions. Soil pH values ranged from 3.9 to 4.4 (Table 1), reflecting a highly acidic environment typical of many tropical soils in Malaysia, particularly those developed under highly weathered conditions (Paramananthan, 2000).

The macronutrient status shows clear limitations in the major nutrients required for plant growth. Available phosphorus was extremely low, with most samples recorded as not detectable (ND), and only trace amounts were detected in the surface layer (0–15 cm), reaching a maximum of 5.25 ppm in Rep 5. Nitrogen content was also low, ranging from 0.02% to 0.18%, indicating limited soil fertility. Exchangeable potassium levels were generally low but variable across replicates, with values between 0.20 and 2.20 cmol kg^{-1}. Organic carbon content ranged from 1.15% to 2.94%, with higher concentrations observed in the topsoil, reflecting the accumulation of organic matter near the surface (Table 1).

In terms of physical properties, the soil exhibited a heavy texture dominated by clay (40–51%) and coarse sand (47–58%), while silt and fine sand fractions were minimal (<10%), suggesting a sandy clay to clay loam texture (Table 1). Such a texture can enhance water and nutrient retention due to the high clay content; however, the combination of high clay and strong acidity may increase the risk of soil compaction and poor aeration.

The CEC ranged from 6.36 to 21.00 cmol kg^{-1}, indicating a moderate capacity for nutrient retention (Table 1). Despite these moderate CEC values, nutrient availability remained low, highlighting the need for appropriate soil management to support optimal plant growth.

Based on the results, phosphorus (P) could only be detected in the top 15 cm of the soil. The same trend is observed for nitrogen (N), where levels drop significantly with depth. These data demonstrated that the top 15 cm is the only layer with even marginal fertility. Whereas the soil acidity remains consistently low regardless of the depth, indicating that high acidity is a fundamental characteristic of the entire soil profile at this site.

Table 1 Summary of Soil Physical and Chemical Characteristics at SPF Selandar Progeny Plot

Feature	Description / Value
Location	SPF Selandar, Melaka, Malaysia
Soil Texture	Sandy Clay to Clay Loam (Clay: 40–51%; Coarse Sand: 47–58%; Fine sand: 4-12%; Silt: 0-3%)
Drainage	Well-drained to moderately well-drained (based on high sand/clay mix)
Soil Acidity (pH)	3.9 – 4.4 (Strongly Acidic)
Total Nitrogen (%)	0.02 – 0.18% (Low)
Available P (ppm)	0.25 – 5.25 ppm (Critically Low / Mostly ND)
Organic Carbon (%)	1.15 – 2.94% (Low to Moderate)
Cation Exchange Capacity (CEC)	6.36 – 21.00 cmol kg^{-1}
Dominant Exchangeable Cation	Calcium (Ex. Ca range: 2.75 – 11.08 cmol kg^{-1}) Magnesium (Ex. Mg range: 0.89 -3.39 cmol kg^{-1}) Potassium (Ex. K range:0.2 – 2.2 cmol kg^{-1})

Growth Performance of the 20 Families of *F. falcata*

The height increment data across the 20 families of *F. falcata* show significant genetic variation, $p < 0.001$ (Table 2), with values of height increment (cm) ranging from 7.00 cm to 30.60 cm (Figure 2). Despite the challenging edaphic conditions at SPF Selandar, specifically the extreme acidity (pH 3.9–4.4) and critically low phosphorus (ND at subsoil), the trial exhibited remarkably high survival rates, with most families exceeding 90% (87.5 – 100%) (Figure 2).

Table 2 Analysis of Variance (ANOVA)

		Sum of Squares	Df	Mean Square	F	Sig.
Initial height	**Between Groups**	5446.258	4	1361.565	1.921	.106
	Within Groups	257247.717	363	708.671		
	Total	262693.976	367			
Height after 2 months of planting	**Between Groups**	14351.429	4	3587.857	3.882	.004
	Within Groups	325316.471	352	924.195		
	Total	339667.899	356			
Height increment after 2 months of planting	**Between Groups**	4529.577	4	1132.394	5.529	.000
	Within Groups	63697.512	311	204.815		
	Total	68227.089	315			

Family K-B36 emerged as the top performer, achieving a height increment of 30.60 cm, which was significantly higher than the lowest-performing family, UK-4793 (7.00 cm). The superior growth of K-B36 in this nutrient poor environment suggests superior adaptation to nutrient-poor acidic soils capable of scavenging nutrients from the shallow 0–15 cm topsoil layer, where Nitrogen (0.11%) and Organic Carbon (1.92%) are concentrated.

Conversely, the high survival rate (100%) of the slowest-growing family (UK-4793) indicates that while the soil's chemical constraints (low P and high Al-toxicity risk) are significantly stunting vertical development, they are not exceeding the physiological tolerance limits for survival in this species. This highlights that the selection pressure at the Selandar site is primarily affecting biomass accumulation rather than seedling establishment.

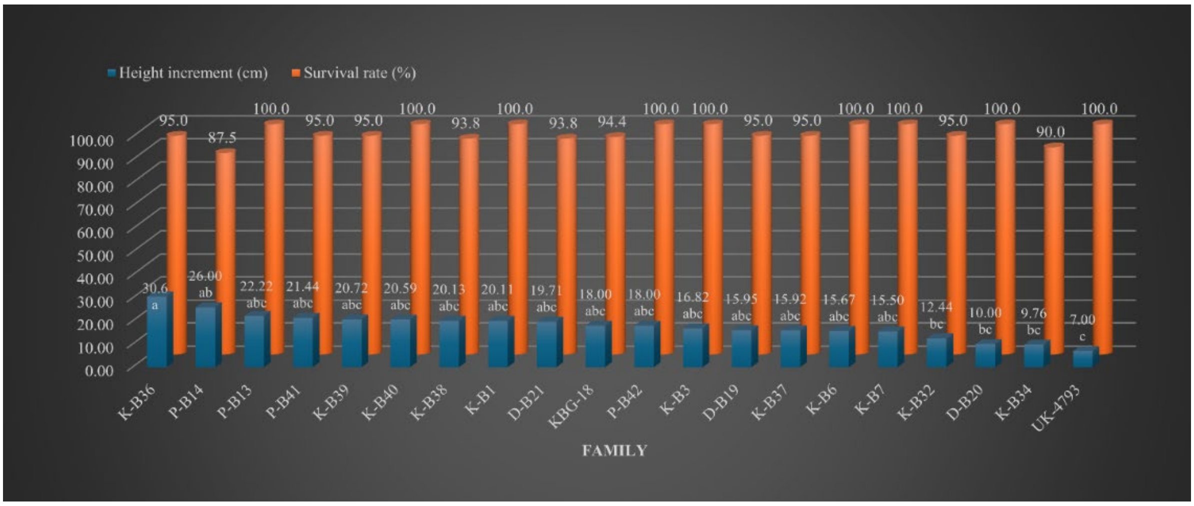

Figure 2 Height increment (cm) and survival rate of 20 families of *F. falcata* tested in the progeny trial plot in SPF Selandar, Melaka

Note: Height increment column with the same lower-case letter indicates no significant difference at $p < 0.005$ based on Tukey's HSD post hoc test

The Univariate ANOVA revealed that both Replicate and Family factors had a significant influence ($p < 0.05$) on the height increment of *F. falcata*. However, the Partial Eta Squared indicated that the Family factor exerted a higher magnitude of influence on growth variance compared to the Replicate factor, Replicate, $F(4, 395) = 6.401$, $p < .001$, $\eta^2_p = .081$ and Family, $F(4, 395) = 2.808$, $p = .025$, $\eta^2_p = .155$ (Table 3).

Table 3 Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	14371.402[a]	23	624.844	3.388	0.000	.211
Intercept	94956.288	1	94956.288	514.843	0.000	.638
Family	9841.825	19	517.991	2.808	0.000	**.155**
Rep	4722.216	4	1180.554	6.401	0.000	**.081**
Error	53855.687	292	184.437			
Total	166760.000	316				
Corrected Total	68227.089	315				

According to Cohen's (1988) benchmarks, the Replicate factor represents a medium effect, accounting for 8.1% of the partial variance. Despite the lower F-statistic, the effect size for Family is considered large, explaining 15.5% of the partial variance, nearly double the explanatory power of the Replicate factor. These values demonstrated that the genetic potential of the progenies remains the primary determinant of growth performance in the trial.

The results indicated that while both experimental replication and family lineage significantly influenced the growth rate, the effect of family was nearly twice as large in magnitude. The large effect size associated with the family factor suggests that inherent group characteristics are the primary drivers of variance in this population, maintaining their influence despite the significant medium-sized effects of environmental or procedural replicates.

CONCLUSION

The site at SPF Selandar is characterized by high acidity and severe phosphorus and nitrogen deficiency, which may limit the growth potential of the *F. falcata* progeny, but the physical soil structure provides good stability for drainage and water holding. Overall survival rate showed that *F. falcata* has high resilience to acidic conditions (pH < 4.5), making it a viable species for rehabilitating degraded tropical lands, provided growth expectations are managed against nutrient availability.

In terms of genetic variation, there is significant genetic variation among the 20 *F. falcata* families, with family K-B36 showing the most potential as a candidate for further breeding or plantation establishment on similar marginal Melaka soils. However, this finding is preliminary, and long-term monitoring will be conducted of both growth performance and soil fertility at the trial site, given that *F. falcata* is a nitrogen-fixing species.

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EFFECT OF PLANT SPACING ON CASSAVA YIELD AND SOIL PROPERTIES IN TROPICAL SOIL

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INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is widely grown in tropical regions due to its ability to tolerate low soil fertility and adverse environmental conditions (Kintché *et al.*, 2017). Cassava can be harvested between 6 to 24 months after planting. However, under less favourable conditions, maturity may be delayed up to 18 months (Otálora *et al.*, 2024). It is widely acknowledged that cassava is cultivated for its starch roots, which serve as a source of carbohydrates in some countries. An advantage of cassava is its ability to remain in the soil for a long period thus contributing to food security (Benti *et al.*, 2022). In recent years, cassava has been used as a livestock feed and industrial raw materials (Malik *et al.*, 2020; Streck *et al.*, 2014). Global production reached approximately 333.7 million metric tonnes (MT) in 2023 with Malaysia contributing about 45,226.7 metric tonnes (MT), making it one of the important agriculture commodities (Rawaida *et al.*, 2024; Department of Statistics, 2023).

Despite its adaptability, cassava yield is influenced by agronomic factors, particularly plant spacing (Cock, 1985). It is widely acknowledged that high planting density can intensify competition for nutrients, water, and light, thereby reducing root yield. Whereas, wider spacing may lead to inefficient land usage. Therefore, optimising plant spacing is essential to maximize cassava yield. Although a standard recommendation of 10,000 plants per hectare is practically used, the optimal spacing may vary depending on soil conditions and agronomic practices. Previous studies have shown that plant density can influence yield and growth characteristics of cassava (Abrell *et al.*, 2022; Mashuubu *et al.*, 2024). Furthermore, planting density can affect canopy closure and the timing of crop maturity (Hidoto and Loha, 2013). Despite the importance of cassava as a source of carbohydrate, there has been growing interest in identifying the optimum planting distance for maximising cassava yield. While numerous studies have focused on yield response, few address the effects of plant spacing on yield and soil properties under tropical conditions. The purpose of this study is to evaluate the influence of different plant spacings on cassava root yield and soil characteristics in tropical soils.

MATERIALS AND METHODS

Experiment design and agronomic management

The field study was conducted at Malaysian Agricultural Research and Development Institute (MARDI), Serdang, Selangor, Malaysia (2.9932384˚ N, 101.6976681˚ E). The experiment site was cleared, followed by ploughing and harrowing. The plot size was 6.0 m × 4.5 m and each plot was separated by 1.0 m and replications were separated by 1.5 m. The experiment was arranged in a randomised complete block design (RCBD). Five plant spacings were evaluated: T1) 0.5 m × 1.5 m, T2) 0.75 m ×1.5 m, T3) 1.0 m×1.5 m, T4) 1.25 m × 1.50 m and T5) 1.50 m × 1.50 m, representing plant densities 13 333 plants ha^{-1}, 8 888 plants ha^{-1}, 6 666 plants ha^{-1}, 5 333 plants ha^{-1}, and 4 444 plants ha^{-1}, respectively. Although the recommended planting density for cassava is 10, 000 plants ha^{-1}, the inter plant spacing in this study was fixed to 1.5 m to accommodate the bed system. Consequently, T3 was selected as the reference treatment because it represents the standard planting system. The cassava stem cuttings used were about 25 cm and were planted following to standard practices. Fertilisation was carried out using urea as nitrogen (N) source, triple super phosphate for phosphorus (P) and muriate of potash for potassium (K). Fertiliser were applied at 21 days after planting according following recommended rates of 100 kg N ha^{-1}, 50 kg P ha^{-1}: 100 kg K ha^{-1} (MARDI, 2005; Nurul Nahar *et al.*, 2024). Watering was applied daily during the early growth stage first five months of growth. Pest and disease control measures were applied as required based on field observations.

Soil characteristics

Soil samples were collected at a depth of 0–10 cm before planting and at harvest. Ten sub-samples were randomly selected from experiment site and homogenised to form a composite sample. Approximately 1 kg of the composite soil was kept for laboratory analysis. Soil samples were air-dried, ground, and sieved through a 2 mm mesh for analysis. The soil samples were analysed for pH value, electrical conductivity (EC), total N, P, K, calcium (Ca) and cation exchange capacity (CEC). Soil pH value was measured in a 1:2.5 soil: water suspension using glass electrode. Available P was determined using Bray and Kurtz No. 2 method (Bray & Kurtz, 1945). Total N was analysed using the Kjeldahl method (Kjeldahl, 1883). Exchangeable bases and CEC were extracted using ammonium acetate (NH_4OA) measured using an inductively coupled plasma mass spectrometry-optical emission spectrometer (ICP-OES) Model DV 7400 Perkin Elmer.

Data collection and analysis

The cassava yields were harvested from the center area of each plot using a 6.0 m × 1.5 m quadrat and calculated in kg per hectare. The data were analysed using SAS software version 9.2 (SAS Institute Inc., USA). Treatments means were compared using least significant difference (LSD) test at a significance level of $p \leq 0.01$.

RESULTS AND DISCUSSION

Soil chemical properties

The soil chemical properties measured before planting and after harvest were evaluated with the optimum ranges for cassava production (Table 1). The initial soil condition was strongly acidic (pH 4.83). After harvest, soil pH increased significantly among treatments ranging from 6.51 and 6.70. The highest pH was observed in T2, while the lower pH values were recorded in T4 and T5. This increment in soil pH value is likely associated with the combined effects of fertiliser and liming application on soil chemical properties, which likely altered soil chemical properties through the addition of nutrients thereby enhancing nutrient availability throughout crop development. Electrical conductivity EC values ranged from 29.81 to 33.41 µS/cm within the optimum range for cassava cultivation. A slight decrease in EC values compared to initial values likely reflects nutrient uptake and stabilisation of soluble salts during the growing period (Corwin and Lesch, 2004). Similarly, the slight decrease in CEC (0.10 and 0.42 meq/100 g^{-1} soil) may be attributed with the depletion of exchangeable cation through plant uptake and changes in soil pH during crop growth (Sonon *et al.*, 2014). Total N increased after harvest in all treatments although no significant difference was observed among treatments. Soil organic C also showed an increase ranging from 1.70% to 1.87%, indicating improved soil organic matter status. This increase is likely due to the accumulation of plant residues which contribute to enhanced microbial activity and improved soil biological function (Radhakrishnan *et al.*, 2022). In contrast, available P decreased from an initial value of 34.25 mg/kg to between 1.52–1.86 mg/kg across treatments. This decline reflects the high demand for P during root development. Previous findings indicate that cassava harvesting can remove substantial amounts of P from the soil (Howeler, 2014), highlighting the importance of adequate P fertilisation to sustain productivity. Exchangeable Mg was higher in T2 although no significant differences were observed among treatments. The higher exchangeable Mg was likely due to the application of liming, which supplied Mg and increased soil pH through its liming effect. In contrast, T4 exhibited the lowest exchangeable K and Mg concentrations at harvest. This was likely attributed to greater nutrient uptake resulting from higher biomass production and storage root development. However, the low concentrations of both nutrients indicated a potential risk of nutrient depletion, particularly for K, under continuous cropping if nutrients are not adequately replenished through fertiliser application.

Table 1 Physico-chemical properties of soil before and after experiment and soil fertility range for cassava production

Treatment	pH	EC (µs/ cm)	CEC (meq/ 100g soil)	Total N (%)	Organic C (%)	Av. P (µg/ g)	Ex. K (ppm)	Ex. Mg (ppm)	Ex. Ca (ppm)
Initial soil	4.83	36.03	9.47	0.14	1.62	34.25	3.51	0.91	11.91
T1	6.65^{ab}	29.81^{a}	0.23^{a}	1.90^{a}	1.61^{a}	1.70^{a}	4.13^{ab}	9.88^{ab}	3.18^{a}
T2	6.70^{a}	30.98^{a}	0.42^{a}	3.31^{a}	1.87^{a}	1.86^{a}	4.92^{a}	11.33^{a}	4.15^{a}
T3	6.55^{bc}	33.41^{a}	0.10^{a}	1.00^{a}	1.85^{a}	1.58^{a}	4.35^{ab}	11.33^{a}	4.18^{a}
T4	6.51^{c}	32.10^{a}	0.40^{a}	3.11^{a}	1.70^{a}	1.62^{a}	3.41^{b}	9.44^{b}	3.13^{a}
T5	6.51^{c}	32.52^{a}	0.28^{a}	2.30^{a}	1.75^{a}	1.52^{a}	4.30^{ab}	10.10^{ab}	3.33^{a}
Optimum requirement	4.5 - 8.0	10 – 1700	4.2 – 10.7	0.20 - 0.50	4.0 – 10.0	4.2 – 1.0	0.15 - 0.25	0.40 - 1.00	1.0 – 5.0

Note: Means with same letters in the same column were not significant at $p \geq 0.05$. EC – electrical conductivity; CEC – cation exchange capacity; N – nitrogen; C – carbon; Av. – available; P – phosphorus; Ex. – exchangeable; K – potassium; Mg – magnesium; Ca – calcium. Source: Imakumbili *et al.*, 2021; Landon, 2014; Lelago and Buraka, 2019; Motsara and Roy, 2009; Ocaña-Reyes *et al.*, 2024; Vinhal-Freitas *et al.*, 2017.

Root yield

Cassava root yield was significantly influenced by planting distance ($p \leq 0.01$), indicating that plant spacing is a key factor affecting productivity per hectare (Figure 1). The highest yield was recorded in T4 (14.59 t ha^{-1}), which and was significantly higher than those obtained under T1 and T5. Overall, yield followed the order T4> T3>T2>T5>T1, with the lowest yield recorded in T1 at 7.66 t ha^{-1}. The lowest yield under T1 is likely attributed to intense competition among plants for nutrients, water, and light which may have limited canopy development and restricted root expansion. In contrast, the widest spacing (T5) resulted in lower yield (9.17 t ha^{-1}), mainly due to reduced plant population per hectare, despite the possibility of larger tubers per plant. Wider plant spacing has been associated with inefficient of sunlight and soil nutrients, as greater area of the soil surface remain exposed, increasing the risk of nutrient loss through leaching and surface runoff (Basri *et al.*, 2024; Noorsuhaila *et al.*, 2024). Reduce canopy coverage can also lower overall photosynthetic efficiency and limit assimilate partitioning to storage roots. Similarly, lower plant density may increase soil evaporation and reduce nutrient uptake efficiency, thereby negatively affecting plant growth. Plant spacing at 1.00 m (T3) and 0.75 m (T2) produced high yields of 13.65 t ha^{-1} and 10.80 t ha^{-1}, respectively, and were not significantly different from plant spacing at 1.25 m (T4). Taking everything into consideration, a plant spacing between 0.75 m and 1.25 m within plants, with 1.5 m between rows, provides an optimal balance between plant density and nutrient availability especially for nutrients such as P and K that are critical for root development.

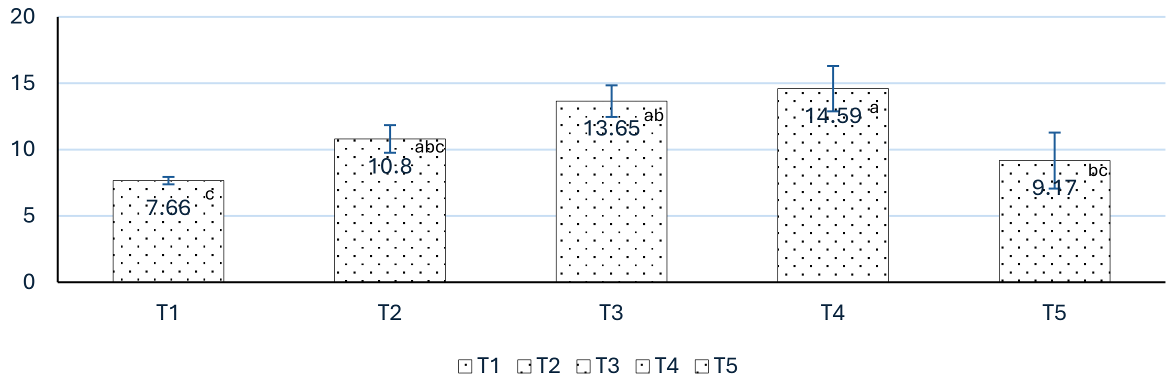

Figure 1 Comparison of fresh roots yield of cassava between treatments

CONCLUSION

It can be concluded that a plant spacing between 0.75 m and 1.25 m (intra-row) and 1.50 m between rows (inter-row) is recommended for achieving higher yields while sustaining soil fertility under tropical soils. This spacing provides a balanced between plant population that optimises nutrient availability, leading to enhanced yield performance and nutrient use efficiency. These findings offer practical agronomic guidance for enhancing cassava production and efficient land usage. Further studies are recommended to estimate optimum harvest age in relation to plant density and soil characteristics.

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PEDOLOGICAL CHARACTERIZATION AND WETLAND RICE SUITABILITY OF LUBA FAMILY (GLEYIC CAMBISOLS) IN NORTHERN SABAH

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INTRODUCTION

Gleyic Cambisols developed from recent alluvial deposits are widely distributed across tropical floodplains of Northern Borneo. A detailed soil survey was conducted in Kg. Rasak Laut, Sabah, Malaysia to characterize the morphological and chemical properties of the Luba Family (Gleyic Cambisols) and evaluate their suitability for wetland rice cultivation. Field surveys were carried out using a 100 m × 100 m grid system, including auger observations and representative soil profile description to 125 cm depth. Laboratory analyses determined soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium and cation exchange capacity (CEC).

The soils are deep, imperfectly drained and exhibit loam to sandy loam textures with moderate subangular blocky structure. Soil pH ranges from 4.6 to 5.3, while CEC values range between 5–12 cmol(+)/kg indicating low to moderate nutrient retention capacity. Nutrient limitations are primarily associated with low fertility status rather than physical constraints. Based on soil-crop suitability evaluation, the soils are classified under Suitability Subclass 1n (Class I), indicating minor nutrient limitations for wetland rice cultivation. With appropriate nutrient and water management, these Luba Family demonstrate strong potential for sustainable rice production in tropical floodplain environments.

MATERIALS AND METHODS

Field Investigation and Soil Sampling

A detailed grid-based soil survey (100 m × 100 m spacing) was conducted. Soil observations and sampling were made at depths of 0–15 cm and 15–30 cm using auger borings. A representative soil profile was excavated to 125 cm for detailed morphological description following standard soil survey procedures, including horizon differentiation, color (Munsell color chart), texture, structure, consistency, drainage condition and rooting depth.

Soil Classification and Soil Crop Suitability

The study employed field mapping, soil sampling and laboratory analysis to classify the soils and determine their suitability for paddy production. GPS-assisted mapping and remote sensing techniques were utilized to delineate soil boundaries, while field observations documented key soil properties, including texture, structure, drainage conditions, horizon differentiation, and rooting depth. Classification was conducted following FAO-UNESCO (1990), The Soils of Sabah (Acres *et al.*, 1975) and Elizabeth *et al.* (2009). Soil-crop suitability for wetland rice was evaluated using the limitation-based classification framework adapted from Wong (1986), considering drainage, nutrient status, soil depth, texture and other limiting factors.

Laboratory Analysis

Collected samples were analyzed for their chemical properties. Chemical properties analysed included pH (H_2O), organic matter content (Walkley-Black method), macronutrient concentrations (N, P, K) were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and CEC was measured using the ammonium acetate (pH 7) method.

RESULTS AND DISCUSSION

Location

The surveyed area is located at Kg. Rasak Laut, Kota Marudu (6°33'37.08"N, 116°51'23.4"E) covers an area of 100 hectares. The terrain consists of flat to undulating floodplains of the Rasak River. The area is well-connected by existing roads and transportation networks, facilitating farm operations. Much of the land was previously planted with oil palm and has been cleared, providing a suitable environment for paddy replanting.

Soil Analysis

Chemically, soil pH ranges from strongly to moderately acidic (4.6–5.3) but is expected to increase under flooded conditions, enhancing nutrient availability (Ponnamperuma, 1972). Organic matter content is moderate, supporting microbial activity while cation exchange capacity (CEC) ranges from 5–12 cmol(+)/kg, indicating low to moderate nutrient retention capacity. Macronutrient status was generally low to moderate. Total nitrogen ranged from 0.08% (very low) to 0.15% (low), available phosphorus from 1.71 ppm (low) to 10.0 ppm (medium) and exchangeable potassium from 0.20 cmol(+)/kg (low) to 0.37 cmol(+)/kg (medium) indicating considerable spatial variability in nutrient availability. The predominance of low nitrogen, phosphorus and potassium levels indicates nutrient imbalance which constitutes the primary limiting factor (1 n) for land suitability classification.

Soils Type and Suitability

Morphologically, the soils have a yellowish-brown matrix with grey mottles, loam to sandy loam textures, moderate subangular blocky structure and a deep profile (>100 cm), providing optimal water retention while maintaining adequate aeration for root growth. Imperfect drainage, characteristic of the floodplain setting, requires controlled water management to maintain appropriate flooding levels. A brief description of physical characteristics of these soils is given in Table 1.

Based on these properties, the Luba family soils are classified under Suitability Subclass 1n, indicating minor nutrient limitations and are well suited for sustained wetland rice cultivation with moderate fertilization and proper water management.

Table 1 A brief description of Luba Family characteristics.

Soil Classification	Soil Characteristics	Soil Suitability for Paddy Cultivation
Luba Family- Gleyic Cambisols 	Yellowish brown (10YR 5/6) with distinct light grey (5YR 7/2) mottles; loam to sandy loam; moderate medium to coarse subangular blocky structure; moist, friable; deep soil profile; imperfectly drained; pH 4.6 – 5.3; cation exchange capacity between 5 – 12 cmol(+) kg^{-1} soil.	The Luba Family are classified as Suitability Subclass 1n (Class I), indicating only minor nutrient limitations associated with moderate CEC levels. Overall, the area is suitable for wetland paddy cultivation.

CONCLUSION

Gleyic Cambisols of the Luba Family in the tropical floodplains of Northern Borneo exhibit favorable morphological characteristics and manageable chemical limitations for wetland rice cultivation. Although soil fertility is moderate to low, the absence of severe physical constraints indicates high suitability potential and supports their classification as Class I soils (Subclass 1n) under appropriate nutrient and water management conditions. Effective nutrient management and water regulation strategies are essential to address fertility limitations, optimize productivity and ensure long-term sustainability. These findings provide valuable information for land-use planning and sustainable rice development in Sabah by supporting the identification of suitable areas for wetland rice expansion and guiding site-specific soil management strategies.

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ROOT REINFORCEMENT EFFECTS OF TWO SHRUB SPECIES ON SOIL UNDRAINED SHEAR STRENGTH

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INTRODUCTION

Role of vegetation in soil improvement has long been recognised as an alternative and sustainable approach for erosion control, slope stability and mitigating of shallow landslides (Gonzalez-Ollauri & Mickovski 2017; Tang *et al.* 2018). Plant roots enhance the soil mechanical behaviour via mechanical reinforcement, hydrological regulation and soil-root interaction mechanisms. The mechanical contribution of roots is often considered the primary factor, controlling short-term stability under undrained shearing conditions. These nature-based options are economically cheaper in materials and installation costs yet possess a similar capacity to combat soil erosion as conventional approaches. Root reinforcement generally increases soil shear strength through the tensile resistance of root, enhancing interparticle bonding and refraining soil deformation during shearing. The presence of roots may modify the apparent cohesion and friction angle of soils, depending on root morphology, diameter, orientation and distribution in soil matrix (Li *et al.*,2022.). However, majority of the previous studies have focused on consolidated-drained (CD) or consolidated-undrained (CU) conditions, while fewer studies have examined under unconsolidated-undrained (UU) state which represents a rapid loading scenario such as intense rainfall-induced slope failures. Soil structure is subjected to rapid shearing in UU conditions without permitting consolidation/drainage, causing the mechanical interaction of soil-root becomes critical. The stress transfer mechanism between roots and soil particles as well as root tensile resistance's mobilisation may significantly affect the parameters of shear strenght envelope (apparent cohesion intercept, c and friction angle, θ). Despite huge interest in nature-based solutions in slope improvement, comparative studies examining the contribution of different shrub species under UU conditions remain limited. This study aimed to examine the effects of two shrub species of *Pseuderanthemum carruthersii* (Pc) and *Strobilanthes crispa* (Sc) on shear strenghth under UU conditions. These species were selected due to their adaptability to tropical environments, rapid growth characteristics and well-developed root systems, which are expected to contribute to soil reinforcement. The findings of this study contribute to a better understanding on stress-dependant root reinforcement mechanism and provide insight for the application of shrub species in bio-engineering and slope stabilization practices.

MATERIALS AND METHODS

Plant Materials and Soil Preparation

Two shrub species of *Pseuderanthemum carruthersii* (Pc) and *Strobilanthes crispa* (Sc) were selected for this study. The species were initially propagated using the plant cutting techniques, later grown in polybags under controlled conditions for six months. Then, the root samples were washed to remove adhered soil particles without altering their integrity. Roots were then air-dried under room conditions and sorted according to diameter. A root diameter range of 1.5 – 2.0 mm were selected for the standardization purpose for testing. This diameter range was chosen to minimize variability and ensure consistency between samples. The selected roots were cut into 5 cm in length prior preparation of soil samples. Remoulded soil sample was used to ensure uniformity among the samples. The soil was thoroughly mixed with 20% water content (by weight) to achieve a consistent and workable consistency. The estimated degree of saturation, S_r calculated based on imposed 20 % water content, was 0.56, indicating that the remoulded soil samples were in a moderately unsaturated condition during UU test. After mixing, the moist soil was sealed and left for 30 minutes to allow uniform moisture distribution. The physico-chemical characteristics of the soil used are shown in Table 1.

Table 1 Summary of the physico-chemical characteristics of the soil

Parameter	**Soil**
pH	4.62±0.33
Moisture content, %	29.21±12.56
Organic content, %	6.14±1.01
Bulk density, gcm^{-3}	1.08±0.05
Hydraulic conductivity, cmhr^{-1}	1.71±0.80
Specific gravity, G_s	2.96±0.06
Particle size distribution, %:	
Clay	31.29±9.65
Silt	30.43±15.19
Sand	38.28±7.75
Soil texture	Clay loam
Liquid limit, L_L, %	27.31±2.32
Plastic limit, P_L, %	32.52±2.32
Plasticity Index, P_I	5.21±2.22

Sample Preparation and Experimentation

Samples were prepared using a cylindrical mould with dimensions of 45 mm (diameter) and 90 mm (height). Five root samples of 5 cm length were vertically arranged in the cylindrical mould prior to soil placement, representing reinforced soil. The roots were positioned parallel to the axis of loading to simulate vertical root reinforcement commonly observed in shallow soil layers. Soil was carefully filled into the mould in three layers, each layer received gently tamped to establish uniform density with minimum disturbance to the root arrangement. The control samples without roots were also prepared for reference. Shear strength tests were performed under unconsolidated–undrained (UU) triaxial compression tests. Confining pressures, σ_3 of 50, 100 and 200 kPa were applied, representing shallow subsurface stress conditions. Shearing was performed at a constant axial displacement rate of 1 mm/min up to 20% axial strain. The shear strength envelopes and parameters were determined from each confining of sample. After completion the tests, samples were carefully dismantled and soil samples were collected for moisture content, w determination. The root segments were extracted and their biomass was measured for further analysis.

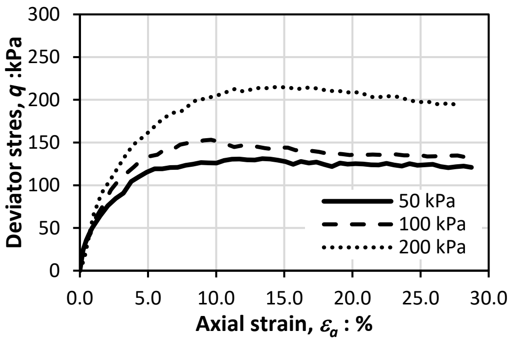
RESULTS AND DISCUSSION

Stress-Strain Behaviour (UU test)

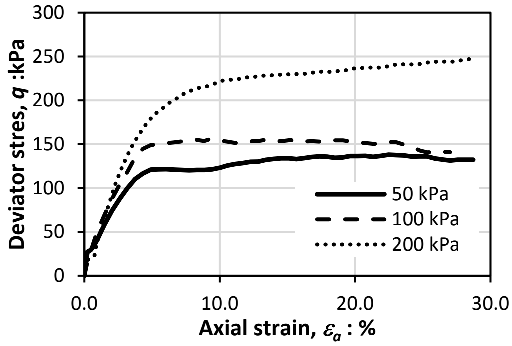
All samples exhibited typical undrained behaviour, characterised by a rapid initial increase in deviator stress, q, followed by peak strength at low-to-moderate axial strain, ε_a and subsequent strain softening/hardening depending on the confining stress (Figure 1(a) – 1(c)). The inclusion of roots significantly affected peak strength, q_{max} and post-peak response compared with the control soil. Under σ_3 of 50 kPa confinement, shear strength was mobilised rapidly within approximately the first 5% axial strain, reflecting undrained loading behaviour where pore pressure development governs effective stress changes (Das and Sobhan, 2014).

Effect Root on Peak Shear Strength

At confinig stress, σ_3 of 50 kPa, species Sc showed the highest peak deviator stress, q_{max} whilst Pc indicated moderate improvement (Figure 1a). The control soil displayed the lowest strength. This suggests that the root tensile mobilisation was effective even at low normal stress. Hence, root reinforcement has primarily contributed through additional apparent cohesion generated by root tensile resistance bridging the shear plane (Wu *et al.* 1979). At σ_3 of 100 kPa of intermediate confining condition, both species showed clear strength enhancement relative to control soil, C. It is clear that the reinforcement effet became more pronounce compared to 50 kPa, indicating the stress-dependent mobilisation of root resistance (Figure 1b). As confining pressure increases, soil-root interface friction improves, enhancing load transfer efficiency (Gray and Ohashi, 1983). At confining stress, σ_3 of 200 kPa (Figure 1c), Sc reached the highest maximum shear strength compared to others (Pc and C). This indicates that the effectiveness of root reinforcement increases with the applied confining stress, σ_3. Higher stress confining causes enhance the root contribution through the improvement of soil-root frictional anchorage (Operstein and Frydman 2000). It is noted that Sc demonstrated strain hardening behaviour, suggesting progressive mobilisation of root tensile resistancerather than brittle failure.



(a)



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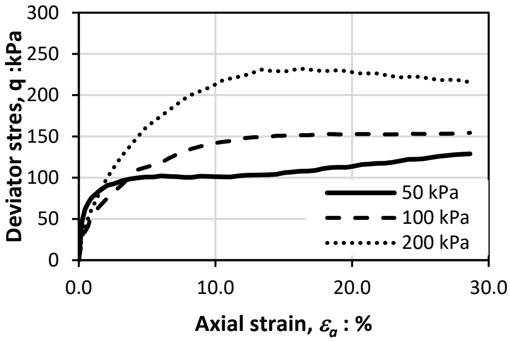

(c)

Figure 1 Devaitor stress, q vs. axial strain, ε_a curves of (a) control soil (withourt roots), (b) species Sc and (c) species Pc under confining stresse of 50, 100 and 200 kPa.

Shear Strength Envelopes

The shear strength envelopes derived from the peak stresses for the C, Sc and Pc are shown in Figure 2. The shear strenght parameters of apparent cohesive, c_c and friction angle, θ can be extracted from the regression equations.

Apparent cohesion, c_c

The apparent cohesion, c_c for the control soil, C achieved the highest intercept (100.3 kPa) compared to Sc (91.8 kPa) and Pc (90.1 kPa). This reveals that under the UU conditiond, root did not significantly increase the c_c. The reason due to undrained condition; pore water pressure increases as shearing occur, limiting the effective stress. Soil skeleton as well as root tensile stress cannot fully mobilise as pore pressure water development. The results differs from many drained direct shear studies where roots increase cohesion substantially (Ali & Osman 2008).

Friction angle, θ

The friction angle of reinforced soils (Sc and Pc) showed higher values than the control, C (Figure 2). In comparison, Sc displayed the higher frictional enhancement than Pc. This suggests that roots primarily enhanced shear resistance through the improve of soil particles interlocking and increase dilation resistance. These susbsequently enhance the stress transfer under confinement conditions. Mickovski *et al.* (2009) and Hao *et al.* (2023) stated similar behaviour that root morphology and orientation can influence the frictional component under triaxial loading.

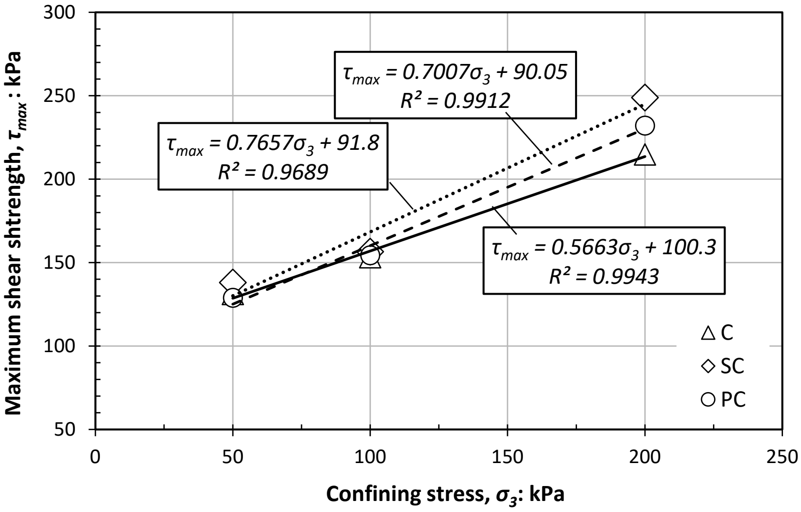

Figure 2 The shear strength envelopes of the enforced soil and control soil

CONCLUSIONS

The effects of two shrub species on soil shear strength under undrained conditions (UU tests) are examined. The stress – strain of both species indicated by stress-dependant behaviour. The inclusion of roots significantly affects peak strength, q_{max} and post-peak response compared with the control soil. The apparent cohesion, c_c for the control slightly higher than the shrub species. In UU states, the inclusions of roots did not increase total apparent cohesion due to localized pore pressure development dominating initial shearing resistance. However, the total friction angle become significantly pronounced with increasing confining stress, as higher confining pressure enhanced soil-root surface contact, interlocking and pull-out resistance.

ACKNOWLEDGEMENTS

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UNLOCKING THE POTENTIAL OF MALAYSIAN SOIL MICROBES: A SUSTAINABLE BIOCONTROL STRATEGY FOR PINEAPPLE BACTERIAL HEART ROT

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INTRODUCTION

Pineapple bacterial heart rot (BHR) caused by *Dickeya zeae* is a devastating disease leading to significant economic losses in Malaysia. Hawaii, Indonesia, and Brazil have recorded 40% of yield losses from this disease (Young *et al.*, 2022). BHR induces internal rotting in pineapple stems and heart leaves, often rendering entire plants unmarketable (Young *et al.*, 2022). Traditional reliance on chemical pesticides has raised escalating concerns regarding environmental pollution, non-target organism toxicity, and human health risks (Pathak *et al.*, 2022). The emergence of pesticide-resistant *Dickeya* strains has further complicated control efforts (Lahlali *et al.*, 2022), creating an urgent need for effective, sustainable alternatives.

Biological control using beneficial soil microorganisms offers a promising solution. Among bacterial biocontrol agents, *Bacillus velezensis* has gained considerable attention for its potent antimicrobial properties and plant growth-promoting activities (Tao *et al.*, 2019; Wockenfuss *et al.*, 2024). This species produces a wide range of bioactive compounds including lipopeptides (surfactin, iturin, fengycin), polyketides (difficidin), and the dipeptide antibiotic bacilysin (Fan *et al.*, 2019).

Malaysia's diverse soil ecosystems may harbor unique bacterial strains with enhanced biocontrol potential. This study focuses on isolating and screening bacteria from Malaysian soil for antagonistic activity against *Dickeya zeae*, with the goal of identifying potential biocontrol agents that can support sustainable disease management in pineapple cutivation. By identifying effective biocontrol agents, this research aims to reduce reliance on chemical pesticides and promoting environmentally friendly agricultural practices.

MATERIALS AND METHODS

Pathogen Isolation and Identification

The BHR pathogen was isolated from infected pineapple plants exhibiting typical symptoms at MARDI Pontian, Johor, Malaysia. Diseased tissue samples were surface-sterilized in 1% sodium hypochlorite for 30 seconds, rinsed three times with sterile distilled water, and dried. Tissues were placed on Nutrient Agar (NA) and incubated at 28 ± 1.5 °C for 48 hours. Pathogenicity was confirmed using Koch's Postulate. Molecular identification was performed by amplifying the 16S rRNA gene through PCR, with sequencing by Apical Scientific.

Soil Collection and Bacterial Isolation

Rhizospheric soil samples were collected from four agricultural locations across Peninsular Malaysia: (i) Serdang, Selangor; (ii) Bachok, Kelantan; (iii) Jerangau, Terengganu; and (iv) Cameron Highlands, Pahang. All samples were collected from rhizosphere of actively cultivated crops, representing diverse agricultural land-use types. One gram of soil was suspended in 100 mL of sterile distilled water and stirred for 1 hour using a magnetic stirrer.

Serial ten-fold dilutions (10^{-1} to 10^{-8}) were prepared by transferring 1 mL of suspension into 9 mL of sterile distilled water. From the 10^{-4}, 10^{-6}, and 10^{-8} dilutions, 200 µL was spread onto NA plates. After incubation at 28 °C for 48 hours, colonies exhibiting distinct morphological characteristics were subcultured and purified. A total of 446 microbial isolates were obtained: 211 from Selangor, 47 from Kelantan, 34 from Terengganu, and 154 from Pahang. Isolates showing inhibition against *D. zeae* were identified via 16S rRNA gene sequencing (Apical Scientific). The resulting 16S rRNA sequences were compared against the NCBI GenBank database using BLAST analysis and species identified was confirmed based on ≥99% sequence similarity to reference strains.

***In vitro* Antagonistic Assay**

Antagonistic activity was evaluated using the well diffusion technique (Li *et al.*, 2020). The pathogenic bacteria was grown overnight in 50 mL of Nutrient Broth (NB) at 28 °C shaken at 200 rpm. A 200 µL aliquot of the pathogen suspension was spread onto NA plates. A 5 mm well was punched into the agar, and 10 µL of a 48-hour antagonistic bacteria was added. Sterile distilled water served as a negative control. Plates were incubated at 28 °C for 4 days (Li *et al.*, 2020) with five replicates per treatment. Inhibition zones (clear halos around wells) were measured in millimeters.

Data analysis

Data taken was computed using statistical analysis software (SAS) version 9.4 (SAS Institute Inc., Cary, NC). General Linear Model (GLM) procedure was used to do an analysis of variance (ANOVA) and mean comparisons were calculated using Tukey's Honest Significant Difference (HSD) at $P \leq 0.05$.

RESULTS AND DISCUSSION

From 446 initial isolates, eight showed antagonistic activity against *D. zeae* and were selected for detailed analysis (Figure 1).

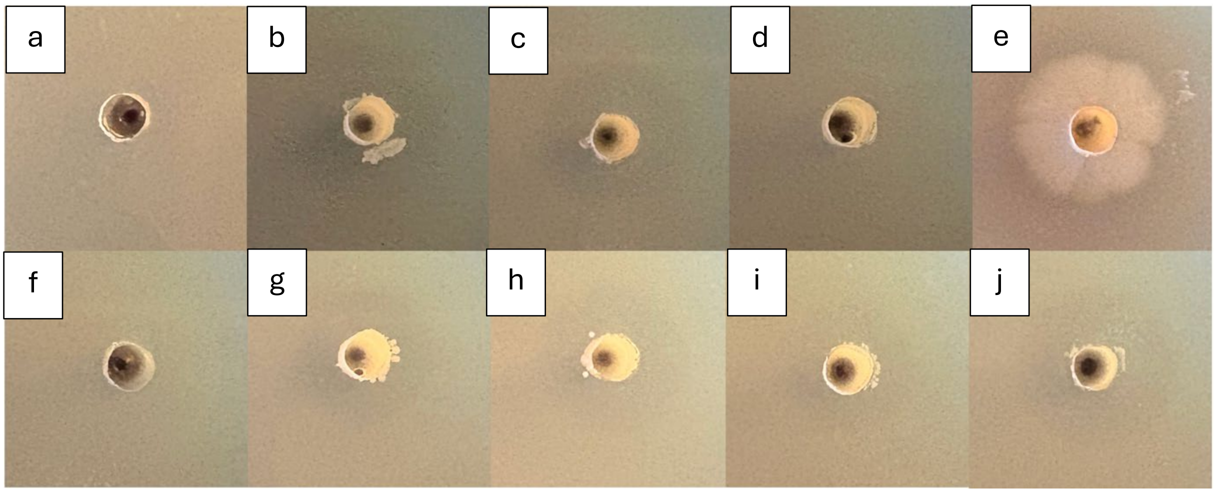

Figure 1 Inhibitory activities of antagonistic bacteria against BHR using the well diffusion technique at day 4 after inoculation. Pathogenic BHR in treatments (a) control; (b) KC2.5; (c) KC13.3; (d) PT7.1; (e) PT14.1; (f) PT16.1; (g) PT17.1; (h) 17.2; (i) 17.3; and (j) PT17.4.

As shown in Table 1, PT17.4, PT14.1, KC2.5, and PT17.2 inhibited the pathogen significantly at $p < 0.001$. PT17.4 had an inhibition zone of 17.34 mm, the highest compared to the other isolates tested. This superior performance may be attributed to the production of antimicrobial compounds, thereby enhancing disease resistance (Zhang *et al.*, 2024).

Table 1 Antagonistic activity of selected bacterial isolates (KC2.5, KC13.3, PT7.1, PT14.1, PT16.1, PT17.1, PT17.2, PT17.3 and PT17.4) against *Dickeya zeae* using the well diffusion technique at day 4 after inoculation

Treatment	Microbe	Diameter of inhibition zone (mm)	Identity through molecular
T1	Control	5.00 ± 0.00 d	-
T2	KC2.5	15.99 ± 0.94 abc	*Bacillus velezensis*
T3	KC13.3	13.54 ± 1.99 c	*Bacillus velezensis*
T4	PT7.1	6.08 ± 2.42 d	-
T5	PT14.1	16.97 ± 3.00 ab	*Pseudomonas aeruginosa*
T6	PT16.1	5.00 ± 0.00 d	-
T7	PT17.1	13.65 ± 0.45 bc	*Bacillus velezensis*
T8	PT17.2	14.32 ± 1.99 abc	*Bacillus velezensis*
T8	PT17.3	12.66 ± 0.75 c	*Bacillus velezensis*
T10	PT17.4	17.34 ± 1.11 a	*Bacillus velezensis*

Note: Values are expressed as mean ± SD. Means with different letters within the same column are significantly different at $p < 0.05$ using Tukey's Studentized Range (HSD) Test. The dash (-) indicates that molecular identification was not performed for isolates that showed no significant antagonistic activity against *Dickeya zeae* (Control, PT7.1, and PT16.1).

There is limited research on the use of *B. velezensis* against BHR. However, a study by Husin and Sapak (2022) on *Bacillus cereus* demonstrated significant antagonistic activity against BHR, with an inhibition zone of 18.10 ± 0.36 mm, indicating that *Bacillus* species have biocontrol potential against this pathogen. In the present study, PT17.4 (*B. velezensis*) produced a comparable inhibition zone of 17.34 ± 1.11 mm, confirming that *B. velezensis* is a promising candidate for BHR biocontrol. Previous studies have reported that *B. velezensis* produces antimicrobial compounds including difficidin, bacilysin, and various lipopeptides (Fan *et al.*, 2019; Tao *et al.*, 2019), suggesting that PT17.4 may possess similar biosynthetic capabilities.

Bacillus velezensis is recognized as a potent biocontrol agent that inhibits a wide range of microbial pathogens and also promotes plant growth (Tao *et al.*, 2019). Recent studies have confirmed that difficidin and bacilysin synthesized by *B. velezensis* FZB42 are key antimicrobial compounds (Fan *et al.*, 2019). Furthermore, *B. velezensis* engages in beneficial interactions with plants, including plant growth promotion, biofilm formation, and enzyme synthesis through specific metabolic pathways (Keshmirshekan *et al.*, 2024).

Different strains of *B. velezensis* exhibit varying effects against pathogens (Wockenfuss *et al.*, 2024). The stability of biocontrol effects can be influenced by environmental conditions in the field, such as soil type and weather conditions. Therefore, further trials using live samples at the nursery stage are necessary before commercial recommendation.

Pseudomonas aeruginosa has been reported to exhibit antimicrobial effects against *D. zeae* (Wen *et al.*, 2024; Tan *et al.*, 2025). Pyocyanin is a crucial virulence factor uniquely secreted by *P. aeruginosa* (Tan *et al.*, 2025). This compound inhibits *D. zeae* by disrupting pathogen membranes and halting growth. In this study, *P. aeruginosa* PT14.1 showed strong antagonistic activity against *D. zeae* with an inhibition zone of 16.97 ± 3.00 mm. While promising, *P. aeruginosa* strains require thorough safety assessment before agricultural application due to their opportunistic pathogen status in humans.

CONCLUSION

This study successfully isolated indigenous Malaysian soil microbes with *in vitro* antagonism against *D. zeae*. *Bacillus velezensis* PT17.4 demonstrated the strongest activity with a 17.34 ± 1.11 mm inhibition zone. The result is comparable to the 18.10 ± 0.36 mm inhibition zone reported for *Bacillus cereus* against BHR (Husin and Sapak, 2022), confirming PT17.4 as a highly promising lead candidate for biopesticide development. Other effective isolates included PT14.1 (*P. aeruginosa*, 16.97 ± 3.00 mm) and KC2.5 (*B. velezensis*, 15.99 ± 0.94 mm). The variation in antagonistic activity among the tested isolates, ranging from 5.00 mm to 17.34 mm, demonstrates that biocontrol potential is strain-dependent, even among isolates of the same species (*B. velezensis*). Therefore, screening a large number of isolates is essential to identify the most effective candidates for biopesticide development.

Biological control is a key component of Integrated Pest Management (IPM) strategies, which combine multiple control methods (cultural, mechanical, biological, and chemical) to manage plant diseases in a sustainable way. By incorporating biocontrol agents, farmers can reduce reliance on chemical treatments, improve biodiversity, and enhance long-term soil health. Further field trials are necessary to validate the efficacy of PT17.4 under field condition.

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BIOTOXICITY POTENTIAL OF GEOGENIC HEAVY METALS IN SERPENTINITE SOILS: IMPLICATIONS FOR PLANTATION AND FOREST ECOSYSTEMS IN CHEROH, PAHANG

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INTRODUCTION

Serpentinite-derived soils, formed through the weathering of ultramafic rocks, are characteristically enriched in heavy metals such as nickel (Ni), cobalt (Co), and chromium (Cr) (Abdul Rashid *et al.*, 2023; Tashakor *et al.*, 2011; Tashakor *et al.*, 2014). Most of the previous work has emphasized on the bulk concentrations without adequately addressing their mobility, leachability, and ecological risks under different land-use settings. This study fills that gap by adopting a comparative ecosystem approach, examining serpentinite soils in Cheroh, Pahang under both plantation and forest conditions. The novelty lies in integrating mineralogical characterization, geochemical quantification, and leaching assessments to link soil composition with biotoxicity potential. Accordingly, the objectives are to characterize the mineralogical content of serpentinite soils, quantify heavy metal concentrations, and evaluate their biotoxic effects with emphasis on ecological risk and land-use differences.

MATERIALS AND METHODS

Serpentinite soil samples were collected from ten sampling sites of fresh cutslope outcrops at depths of approximately 1 - 2 m below the ground surface using a plastic soil shovel scoop. Each sample, weighing about 250 g, was immediately placed in clean plastic bags to minimize contamination and preserve in-situ conditions. The samples were then transported to the laboratory for subsequent mineralogical and geochemical analyses.

The mineral composition of the serpentinite soils was analyzed using X-ray Diffraction (XRD). Major and trace elements in the serpentinite soil samples were identified using X-Ray Fluorescence (XRF) with the fused-glass bead technique. Total heavy metal concentrations were determined through acid digestion following USEPA Method 3050B, employing concentrated nitric acid and hydrogen peroxide. To assess the mobility and potential biotoxicity of these metals, the Toxicity Characteristic Leaching Procedure (TCLP) was conducted in accordance with USEPA SW-846 Method 1311. Extracts obtained from both digestion and leaching processes were subsequently analyzed using Microwave Plasma Atomic Emission Spectrometry (MP-AES).

RESULTS AND DISCUSSION

Mineralogical analysis confirmed the presence of serpentine group minerals, including chrysotile, antigorite, and lizardite, in both parent rocks and their derived soils. These minerals are characteristic of ultramafic terrains and strongly influence the geochemical composition of associated soils (Oze *et al.*, 2004; Kumarathilaka *et al.*, 2014).

XRF elemental analysis indicated a low silica SiO_2 content in both the rock (44.6%) and soil (27.8%) samples, which is consistent with their ultramafic origin. Conversely, iron oxide Fe_2O_3 levels were significantly higher in the weathered soil (53%) compared to the parent rock (11.7%). Trace element analysis recorded highly elevated levels of geogenic metals in the soil such as Cr at 8550 ppm, Ni at 3730 ppm, and Co at 490 ppm. Low SiO_2 content and high Fe_2O_3 enrichment are well supported by the findings reported by Caillaud *et al.* (2009) and Tashakor *et al.*, 2011; Tashakor *et al.*, 2014).

The results of MP-AES analysis following acid digestion are presented in Table 1. The table presents the concentrations of heavy metals in serpentinite soils showing both individual sample values and statistical summaries. Based on the dataset provided, the mean values indicate that manganese (Mn) had the highest average concentration (5.74 ± 5.32 mg/kg), followed by nickel (Ni, 3.22 ± 3.13 mg/kg) and chromium (Cr, 3.74 ± 1.23 mg/kg), while cadmium (Cd) and lead (Pb) were present at very low levels (0.015 ± 0.01 mg/kg and 0.038 ± 0.02 mg/kg respectively). The highest recorded values for specific toxic metals in the samples were 21.14mg/kg for Mn, 11.37 mg/kg for Ni, 6.17 mg/kg for Cr, and 4.44 mg/kg for Co. The results demonstrated that the heavy metal concentrations in the serpentinite soil follow a descending sequence of Mn> Ni > Cr >Co>As>Zn>Cu>Pb>Cd. The results in Table 1 were also compared with the Contaminated Land Management and Control Guidelines (Department of Environment, 2009), where several heavy metals particularly Ni, Co, Mn and Cr exceed the recommended soil quality standards (highlighted by bold numbers), suggesting potential geogenic contamination risks and the need for careful ecological and land-use management.

Table 1 Heavy metals concentration in serpentinite soil samples (mg/kg)

Sample	**Heavy metals concentration (mg/kg)**								
(n = 10)	Zn	Cd	Cu	Ni	Co	Pb	Mn	Cr	As
CS01	0.091	0.006	0.049	1.062	0.094	0.023	1.146	1.388	0.19
CS04	0.199	0.011	0.028	2.238	0.732	0.032	3.877	4.014	0.39
CS05	0.483	0.029	0.032	**11.368**	**4.441**	0	**21.137**	**6.165**	0.77
CS06	0.383	0.009	0.039	**6.214**	1.507	0.032	**5.651**	3.431	0.35
CS12A	0.185	0.015	0.032	2.710	0.629	0.035	**5.677**	3.235	0.62
CS12B	0.248	0.018	0.022	1.351	0	0.061	**3.920**	4.008	0.78
CS13	0.160	0.012	0.044	0.553	0	0.044	2.579	2.452	0.44
CS01B	0.198	0.015	0.139	3.047	0.291	0.057	3.657	4.187	0.73
CS06B	0.231	0.018	0.049	2.864	1.165	0.037	**5.976**	4.872	0.61
CS13B	0.171	0.018	0.059	0.749	0	0.057	3.763	3.639	0.8
Mean	0.235	0.015	0.049	3.216	0.886	0.038	5.738	3.739	0.568
Max	0.483	0.029	0.139	11.368	4.441	0.061	21.137	6.165	0.8
Min	0.091	0.006	0.022	0.553	0	0	1.146	1.388	0.19
Standard Deviation	0.11	0.01	0.03	3.13	1.29	0.02	5.32	1.23	0.20
Soil Standard (*)	21.9	14.4	13.8	5.77	7.90	10.37	3.97	6.00	15.6

Bold concentration values exceed the standard value in soil.
(*) Department of Environment Malaysia. (2009)

The results of this study are consistent with previous research, which has reported that Malaysian ultramafic soils contain the highest geogenic concentrations of chromium (Cr), nickel (Ni), and cobalt (Co) (Osama, 2007; Abdul Rashid *et al.*, 2023; Tashakor *et al.*, 2011; Tashakor *et al.*, 2014).

The heavy metals such as Cr, Co, Ni, Pb, Cu, and Cd contents extracted from the Toxicity Characteristic Leaching Procedure (TCLP) test for soil samples are depicted in Figure 1 and Figure 2. All heavy metal concentrations extracted via TCLP were well below the permissible limits outlined by Malaysian Department of Environment (2009) except for two heavy metals Cr and Ni. Despite elevated total metal concentrations, TCLP (Toxicity Characteristic Leaching Procedure) results indicated low leachable fractions, suggesting limited immediate mobility and low short-term toxicity risk. This finding aligns with previous studies showing that serpentinite soils often retain metals in residual fractions, reducing their short-term bioavailability (Khorasanipour & Eslami 2014; Kierczak *et al.*, 2021). However, the persistent presence of Ni, Cr, and Co raises concerns about chronic biotoxicity. Over time, soil-plant interactions, particularly under conditions of soil acidity, organic matter decomposition, and root exudation, may enhance the bioavailability of these metals (Abdul Rashid *et al.*, 2023; Tashakor *et al.*, 2014).

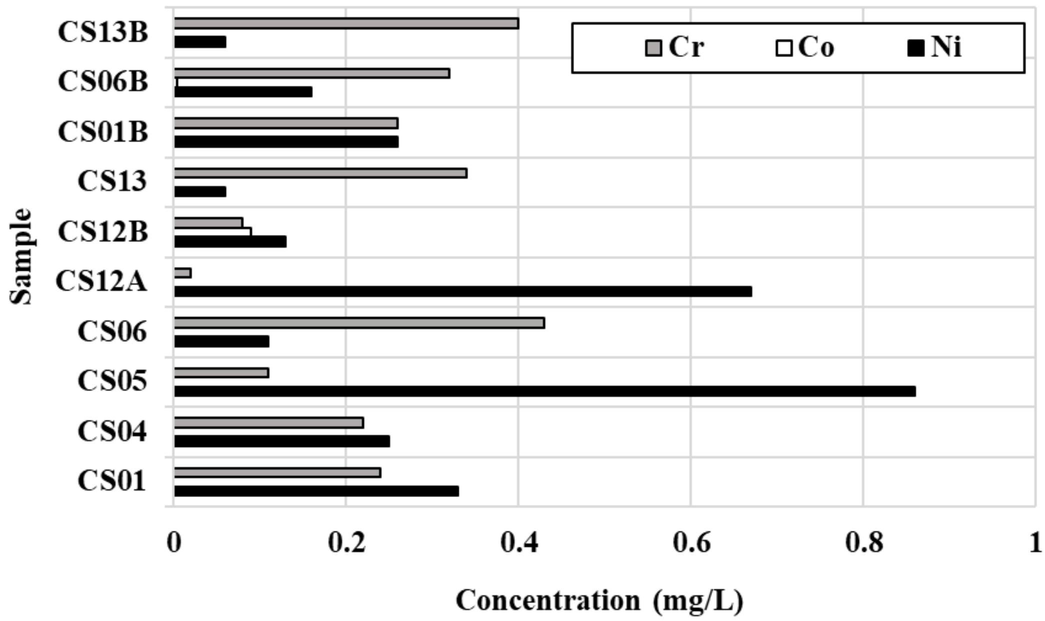

Figure 1 Cr, Co, and Ni contents extracted from the Toxicity Characteristic Leaching Procedure (TCLP) test for soil samples (mg/L). Standard from DOE (2009)

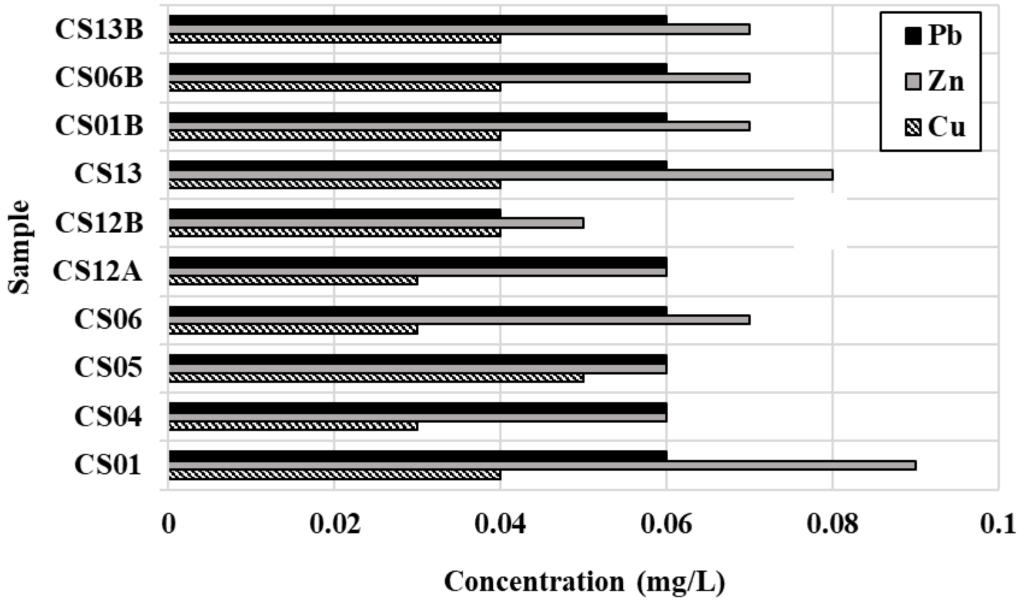

Figure 2 Pb, Cu, and Cd contents extracted from the Toxicity Characteristic Leaching Procedure (TCLP) test for soil samples (mg/L). Standard from DOE (2009).

CONCLUSION

The findings demonstrate that serpentinite soils in Cheroh, Pahang represent a geogenic heavy-metal environment, characterized by naturally elevated concentrations of Mn, Ni, Cr, and Co. Overall, leaching tests suggest a generally low risk of immediate metal mobility, consistent with the tendency of serpentinite soils to retain metals in residual fractions. However, Cr and Ni exhibited leaching capabilities that exceeded groundwater quality standards, underscoring their potential to migrate into subsurface water systems.

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ADSORPTION-DESORPTION DYNAMICS OF NITROGEN IN PLANTING MEDIA AMENDED WITH PINEAPPLE LEAF BIOCHAR (PLB) AND *TRICHODERMA* BIOFERTILIZER (TBF)

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INTRODUCTION

Nitrogen (N) retention in soilless planting media is mainly controlled by adsorption and desorption processes, which influence nutrient availability and potential nutrient loss under fertigation. In fertigated systems, frequent irrigation may accelerate nutrient movement; therefore, improving N retention is important for enhancing nutrient-use efficiency and sustaining crop growth. In this study, N retention was evaluated through adsorption–desorption behavior in cocopeat media rather than indirect plant-based measurements such as tissue analysis (White & Ding, 2023). Cocopeat is widely used as a soilless substrate because of its water-holding capacity, low bulk density, and nutrient-retention potential. The cocopeat used in the related *Capsicum chinense* fertigation study had pH 5.26, cation exchange capacity of 93.13 cmol kg^{-1}, bulk density of 0.14 g cm^{-3}, organic carbon of 42.71%, and initial N, P, K, Ca, and Mg contents of 0.60%, 0.05%, 0.30%, 0.09%, and 0.09%, respectively (Mahdian *et al.*, 2025). Organic amendments such as biochar and biofertilizer may further improve nutrient regulation in soilless media. Biochar improves nutrient sorption through its porous structure, surface area, and functional groups, while *Trichoderma* spp. enhances nutrient transformation through microbial activity (Karmaita *et al.*, 2023). Pineapple leaf biochar (PLB) produced at 500 °C was previously reported to contain porous surfaces, functional groups such as O-H, C≡C, C=C, and C-O, and stable carbon-rich properties, suggesting its potential to improve substrate quality (Mahdian *et al.*, 2025). However, the adsorption–desorption behavior of N in cocopeat amended with PLB and TBF remains less understood. Their combined application may improve synchronization between N retention and release by altering adsorption strength and reversibility (Kubheka & Ziena, 2022). Therefore, this study quantitatively evaluated NH_4^+ adsorption and desorption in cocopeat media amended with different PLB and TBF ratios before and after cultivation of *C. chinense* under fertigation.

MATERIALS AND METHODS

Media samples were collected before and after planting, 20 weeks after treatment application, from *C. chinense* grown under a rain shelter equipped with a fertigation system. The base planting medium was cocopeat, a soilless substrate previously characterized by Mahdian *et al.* (2025). The planting medium consisted entirely of cocopeat (100% soilless substrate) without mineral soil addition. Cocopeat was selected due to its high water-holding capacity, low bulk density, and suitability for fertigation-based crop production. Six treatments were evaluated: T0 (control), T1 (50 g PLB), T2 (50 g TBF), T3 (37.5 g PLB + 12.5 g TBF), T4 (25 g PLB +

25 g TBF), and T5 (12.5 g PLB + 37.5 g TBF). The total amendment rate was fixed at 50 g per planting bag, with varying proportions of PLB and TBF. Samples for adsorption–desorption analysis were air-dried at room temperature to constant weight, gently crushed, and sieved (2 mm) to obtain uniform particle size. The processed samples were homogenized and stored in airtight containers prior to analysis.

The NH_4^+ adsorption–desorption analysis followed Palanivell *et al.* (2020). A 2 g sample from each treatment was placed in a 250 mL centrifuge bottle. Nitrogen solutions of 0, 100, 200, 300, and 400 mg N L^{-1} were prepared using NH_4Cl in 0.2 M NaCl to maintain uniform ionic strength and provide competing ions for exchange sites. Then, 20 mL of solution was added to each bottle, corresponding to 0–4000 µg N per sample. Adsorption-desorption measurements specifically evaluated ammonium nitrogen (NH_4^+-N), as NH_4Cl was used as the N source throughout the experiment. Therefore, the reported adsorption and desorption behaviour represents NH_4^+ retention and release rather than total mineral nitrogen. Two drops of toluene were added to inhibit microbial activity. Samples were agitated for 24 h at 180 rpm and centrifuged at 10,000 rpm for 15 min to obtain equilibrium solutions. Nitrogen content was determined using steam distillation, and adsorbed N (µg N g^{-1}) was calculated from the difference between added and equilibrium N. For desorption, the residues were washed with ethanol and centrifuged at 10,000 rpm for 10 min. After discarding the ethanol, 20 mL of 2 M KCl was added, and samples were shaken for 24 h at 180 rpm. The mixtures were then centrifuged at 10,000 rpm for 15 min, and the supernatants were collected for N determination using the steam distillation method. The NH_4^+ adsorption data were fitted to Langmuir and Freundlich isotherms (Table 1).

The linear form of the Langmuir isotherm is reported as:

$$C_e/q_e = C_e/q_m + 1/(q_m K_L)$$

where: C_e is the equilibrium concentration in a liquid phase (mg L^{-1}); q_e is the maximum amount of ions adsorbed at equilibrium (mg g^{-1}); q_m is the maximum theoretical adsorbed amount at equilibrium (mg g^{-1}); K_L is the sorption equilibrium constant (L mg^{-1}).

The linear form of the Freundlich isotherm is reported as:

$$\log(q_e) = \log(K_F) + 1/n \log(C_e)$$

where: C_e is the equilibrium concentration in a liquid phase (mg L^{-1}); q_e is the maximum amount of ions adsorbed at equilibrium (mg g^{-1}); K_F is the Freundlich adsorption capacity; $1/n$ is the sorption constant having a value range between 0 and 1.

Table 1 List of adsorption isotherms models used in this study

Isotherm	Linear Form	Plot	Variables
Langmuir	$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_L q_m}$	$\frac{C_e}{q_e}\ vs. C_e$	$K_L = \frac{slope}{intercept}$ $q_m = slope^{-1}$
Freundlich	$\log(q_e) = \log(K_F) + \frac{1}{n}\log(C_e)$	$\log(q_e)\ vs. \log(C_e)$	$K_F = antilog\ (intercept)$ $\frac{1}{n} = slope$

Note: C_e = equilibrium concentration (mg L^{-1}); q_e = adsorbed NH_4^+ (mg g^{-1}); K_L = Langmuir constant; q_m = maximum adsorption capacity; K_F = Freundlich adsorption coefficient; n = adsorption intensity.

Adsorption–desorption data were analyzed descriptively based on observed trends, as no inferential statistical analysis was conducted. Linear regression was used to examine the relationship between added N concentration and equilibrium solution N, with R^2 values obtained for each equation.

RESULTS AND DISCUSSION

T4 recorded the highest R^2 value before planting and after planting, suggesting that the Langmuir model described NH_4^+ adsorption behavior in this treatment more effectively than in the other treatments tested. The higher K_L value of T4 after planting (0.029851 µg g^{-1}) further indicates stronger apparent N binding affinity under this treatment. However, this interpretation should be limited to the model-fitting results because surface charge, post-planting functional groups, redox condition, and microbial population were not directly measured in this study.

Table 2 Variable from Langmuir isotherm for NH_4^+ adsorption of different treatments before and after planting

Treatment	Regression Equation	R^2	K_L (µg g^{-1})	q_m	MBC (µg g^{-1})
Before planting					
T0	y = 0.0001x + 0.0146	0.5461	0.006849	10000	68.4900
T1	y = 0.00009x + 0.0218	0.4210	0.004128	11111	45.8662
T2	y = 0.0001x + 0.0452	0.4783	0.002212	10000	22.1200
T3	y = 0.0001x + 0.0470	0.2460	0.002128	10000	21.2800
T4	y = 0.0001x + 0.0412	0.7113	0.000141	10000	1.4100
T5	y = 0.0001x + 0.0746	0.4382	0.001340	10000	13.4000
After planting					
T0	y = 0.0001x + 0.0230	0.3712	0.004348	10000	43.4800
T1	y = 0.0001x + 0.0126	0.3830	0.007937	10000	79.3700
T2	y = 0.00003x + 0.0280	0.0180	0.001071	33333	35.6996
T3	y = 0.00008x + 0.0210	0.0179	0.003810	12500	47.6250
T4	y = 0.0002x + 0.0067	0.8467	0.029851	5000	149.2550
T5	y = 0.0001x + 0.0215	0.6783	0.004651	10000	46.5100

Before planting, the Langmuir model showed moderate fit only for T4 (R^2 = 0.7113) and T0 (R^2 = 0.5461), while the remaining treatments recorded lower R^2 values. After planting, T4 showed improved Langmuir fit, whereas T2 and T3 recorded very low R^2 values of 0.0180 and 0.0179, respectively. These values indicate that the Langmuir model was not suitable for explaining NH_4^+ adsorption behavior in T2 and T3 after planting. Such deviations may reflect heterogeneous adsorption surfaces, variable exchange sites, or complex interactions between cocopeat, PLB, TBF, and the cultivated root environment, rather than ideal monolayer adsorption behavior (Song *et al.*, 2024). The relatively stronger Langmuir fit in T4 after planting may be associated with a balanced interaction between PLB and TBF in cocopeat media. Mahdian *et al.* (2025) reported that PLB produced at 500 °C had a porous structure, surface functional groups, and stable carbon-rich properties, while TBF contained higher N, P, and K contents than PLB. These characteristics may have influenced the observed adsorption behavior, although the specific mechanisms were not directly evaluated in the present study. Nevertheless, because the present study did not directly assess post-planting surface chemistry or microbial activity, the role of PLB and TBF should be interpreted as a possible contribution rather than a confirmed mechanism.

Table 3 Variable from Freundlich isotherm for NH_4^+ adsorption of different treatments before and after planting

Treatment	Regression Equation	R^2	K_F (µg g^{-1})	$1/n$
Before planting				
T0	y = 3.37x - 4.3035	0.5872	2.0114E+04	3.3700
T1	y = 2.4465x - 2.8062	0.1842	6.4003E+02	2.4465
T2	y = 3.7033x - 7.0141	0.7120	1.0330E+07	3.7033
T3	y = 4.5503x - 9.0178	0.6496	1.0418E+09	4.5503
T4	y = 2.8266x - 4.6194	0.6143	4.1629E+04	2.8266
T5	y = 3.5861x - 7.012	0.7946	1.0280E+07	3.5861
After planting				
T0	y = 0.3092x + 2.0811	0.0024	1.2053E+02	0.3092
T1	y = 3.2909x - 4.4056	0.2814	2.5445E+04	3.2909
T2	y = 3.0296x - 3.8772	0.1152	7.5370E+03	3.0296
T3	y = 9.6142x - 18.286	0.4758	1.9320E+18	9.6142
T4	y = 2.1855x - 2.2041	0.2630	1.5999E+02	2.1855
T5	y = 1.4199x - 0.8085	0.1404	6.4343	1.4199

The Freundlich isotherm showed that NH_4^+ adsorption was not consistently explained by the Langmuir model. Before planting, T5 recorded the highest Freundlich R^2 value (0.7946), followed by T2 (0.7120) and T3 (0.6496), suggesting heterogeneous adsorption behaviour in these treatments. This may be due to differences in PLB and TBF properties, which create variable adsorption sites in cocopeat media, as biochar pore structure and surface variability can influence adsorption (Skic *et al.*, 2024). After planting, Freundlich model generally showed weaker fit compared with before planting. The highest R^2 was observed in T3 (0.4758), indicating only moderate to weak fit. The exceptionally high K_F value observed in T3 after planting likely reflects instability in parameter estimation caused by poor model fit and should not be interpreted as a realistic adsorption capacity. This is particularly important because isotherm models assume equilibrium conditions, while amended biological media may involve multicomponent interactions and variable adsorption sites (Nworie *et al.*, 2019). Most $1/n$ values were greater than 1, indicating less favourable adsorption under the tested concentration range (He *et al.*, 2023). This suggests that NH_4^+ adsorption in the amended cocopeat media did not follow a simple adsorption pattern across all treatments.

Overall, comparison of the Langmuir and Freundlich models showed that no single isotherm fully described NH_4^+ adsorption across all treatments and sampling stages. The Langmuir model best fitted T4 after planting, suggesting stronger and more predictable NH_4^+ adsorption, whereas the Freundlich model better described T5, T2, and T3 before planting, indicating heterogeneous adsorption behaviour. These findings suggest that N retention in PLB and TBF amended cocopeat was treatment-specific and influenced by amendment ratio and crop cultivation stage. Although Mahdian *et al.* (2025), reported that combined PLB and TBF improved *C. chinense* growth, yield, and nutrient uptake, the present results should be interpreted as model-based evidence of N retention behaviour rather than direct evidence of reduced leaching or improved plant uptake.

Several treatments exhibited relatively low R^2 values (<0.50), particularly T2 and T3 after planting. These results indicate that neither Langmuir nor Freundlich models adequately explained NH_4^+ adsorption behaviour under all amendment combinations. The low coefficients of determination suggest the presence of multiple adsorption mechanisms, heterogeneous adsorption sites, or biological influences that were not captured by the classical isotherm models. Therefore, adsorption parameters derived from poorly fitted models should be interpreted cautiously.

CONCLUSION

This study demonstrated that pineapple leaf biochar (PLB) and *Trichoderma* biofertilizer (TBF) influenced NH_4^+ adsorption-desorption behavior in cocopeat-based fertigation media cultivated with *C. chinense*. The Langmuir model provided the best fit for treatment T4 after planting, suggesting relatively predictable adsorption behavior under balanced PLB and TBF application, whereas the Freundlich model better described several treatments before planting, indicating heterogeneous adsorption surfaces. However, low R^2 values observed in several treatments indicate that classical adsorption models did not fully explain NH_4^+ retention behavior across all amendment combinations. Overall, NH_4^+ retention was treatment-specific and influenced by amendment ratio and cultivation stage. Further studies involving surface chemistry characterization, microbial population analysis, and nutrient leaching assessment are required to confirm the mechanisms governing adsorption-desorption processes in amended cocopeat systems.

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ASSESSMENT OF SOIL QUALITY IN FRUIT ORCHARDS AND AN ARBORETUM USING THE TROPICAL SOIL QUALITY INDEX (TSQI)

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INTRODUCTION

Soil quality is fundamental to the long-term productivity and environmental performance of perennial fruit orchards, yet it is often the first resource to show cumulative effects from decades of cultivation. In tropical orchards, prolonged management typically leads to reductions in soil organic matter and nutrient reserves as well as degradation of soil physical structure. This includes weakened aggregation and lower porosity, especially under intensive traffic and periodic disturbance, unless organic inputs and soil cover strategies are consistently applied. Because these changes occur gradually, managers often lack clear benchmarks to determine when soils have shifted from resilient to constrained conditions or to identify which soil functions most limit orchard performance. Benchmarking orchards against a nearby arboretum helps identify changes in soil functions under perennial fruit production, particularly in humid tropical regions where differences between reference and managed sites often reflect shifts in nutrient cycling and microbial activity. In tropical regions such as Kedah, Malaysia, challenges associated with intensive orchard management pose significant risks to soil sustainability. Addressing these region-specific issues requires a targeted analysis of management practices and their direct effects on soil properties, generating essential data to support both orchard productivity and environmental sustainability. This study assesses soil quality in the selected orchards with arboretum and examines the effectiveness of the Tropical Soil Quality Index (TSQI) in representing the condition and variability of these tropical acidic soils for local soil management and planning. The soil properties show significant differences due to differences in crop type and management practices. The arboretum recorded a higher index score (63.64%) than the fruit orchards (50.00%). The result indicate that orchard soils are progressing toward improved fertility levels, approaching those of the arboretum. The results also confirm that the TSQI is a sensitive and effective tool for assessing soil condition in tropical agroecosystems. The findings will assist MARDI Sintok in selecting appropriate approaches for improved crop management and soil treatment in the future.

MATERIALS AND METHODS

This study used a comparative, field-based design to assess soil quality in long-established tropical fruit orchards relative to a nearby, minimally disturbed forest reference within the same agro-climatic zone. The research was conducted at MARDI Sintok, Kedah, Malaysia (6°29′20″ N, 100°29′03″ E), a 345.6 ha tropical fruit research station located in Agro-climatic Zone 1, which experiences a clear drought season. An undisturbed arboretum area of approximately 20 ha within the station served as the ecological benchmark because it has not been converted for agricultural use since establishment, thereby providing a reference condition for interpreting orchard-associated changes in soil functioning. To improve comparability and limit confounding from stand age, all selected orchards were 25 years old. Orchard types represented key tropical fruit systems cultivated at the site namely *Artocarpus integer* (chempedak), *Mangifera indica* (mango), *Averrhoa carambola* (starfruit), *Durio zibethinus* (durian), and *Garcinia mangostana* (mangosteen).

Each field was divided into nine equal areas according to their own acreage size. From each area, soil was collected at a depth of 0–30 cm using an auger in a zigzag pattern (Arshad and Martin, 2002). Approximately 500 g of the resulting composite sample was retained, placed in a clean plastic bag, and labelled. These samples were then air-dried for 48 hours and stored in polyethylene bags for further analysis. For microbial biomass carbon and microbial biomass nitrogen, fresh soil samples were kept in an ice box at approximately 4 °C and transported to the laboratory for immediate analysis (Gupta, 2007).

The laboratory analyses involve detailed measurements of soil texture, moisture content, pH, nutrient levels, and microbial biomass using established scientific methods. These analyses are designed to meet the requirements of the TSQI. Bulk density was determined using the disturbed soil sample approach described by Gupta (2007). Particle size distribution with emphasis on coarse fragment was measured using the Universal pipette method (Teh and Talib, 2006). Soil acidity was determined using a pH meter following the approach described by Kereen *et al.* (2019). Total carbon and total nitrogen were measured using a CNS analyzer through the dry combustion, enabling determination of soil organic matter proxies and overall nitrogen reserves. Exchangeable base cations (K, Ca, Mg, Na) were extracted using a leaching method with pH 7.0, 1 M ammonium acetate (NH_4OAc) and 0.1 N potassium sulfate (K_2SO_4) (Thomas, 1982). Exchangeable aluminium was determined through 1 M potassium chloride (KCl) extraction (Thomas, 1982). Available phosphorus was determined using the Bray and Kurtz II extraction. Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were estimated using the chloroform fumigation-extraction method (Vance *et al.,* 1987; Wu *et al.*, 1990). For MBC, carbon in extracts was determined using dichromate digestion (Vance *et al.,* 1987), whereas MBN was quantified using an Auto Analyzer (SEAL Analytical, AA500).
The Tropical Soil Quality Index framework by Arifin *et al.* (2012) was used to integrate multiple soil indicators into a single, interpretable measure of soil functioning. Raw TSQI scores were calculated by summing across all indicators and then standardized to a percentage (TSQI %) by dividing by the maximum score (22) and multiplying by 100. This percentage scale was used to assess relative soil functioning, where low TSQI % indicated multiple constraints (e.g. nutrient depletion, acidity, low microbial activity), moderate values reflected partial recovery, and high values signalled favourable soil conditions with most indicators in non-limiting ranges (Arifin *et al.*, 2012; Bodos *et al.*, 2024).

The variables were analysed using analysis of variance (ANOVA) followed by Duncan's Multiple Range Test (DMRT) for mean comparison analysis. All analyses were run in SAS (version 9.4). The soil quality scoring was determined using the TSQI scoring (Arifin *et al.*, 2012).

RESULTS AND DISCUSSION

Table 1 summarizes the comparative analysis of soil physicochemical and biological properties across various orchards such *Artocarpus integer, Mangifera indica, Averrhoa carambola, Durio zibethinus,* and *Garcinia mangostana* including an arboretum using the TSQI scoring. According to Bodos *et al.* (2024), a higher TSQI % indicates better soil quality, as it reflects a greater number of indicators falling within the adequate ranges. A moderate TSQI % (approximately 35–65 %) suggests partial recovery, where some indicators fall within adequate ranges while others remain limiting. The calculated TSQI % in this study show similar findings with Bodos *et al.* (2024) for benchmark indicator although the comparable vegetation are different. The arboretum showed the highest overall performance with a score of 63.64%. This superiority was evident as the arboretum outperformed other land-use types in total carbon, total nitrogen, and exchangeable magnesium content. Other fruit orchards including *Artocarpus integer*, *Mangifera indica*, *Averrhoa carambola*, and *Durio zibethinus*, shared similar scores of 50.00% which indicating comparable soil quality among these management systems. The lower TSQI percentages in fruit orchards relative to the arboretum highlight the challenges associated with intensive agricultural practices in tropical environments. Low levels of soil organic matter in orchard systems may compromise long-term soil fertility and resilience (Lal, 2015).

The physical indicators show that orchard management has caused a lasting structural change compared to the arboretum benchmark, most likely due to compaction and pore alteration from long-term traffic and cultivation. Although bulk density did not differ significantly among orchard species, its consistent elevation above the arboretum level indicates that compaction effects are now widespread across the orchard plots (Table 3). The measured orchard bulk densities (1.31–1.35 g cm^{-3}) align with values typical of managed tropical land uses, whereas native benchmarks, often found in well-structured soils under natural vegetation, tend to range from 0.9 to 1.1 g cm^{-3} (Pinto *et al.*, 2019). This indicates that the structural differences between the arboretum and the orchards represent a long-term equilibrium under management, rather than a temporary condition.

Table 1 Summarizes the scoring of soil physicochemical and biological properties using the Tropical Soil Quality Index (TSQI)

No.	Parameter	Unit	Arboretum	*Artocarpus integer*	*Mangifera indica*	*Averrhoa carambola*	*Durio zibethinus*	*Garcinia mangostana*
1	Bulk density	g cm^{-3}	1	1	1	1	1	1
2	Coarse fragments	%	1	1	1	1	1	1
3	Soil acidity	pH	1	1	1	1	1	1
4	Total carbon in soils	%	1	0	0	0	0	0
5	Total nitrogen in soils	%	1	0	0	0	0	0
6	Exchangeable Na	%	1	1	1	1	1	1
7	Exchangeable K	$cmol^{+} kg^{-1}$	1	1	1	1	1	1
8	Exchangeable Mg	$cmol^{+} kg^{-1}$	1	0	0	0	0	0
9	Exchangeable Ca	$cmol^{+} kg^{-1}$	1	1	1	1	1	1
10	Exchangeable Al	$cmol^{+} kg^{-1}$	1	1	1	1	1	1
11	Available P	mg kg^{-1}	0	0	0	0	0	0
12	Microbial biomass C	µg g^{-1}	2	2	2	2	2	2
13	Microbial biomass N	µg g^{-1}	2	2	2	2	2	2
	Total score		**14**	**11**	**11**	**11**	**11**	**11**
	Percentage (%)		**63.64**	**50.00**	**50.00**	**50.00**	**50.00**	**50.00**

Table 2 The heat map color indicator for the Tropical Soil Quality Index (TSQI)

Description	Very Low Range (Depletion) Score = -1	Low Range (Deficient) Score = 0	Acceptable Range (Sufficient) Score = 1	High Range (Abundance) Score = 2
Color indicator				

Table 3 Comparison of soil physicochemical and biological properties across the study sites.

No.	Soil properties	Unit	Arboretum	*Artocarpus integer*	*Mangifera indica*	*Averrhoa carambola*	*Durio zibethinus*	*Garcinia mangostana*
1	Bulk Density	g/cm^3	1.19 b	1.35 a	1.31 a	1.32 a	1.33 a	1.35 a
2	Organic matter	%	1.76 a	0.70 bc	0.85 b	0.70 bc	0.77 bc	0.64 c
3	Total carbon	%	1.36 a	0.54 bc	0.65 b	0.54 bc	0.59 bc	0.49 c
4	Total nitrogen	%	0.10 a	0.03 b	0.03 b	0.02 b	0.02 b	0.03 b
5	Exchangeable magnesium	$cmol^+/kg$	0.57 a	0.03 c	0.33 b	0.34 b	0.09 c	0.03 c
6	Available phosphorus	mg/kg	1.09 c	2.85 a	2.24 abc	1.83 abc	2.70 ab	1.47 bc
7	Microbial biomass carbon	µg/g	10152.8 c	17104.3 a	14376.3 b	13866.5 b	15016.9 b	14141.5 b

Mean values with different letters indicate a significant difference $p<0.05$ between plots using Duncan's Multiple Range Test (DMRT).

The chemical indicators show that the most significant differences between the arboretum and the orchards occur in fertility variables associated with organic matter, with the magnitude of these differences indicating long-term depletion of soil organic inputs under orchard management. Organic matter in the arboretum (1.76%) was significantly higher approximately two to three times than in orchard soils (0.64–0.85%). A similar trend appears for total carbon (1.36% vs. 0.49–0.65%) and total nitrogen (0.10% vs. 0.02–0.03. These patterns are consistent with a mechanistic explanation in which reduced litter return, removal of pruned materials and biomass export through harvesting gradually lower soil organic inputs compared to forest reference systems (Giweta, 2020). After 25 years, orchard plots still cluster at low carbon and nitrogen levels, indicating that organic inputs have not been sufficient to offset losses from decomposition and cultivation. In contrast, magnesium was sufficient only in the arboretum (0.57 $cmol^+ kg^{-1}$) and deficient in most orchards. The depletion of magnesium aligns with its higher leaching potential in acidic soils (Zuza *et al.,* 2023). Available phosphorus was lowest in the arboretum (1.09 $mg\,kg^{-1}$), while *Artocarpus integer* and *Durio zibethinus* recorded the highest levels (2.85 and 2.70 $mg\,kg^{-1}$, respectively), though all plots remain phosphorus-deficient. This reflects ongoing phosphorus limitation in acidic tropical soils, where phosphorus binds strongly to iron and aluminium oxides. Long-term nitrogen additions can further reduce phosphorus availability by altering soil pH and phosphorus chemistry (Chen *et al.,* 2020). The slightly higher available phosphorus in orchard soils compared to the arboretum hints that fertilizer application has increased extractable phosphorus, but not enough to overcome overall deficiency.

The microbial biomass results differ from the organic matter pattern, indicating that biological function is shaped by more than total carbon content. *Artocarpus integer* recorded the significantly highest microbial biomass carbon (17,104.3 µg g^{-1}) despite having low organic matter, while the arboretum with the highest organic matter showed the lowest MBC (10,152.8 µg g^{-1}). The results indicate that microbial biomass is influenced by substrate quality, disturbance history and nutrient availability, rather than organic matter quantity alone (Zhang *et al.,* 2021).

CONCLUSION

This study concludes that long-term tropical fruit orchard cultivation at MARDI Sintok has produced measurable and persistent shifts in soil quality relative to the undisturbed arboretum benchmark, and that these shifts are expressed most strongly through linked changes in soil structure, organic matter reserves, and nutrient retention capacity. The arboretum showed substantially higher organic matter, total carbon, total nitrogen, and cation exchange compared with orchard plots, supporting the interpretation that intensive orchard practices have reduced organic inputs and weakened soil buffering functions over time. When these indicators were integrated into TSQI scoring, the arboretum achieved a higher score (63.64%) than all orchards (50.00%). The similarity of TSQI scores among the fruit orchards suggests that shared land-use history and management intensity have a greater influence on soil quality. This lower scoring at fruit orchards due to differences in total carbon, total nitrogen, and exchangeable magnesium. This indicates that rebuilding organic matter to boost nutrient retention and fixing magnesium deficiencies are the most effective ways to improve orchard soil health. Collectively, the findings validate the use of TSQI as a practical framework for assessing tropical orchard soil quality at MARDI Sintok and demonstrate that improving organic matter and nutrient retention, while protecting soil structure, is central to sustaining long-term soil function in these orchard systems.

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VARIATION IN FUNGAL FUNCTIONAL GUILD COMPOSITION ACROSS TREE-DOMINATED ZONES IN AN URBAN DIPTEROCARP FOREST

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INTRODUCTION

Fungal communities play a central role in forest soil ecosystems, regulating nutrient cycling, organic matter decomposition, and plant-soil interactions (Li *et al.*, 2022; Frey, 2019). In tropical forests, these roles are particularly pronounced, where ectomycorrhizal (ECM) fungi form symbiotic associations with dominant tree species, influencing nutrient uptake and vegetation dynamics (Corrales *et al.*, 2018). Dipterocarpaceae are among the dominant tropical tree families that depend heavily on ectomycorrhizal symbioses, making fungal community composition closely linked to host tree distribution and diversity. In dipterocarp forests, fungal communities are closely linked to host tree composition, with variations in litter quality, root traits, and substrate availability shaping the distribution of functional guilds such as ectomycorrhizal, saprotrophic, and pathogenic fungi (Adnan *et al.*, 2022; Essene *et al.*, 2017). However, in urban or man-made forests, these relationships may be altered by environmental disturbance, modified microclimates, and designed vegetation structures. Previous studies by Rusterholz and Baur (2023) indicate that urbanization can shift fungal community composition, often reducing symbiotic fungi while increasing saprotrophic and opportunistic groups (Lin *et al.,* 2024). Despite this, most research has focused on broad urban-natural comparisons or abiotic drivers, with limited attention to how variation in tree species composition within a single urban forest influences fungal functional guild distribution. As a result, fine-scale patterns associated with vegetation heterogeneity remain insufficiently explored.

This study therefore investigates variation in fungal functional guild composition across tree-dominated zones within an urban dipterocarp forest and examines how differences in dipterocarp composition influence fungal distribution. By focusing on intra-forest variation rather than large-scale comparisons, this work provides a more localized and functionally oriented perspective on soil fungal ecology, offering insights into how vegetation heterogeneity shapes belowground process in managed tropical forest systems. Because fungal functional guilds regulate complementary ecosystem processes, including nutrient acquisition, decomposition, carbon storage, and forest regeneration, understanding their spatial distribution is essential for sustainable management of urban tropical forests.

MATERIALS AND METHODS

Sampling Site

The study was conducted in an urban dipterocarp forest at Taman Rimba Alam, Putrajaya, Malaysia. A comparative field-based research design was employed to investigate variation in fungal functional guild composition across spatially distinct tree-dominated zones. Four zones (A, B, C, and G) were selected based on differences in vegetation structure and dipterocarp dominance, representing intra-forest variation within a managed forest system.

Vegetation Assessment

Within each zone, dipterocarp genera were recorded based on their relative abundance to characterise vegetation composition. This provided a qualitative comparison of tree dominance and composition across the selected zones.

Fungi Collection and Identification

Macrofungal surveys were conducted monthly between May and October 2025, covering both wet and dry periods. Fungal sporocarps were collected along trail across all zones, including transect-based searches and opportunistic sampling. Each specimen was photographed in situ prior to collection, and a voucher number was assigned for documentation. Relevant ecological information, including substrate type and location, was recorded. Identification was based on macro- and micromorphological characteristics, with representative specimens verified using ITS rDNA sequencing to improve taxonomic accuracy.

Functional Guild Classification

Identified fungal taxa were classified into functional guilds, namely ectomycorrhizal (ECM), saprotrophic, and pathogenic, based on established ecological roles from relevant literature and databases.

Data Analysis

Comparative analysis was conducted to assess variation in fungal functional guild composition across zones. Relative richness and distribution of fungal functional guilds were compared among sampling zones. The analysis focused on identifying trends and spatial patterns in guild dominance across zones.

RESULTS AND DISCUSSION

A total of 76 macrofungal taxa were recorded across four zones (A, B, C, and G), occurring on a range of substrates including soil, dead wood, branches, and decomposed material. Zone C exhibited the highest diversity of fungal taxa, comprising both soil-associated and wood-decaying species such as *Ganoderma*, *Xylaria*, and *Favolus*, indicating a structurally and functionally heterogeneous environment. In contrast, Zone B showed the lowest diversity, with fewer taxa and limited substrate variation, while Zones A and G displayed moderate diversity dominated primarily by soil-associated macrofungi.

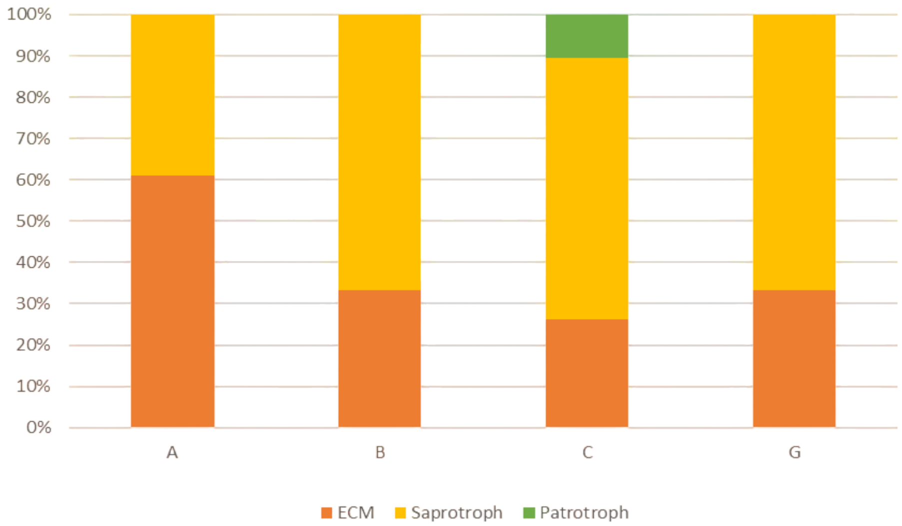

Figure 1 Distribution of macrofungal functional groups across dipterocarp forest zones

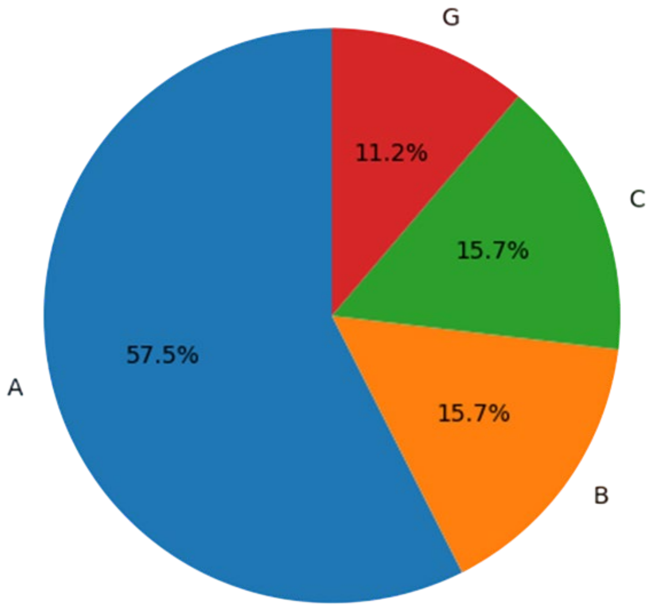

Figure 2. Relative abundance (%) of dipterocarp individuals recorded forest zones

Distinct variation in fungal functional guild distribution was observed across zones. Ectomycorrhizal (ECM) fungi were most abundant in Zone A (11 taxa), followed by Zones C (5) and G (4), and were least represented in Zone B (2) (Figure 1). This pattern is consistent with the ecological dependence of ectomycorrhizal fungi on compatible dipterocarp hosts, suggesting that host availability is a primary driver of fungal functional guild composition across the study zones. Zone A had the highest proportion of dipterocarp individuals (57.5%) consisting of *Anisoptera, Dipterocarpus, Dryobalanops, Hopea*, *Neobalanocarpus, Shorea*, and *Vatica* compared to Zone B (15.7%) of *Anisoptera, Dipterocarpus, Dryobalanops, Hopea*, and *Shorea*; Zone C (15.7%) of *Anisoptera, Anthoshorea*, *Dipterocarpus, Dryobalanops, Hopea, Neobalanocarpus, Rubroshorea*, and *Shorea*; and Zone G (11.2%) of *Dipterocarpus, Hopea, Parashorea,* and *Shorea* (Figure 2). The high ECM representation in Zone A is consistent with recent studies demonstrating that host tree identity and dominance remain primary determinants of ECM community structure, even under modified environmental conditions (Saitta *et al.*, 2017; Ning *et al.*, 2019). These findings reinforce the role of dipterocarp–ECM associations in maintaining symbiotic fungal communities within tropical systems. This pattern likely reflects greater host root availability and carbon allocation to ectomycorrhizal partners in dipterocarp-rich stands, reinforcing host-specific fungal recruitment.

Saprotrophic fungi were dominant in Zone C (12 taxa), followed by Zone G (8), Zone A (7), and Zone B (4), suggesting enhanced decomposition processes in zones with greater substrate diversity. Greater litter accumulation and woody debris likely increased substrate heterogeneity, supporting lignocellulose decomposition and accelerating nutrient recycling. The abundance of decomposed litter and woody debris in Zone C likely supported this pattern. Recent research in urban and semi-natural forests indicates that increased organic inputs and environmental heterogeneity favour saprotrophic fungi (Irfan *et al.*, 2026), which are more adaptable to fluctuating conditions and disturbance (Kovacs & Kovacs, 2025). The coexistence of saprotrophic and ECM fungi in Zone C further suggests that resource availability and vegetation composition jointly influence functional guild distribution at a fine spatial scale.

Pathogenic fungi were recorded only in Zone C (2 taxa), with no occurrence in the other zones. This localized occurrence may reflect environmental stress or reduced ecological stability, conditions that have been linked to increased opportunistic fungal groups in urban ecosystems (Aguilar-Trigueros *et al.*, 2025). Nevertheless, the low incidence of pathogenic fungi suggests that vegetation heterogeneity may contribute to ecological stability by maintaining balanced fungal functional communities. However, the limited presence of pathogenic fungi contrasts with broader findings that urbanization generally increases pathogen prevalence, suggesting that such patterns may not be uniform across all urban forest patches.

The relatively high abundance of ectomycorrhizal (ECM) fungi observed in Zone A contrasts with recent studies reporting a decline in symbiotic fungi in urban environments (Aguilar-Trigueros *et al.*, 2025). This pattern suggests that urban dipterocarp forests may serve as important refugia for ectomycorrhizal fungi, conserving belowground biodiversity despite ongoing urbanization. The elevated ECM richness in Zone A is likely attributable to its high dipterocarp dominance, which provides abundant suitable hosts for host-specific ectomycorrhizal associations. Recent studies have demonstrated that vegetation composition can mitigate the effects of urbanization on soil microbial communities by maintaining functional stability where compatible host plants persist (Liu *et al.*, 2023). Collectively, these findings indicate that host tree composition acts as an ecological filter shaping fungal functional guild assembly, emphasizing that fine-scale vegetation structure, rather than urbanization alone, is a key driver of fungal community dynamics in managed tropical forests.

CONCLUSION

The study shows that variation in dipterocarp composition within an urban forest is associated with differences in fungal functional guild distribution. Zones with higher dipterocarp dominance supported more ectomycorrhizal fungi, while areas with greater substrate diversity favoured saprotrophic groups, indicating the influence of both vegetation and resource availability. Overall, these findings highlight that intra-forest heterogeneity can sustain functional fungal diversity in managed urban forests, emphasizing the importance of vegetation composition in supporting belowground ecological processes. The findings further suggest that conserving dipterocarp-rich patches within urban forests may help preserve ectomycorrhizal biodiversity and sustain ecosystem functions such as nutrient cycling, decomposition, and forest regeneration.

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IDENTIFICATION OF POTENTIAL ACTINOMYCETES FOR NATURAL RUBBER WASTE DEGRADATION THROUGH AGAR OVERLAY AND SHAKE FLASK STUDIES

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INTRODUCTION

Natural rubber (NR), composed mainly of cis-1,4-polyisoprene, is a recalcitrant biopolymer that poses significant environmental challenges due to its resistance to degradation (Yikmis and Steinbüchel, 2012). Actinomycetes are well known for producing a wide range of extracellular enzymes and have increasingly been explored for their ability to degrade rubber (Yikmis and Steinbüchel, 2012; Basik *et al.*, 2021). Microbial degradation of NR is primarily associated with the latex clearing protein (Lcp), which cleaves the polyisoprene backbone into lower molecular weight compounds (Basik *et al.*,, 2021). This study aimed to identify potential rubber-degrading actinomycetes using a combination of agar overlay and shake-flask methods in order to provide both qualitative and quantitative assessments.

MATERIALS AND METHODS

Medium and Growth Condition

Actinomycetes isolates previously obtained from various substations of the Forest Research Institute Malaysia (FRIM) and preserved in the FRIM Microbial Culture Collection (FRIM MCC) were used in this study. The isolates were revived from glycerol stocks maintained at −80°C by rapid thawing at 36°C and inoculated onto freshly prepared International *Streptomyces* Project 2 (ISP 2) agar plates (Hema *et al.*, 2014). The cultures were incubated at 28°C for 5 to 7 days until fully developed actinomycetes colonies were obtained. The revived cultures were subsequently maintained on ISP 2 medium for further experimental analysis.

Qualitative Method (Agar Overlay Screening)

A total of 29 actinomycetes isolates, previously selected through primary screening based on their ability to degrade cis-1,4-polyisoprene, were subjected to secondary screening using the agar overlay technique. In the primary screening, 147 actinomycetes isolates were evaluated using a modified rubber disc assay coupled with Schiff's reagent staining, where purplish colour observed due to aldehyde formation was used as an indicator of rubber degradation. The 29 isolates showing the most prominent colour changes were selected for further evaluation. For secondary screening, a two-layer mineral salts medium (MSM) agar system was prepared. The bottom layer consisted of MSM agar without cis-1,4-polyisoprene, while the upper layer consisted of MSM agar supplemented with 0.5% (w/v) cis-1,4-polyisoprene (Sigma-Aldrich, Cat. No. 429036). After preparation of the two-layer agar plates, the actinomycetes isolates were inoculated onto the surface of the upper layer and incubated at 28 °C for 14 days. Degradation activity was evaluated based on the formation of halo zones around the growing colonies (Chairat *et al.*, 2018) and microscopic observation of interactions between the mycelia and polyisoprene particles.

Quantitative Method (Degradation of Latex Glove Piece)

The same 29 actinomycetes isolates were further cultivated on ISP 2 agar at 28 °C for 8 days. A seed culture was prepared in 125 mL shake flasks by inoculating a 6 mm agar plug from each selected isolate into 20 mL of mineral salts medium (MSM). The flasks were incubated in a rotary shaker at 200 rpm and 28 °C for 6 days. The inoculum was standardised based on culture age and inoculum volume, as cell density was not measured in this study. For the rubber degradation assay, commercial disposable rubber gloves obtained from a single batch were used as the rubber substrate. The gloves represented a mixed rubber substrate containing natural rubber components together with synthetic rubber components, in contrast to the pure cis-1,4-polyisoprene substrate used during primary screening. This approach was used to evaluate the degradation ability of selected actinomycetes towards a more complex rubber material compared with pure cis-1,4-polyisoprene. The glove material was cut into pieces with similar surface areas, with an initial dry weight ranging from 7 to 9 mg. The latex pieces were washed thoroughly with distilled water, dried to constant weight, and weighed prior to sterilisation. The sterilised rubber pieces were aseptically transferred into conical flasks containing 20 mL of MSM, and each flask was inoculated with 1 mL of the respective seed culture. The flasks were covered with breathable closures to allow gas exchange while minimising contamination. The cultures were incubated at 28 °C under shaking conditions at 200 rpm for 6 weeks, followed by an additional 2 weeks of static incubation at the same temperature. A non-inoculated MSM containing sterilised rubber pieces was maintained as an abiotic control. After 8 weeks of incubation, the rubber pieces were recovered from the fermentation medium and washed thoroughly with distilled water to remove attached biomass and residual medium components. The washed rubber pieces were subsequently dried to constant weight, and the residual rubber weight was measured. Rubber degradation efficiency was determined based on percentage weight loss using the following equation:

Rubber weight loss (%) = 100 × (initial rubber weight minus residual rubber weight after incubation) / initial rubber weight.

Molecular Characterisation

Following the rubber degradation assay, seven selected actinomycetes isolates exhibiting the highest rubber degradation efficiency were subjected to molecular identification. The selection of these isolates was based on their superior degradation performance, determined by the percentage weight loss of rubber pieces after the 8-week incubation period. Genomic DNA was extracted using PrepMan Ultra sample preparation reagent according to the manufacturer's protocol. The 16S rRNA gene was amplified and sequenced as described by Kim *et al.* (1998). Polymerase chain reaction (PCR) amplification was performed using the universal bacterial primers 27F (5′-AGAGTTTGATCMTGGCTCAG-3′) and 1492R (5′-TACGGYTACCTTGTTACGACTT-3′), targeting approximately 1.5 kb of the 16S rRNA gene region. The obtained 16S rRNA gene sequences were analysed using the BLASTn programme available through the National Center for Biotechnology Information (NCBI) website (https://blast.ncbi.nlm.nih.gov/Blast.cgi). Sequence similarity searches were performed against the NCBI nucleotide (nr/nt) database to identify closely related actinomycetes reference sequences. The taxonomic identification of the selected isolates was validated based on the highest sequence similarity with closely related actinomycetes reference strains.

RESULTS AND DISCUSSION

None of the 29 selected actinomycetes isolates produced visible halo zones on MSM agar supplemented with 0.5% (w/v) cis-1,4-polyisoprene (Figure 1). However, the absence of visible clearing zones may not accurately reflect the degradation potential of the isolates, as halo formation is influenced by both microbial characteristics and assay conditions. The formation of clearing zones depends on factors such as extracellular enzyme production, enzyme diffusion through the agar matrix, accessibility of insoluble rubber particles, and utilisation of degradation products by microbial cells (Yikmis and Steinbüchel, 2012; Rose *et al.*, 2005). Since cis-1,4-polyisoprene is a hydrophobic and insoluble polymer, limited dispersion of rubber particles in the agar medium may reduce enzyme–substrate interactions and restrict halo formation. Furthermore, some rubber-degrading microorganisms exhibit adhesive growth on rubber surfaces, where degradation occurs through close microbial–substrate association rather than extensive diffusion of enzymes. Therefore, agar overlay screening should be considered a preliminary assessment method rather than a definitive measure of rubber degradation capability. Microscopic observation showed that 12 isolates formed clustered mycelial structures surrounding polyisoprene particles (Figure 2), indicating close physical interaction with the rubber substrate. Structural interaction was defined by visible attachment and aggregation of actinomycetes mycelia around polyisoprene particles. These observations provided supportive evidence of rubber-associating ability and guided the selection of isolates for subsequent quantitative degradation assessment. However, the observed structural interaction was considered only as supportive evidence of microbial–rubber association, while degradation capability was confirmed through quantitative measurement of rubber weight loss in the shake-flask assay. Such microbial attachment may facilitate access to extracellular oxidative enzymes involved in natural rubber degradation, including latex clearing protein (Lcp), which initiates oxidative cleavage of the polyisoprene backbone and produces lower molecular weight degradation products (Yikmis and Steinbüchel, 2012; Bode *et al.*, 2000).

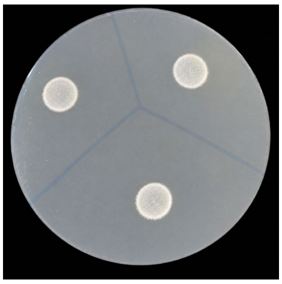

Figure 1 Actinomycetes isolates spotted on MSM agar plates showing no halo zone formation

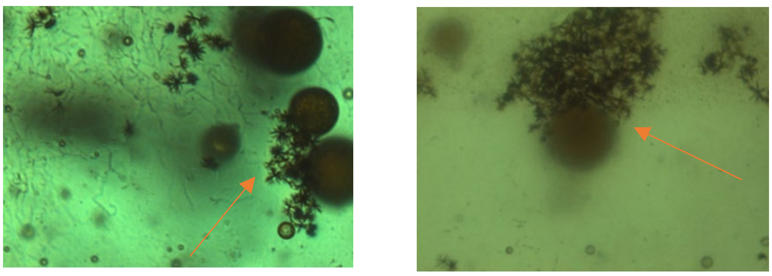

Figure 2 Clustered mycelial structures surrounding polyisoprene particles in MSM agar observed under light microscope (x100)

The weight loss of latex glove pieces after incubation is shown in Table 1. Following an 8-week incubation period, seven out of 29 actinomycetes isolates demonstrated measurable degradation of latex glove pieces, with weight loss ranging from 14.5% to 35% (Table 1). In contrast, the non-inoculated control exhibited only 0.36% weight loss, indicating minimal abiotic changes during the incubation period. During incubation, growth of actinomycetes cells was observed on the surface of the latex glove pieces, indicating microbial attachment and colonisation. The variation among isolates indicates that rubber degradation is strain dependent and may be influenced by differences in rubber-degrading enzyme activity, microbial attachment, and adaptation towards polyisoprene utilisation (Yikmis and Steinbüchel, 2012; Bode *et al.*, 2000). Visible black spots were observed on some latex glove pieces after incubation (Figure 3), indicating microbial colonisation rather than direct evidence of rubber degradation. Therefore, degradation efficiency was evaluated primarily based on quantitative rubber weight loss.

Table 1 Rubber degradation percentages using a combination of continuous shaking and static growing conditions

Working condition	**6 weeks shaking + 2 weeks static**					
Isolates	**Replicate Flasks**	**Initial Weight**	**Final Weight**	**Weight reduction [initial-final weight]**	**Rubber degradation (%)**	**Rubber degradation (Average) (%)**
TY052-057	1	9.0	6.2	2.8	31.11	27.12
	2	8.2	6.3	1.9	23.17	
	3	9.6	7.0	2.6	27.08	
TY052-053	1	8.2	7.0	1.2	14.63	17.23
	2	8.5	7.0	1.5	17.65	
	3	8.9	7.2	1.7	19.4	
TY053-050	1	8.2	6.6	1.6	19.51	16.4
	2	9.7	8.2	1.5	15.46	
	3	8.4	7.2	1.2	14.23	
TY052-059	1	9.7	7.1	2.6	26.8	25.94
	2	9.3	7.0	2.3	24.7	
	3	9.5	7.0	2.5	26.32	
TY053-047	1	9.7	7.6	2.1	21.65	21.47
	2	8.6	6.9	1.7	19.77	
	3	8.7	6.7	2.0	22.99	
TY032-061	1	9.3	7.9	1.4	15.05	14.77
	2	10.0	8.4	1.6	16	
	3	8.3	7.2	1.1	13.25	
TY049-069	1	8.0	4.9	3.1	38.75	35.12
	2	9.1	6.0	3.1	34.07	
	3	8.3	5.6	2.7	32.5	
Control	1	9.2	9.1	0.1	1.09	0.36
	2	8.9	8.9	0	0	
	3	8.5	8.5	0	0	

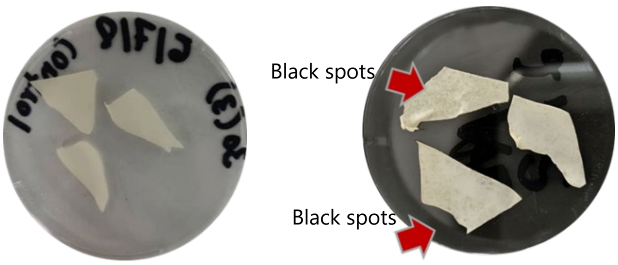

Figure 3 The morphological differences in rubber pieces treated with isolates of different actinomycetes compared to the control

Molecular identification based on partial 16S rRNA gene sequencing assigned the seven selected isolates to closely related actinomycetes taxa, including *Streptomyces gelaticus*, *Actinomadura nitritigenes*, *Nonomuraea aurantiaca*, *Micromonospora yasonensis*, *Nocardia aurantia*, *Streptomyces lannensis*, and *Streptomyces nodosus* (Table 2). Among these, TY049-069 closely related to *Streptomyces gelaticus,* exhibited the highest degradation efficiency (35.12%). Its degradation efficiency was lower than that reported by Tsuchii *et al.* (1996) for a Nocardia strain. However, direct comparison should be interpreted cautiously due to differences in microbial genus and experimental conditions. The previous study used a rubber adapted pre culture and inoculum standardisation based on viable cell numbers, whereas the present study used seed cultures without prior rubber exposure and standardised the inoculum based on culture age and volume. The lack of viable cell enumeration represents a limitation, as differences in cell density and viability among isolates may influence degradation performance. Future studies should include viable cell analysis and microbial growth monitoring during degradation assays.

Table 2 Molecular identification of rubber-degrading actinomycetes isolates based on 16S rRNA gene sequence analysis

Isolates code	Molecular Identification (Reference Strain)	Accession Number	Percentage of similarity (%)
TY052-057	*Actinomadura nitritigenes*	NR_112736.1	99.86
TY052-053	*Nocardia aurantia*	NR_179112.1	99.66
TY053-050	*Streptomyces lannensis*	NR_113181.1	100
TY052-059	*Nonomuraea aurantiaca*	NR_181877.1	98.99
TY053-047	*Micromonospora yasonensis*	NR_149817.1	99.31
TY032-061	*Streptomyces nodosus*	NR_112324.1	99.78
TY049-069	*Streptomyces gelaticus*	NR_112308.1	99.41

CONCLUSION

This study identified seven actinomycetes isolates with promising natural rubber-degrading potential based on their ability to reduce the weight of latex glove pieces after incubation. The absence of halo formation in the agar overlay assay demonstrated the limitation of relying solely on qualitative clearing-zone observations for assessing rubber degradation potential. Although no visible halo zones were detected, microscopic observations provided supportive evidence of microbial attachment and interaction with polyisoprene particles, while quantitative rubber weight loss analysis confirmed degradation capability. Among the identified isolates, TY049-069 closely related to *Streptomyces gelaticus,* exhibited the highest degradation efficiency (35.12%). These findings highlight the potential of actinomycetes for rubber waste biodegradation. However, further studies involving viable cell monitoring, optimisation of degradation conditions, and characterisation of rubber-degrading enzymes are required to better understand and enhance the degradation process.

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EFFECTS OF SOIL MOUNDING ON ROOT DEVELOPMENT AND ROOT NUTRIENT CONTENT IN OIL PALM CULTIVATED ON PEAT SOILS OF MALAYSIA

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INTRODUCTION

Oil palm cultivation in Malaysia covers approximately 5.6 million hectares (MPOB, 2023), with a significant proportion established on peat soils. Of the total planted area, approximately 2.6 million hectares are located on peat which is characterized by low bulk density, high organic matter content and high-water retention capacity (Paramanathan, 2013). These properties create an unstable growing environment that limits root development and weakens root anchorage in oil palm.

The poor structural stability of peat soils results in shallow and poorly distributed root systems due to root displacement. This condition restricts the ability of roots to absorb water and nutrients efficiently, thereby reducing physiological performance including photosynthesis (Nursyamsi, Noor, & Maftu'ah, 2016). Weak root anchorage also increases the risk of palm leaning and lodging, which disrupts canopy structure and reduces productivity. In addition, acidic conditions, waterlogging and weak soil structure further constrain root growth and function (Kanang & Mohidin, 2026).

Soil mounding is widely considered a promising agronomic practice to improve root zone conditions and support root development in peat-based oil palm cultivation. By increasing soil bulk density around the root zone, it enhances mechanical support and encourages deeper and more extensive root growth. Many studies and field observations suggest that soil mounding improves nutrient uptake efficiency and overall plant stability under challenging soil conditions (Sale *et al.*, 2021). However, despite these positive indications, detailed and systematic studies specifically focusing on its direct effects on root development and root nutrient content remain limited.

Soil mounding is also reported to reduce land subsidence and improve soil aeration both of which are important for maintaining healthy root function. Nevertheless, more in-depth research is still required to clearly understand the underlying mechanisms and quantify its effects on root system development in peat soils. Given the critical role of roots in nutrient uptake and plant stability, this study evaluates the effects of soil mounding on root development and root nutrient content in oil palm cultivated on peat soils.

MATERIALS AND METHODS

The study was conducted at PKPP Warisan Sabak estate, Rompin, Pahang, a 1,710.80 ha oil palm plantation on deep peat soil (Terric Histosol; 150–250 cm) with an average annual rainfall of 2,200–2,300 mm (2014–2024). Two 12-year-old oil palm blocks were selected: Block 2A as the control (98.76 ha) and Block 2D as the soil mounding treatment (76.30 ha). Both blocks experienced severe palm leaning (70–80%, <45°) and declining FFB yield and were similar in terms of palm age, low yield (≤18 t ha^{-1}), peat characteristics, water table level, field elevation and management practices.

Soil mounding was applied in Block 2D by piling excavated peat around each palm base, forming mounds approximately 90 cm high and 180 cm wide using a mini excavator between June and December 2022. A comparative field trial was established with five replicates per block, each consisting of 10 recording palms to evaluate treatment effects under comparable field conditions.

Root sampling was conducted every 3 months using destructive sampling to a soil depth of 0–45 cm within the active root zone (Figure 1). Samples were collected from each recording palm using a 30 cm × 30 cm × 45 cm quadrat positioned 1 m from the palm base. Root samples were taken at three soil depths (0–15 cm, 15–30 cm and 30–45 cm) at a distance of 1 m from the palm base.

The collected roots were washed free of soil, oven-dried and submitted for laboratory analysis to determine nutrient concentrations of nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) at each depth. Root morphology and distribution were then analyzed using a root scanner with WinRHIZO software. Data was analyzed using SPSS version 27. ANOVA was used to test differences between treatments and mean separation was done using Duncan's Multiple Range Test (DMRT) at $p < 0.05$.

Figure 1 Destructive root sampling in the soil profile from 0 to 45 centimeters.

RESULT AND DISCUSSION

Root Development

Results from Table 1 showed the soil mounding (T1) significantly enhanced oil palm root distribution compared to the control (T0), particularly in terms of root elongation and branching intensity. Root length increased significantly from 805.12 ± 62.10 cm (T0) to 963.10 ± 55.32 cm (T1) ($F = 8.45, p < 0.05$) indicating improved axial root growth under mounded conditions. Similarly, root branching parameters showed significant improvements under T1. The number of root tips increased from 2208.95 ± 142.33 (T0) to 3014.47 ± 168.25 (T1) ($F = 9.12, p <$

0.05), while root forks increased from 3766.25 ± 221.54 to 4755.87 ± 248.11 ($F = 7.88, p < 0.05$).

The number of crossings also rose significantly from 310.98 ± 21.44 (T0) to 437.80 ± 24.66 (T1) ($F = 8.01, p < 0.05$) reflecting a more complex and highly branched root system architecture under soil mounding (T1). In contrast, no significant differences (p > 0.05) were observed for projected area, surface area, estimated and measured root volume and average root diameter. For instance, projected area remained statistically similar between treatments (80.74 ± 5.12 cm^2 in T0 and 73.97 ± 6.03 cm^2 in T1), while measured root volume decreased slightly from 14.38 ± 1.02 cm^3 (T0) to 12.67 ± 1.15 cm^3 (T1) without statistical significance.

Average measured diameter also declined from 1.03 ± 0.05 mm (T0) to 0.78 ± 0.06 mm (T1), indicating a tendency towards finer roots under T1. No nodulation was recorded in both treatments (0.00 ± 0.00).

Table 1 Oil Palm Root Distribution by Soil Depth (T0 vs T1)

Parameter	T0 (Control)	T1 (Soil mounding)	F-value	P-value	CV (%)
Length (cm)	805.12 ± 62.10^b	963.10 ± 55.32^a	8.45	*	7.8
Projected area (cm^2)	80.74 ± 5.12^a	73.97 ± 6.03^a	1.12	ns	6.9
Surface area (cm^2)	253.66 ± 14.88^a	232.37 ± 16.21^a	1.54	ns	6.2
Volume estimated (cm^3)	7.63 ± 0.52^a	7.01 ± 0.61^a	0.98	ns	7.4
Volume measured (cm^3)	14.38 ± 1.02^a	12.67 ± 1.15^a	1.33	ns	8.1
Avg diameter estimated (mm)	1.15 ± 0.06^a	0.90 ± 0.07^a	2.21	ns	6.5
Avg diameter measured (mm)	1.03 ± 0.05^a	0.78 ± 0.06^a	2.64	ns	7.2
Number of tips	2208.95 ± 142.33^b	3014.47 ± 168.25^a	9.12	*	7.6
Number of forks	3766.25 ± 221.54^b	4755.87 ± 248.11^a	7.88	*	6.9
Number of crossings	310.98 ± 21.44^b	437.80 ± 24.66^a	8.01	*	7.3
Number of nodules	0.00 ± 0.00^a	0.00 ± 0.00^a	–	ns	–

Values are presented as mean ± standard error (SE). Means followed by different superscript letters within the same row indicate significant differences between treatments according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. CV = coefficient of variation.

Figure 2 illustrates oil palm root distribution across three soil depths (0–15 cm, 15–30 cm and 30–45 cm) under T0 (no mounding) and T1 (soil mounding) treatments as analyzed using WinRHIZO software. The results show that root density under T0 is relatively low and predominantly concentrated in the upper soil layer with limited root penetration into deeper layers (30–45 cm).

In contrast, T1 exhibits a higher root density with a more uniform vertical distribution across all soil depths. Root proliferation is more extensive not only in the surface layer but also in the 15–30 cm and 30–45 cm zones, indicating improved root penetration and spatial distribution. Overall, soil mounding enhances oil palm root development by increasing root density and promoting deeper and more uniform root distribution within the soil profile.

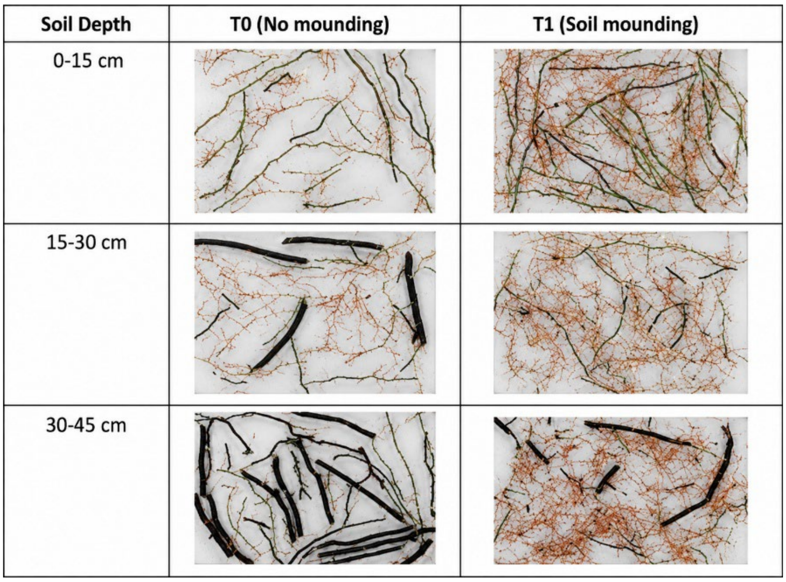

Figure 2 Root distribution at different soil depth using WinRHIZO software.

Root Nutrient Content
Treatment T1 consistently enhanced root nutrient concentrations relative to T0 across the 0–45 cm soil profile. Nitrogen under T1 ranged from 1.15–1.21% (maximum at 0–15 cm: 1.21 ± 0.10%) exceeding T0 values of 0.85–0.90% with a gradual decline observed with increasing depth. Phosphorus exhibited a similar trend with T1 recording 0.046–0.053% compared to T0 (0.031–0.042%) and peak accumulation at 0–15 cm (0.053 ± 0.009%) indicating greater availability and uptake in the surface soil horizon. Potassium concentrations were also higher under T1 (0.20–0.25%) than T0 (0.15–0.16%) particularly within the 0–30 cm layer, reflecting the influence of active root zones on potassium acquisition.

In contrast, magnesium concentrations remained relatively invariant between treatments, ranging from 0.07–0.08% across all depths suggesting a limited treatment effect likely due to strong adsorption within the soil matrix (Brady & Weil, 2016; Sparks, 2003). Overall, nutrient concentrations (N, P and K) were highest in the 0–15 cm layer and decreased with depth, consistent with greater root activity and nutrient cycling in the upper soil layer. These results suggest that soil mounding (T1) improved the rhizosphere environment by creating more favourable soil conditions for root activity, thereby supporting nutrient availability and enhancing nutrient uptake efficiency compared with the control (T0) (Brady & Weil, 2016).

Table 2 Root nutrient content over a 12-month period after treatment was applied

Treatment	Soil Depth (cm)	N (%)	P (%)	K (%)	Mg (%)
T0	0–15	0.90 ± 0.09c	0.042 ± 0.007b	0.15 ± 0.02c	0.07 ± 0.02a
	15–30	0.87 ± 0.09c	0.039 ± 0.006b	0.15 ± 0.02c	0.07 ± 0.02a
	30–45	0.85 ± 0.07c	0.031 ± 0.005c	0.16 ± 0.02c	0.07 ± 0.02a
T1	0–15	1.21 ± 0.10a	0.053 ± 0.009a	0.25 ± 0.05a	0.08 ± 0.02a
	15–30	1.18 ± 0.07ab	0.049 ± 0.008a	0.25 ± 0.05a	0.08 ± 0.02a
	30–45	1.15 ± 0.09b	0.046 ± 0.007ab	0.20 ± 0.03b	0.08 ± 0.02a

Means followed by different superscript letters within the same treatment across soil depths are significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

CONCLUSION

Soil mounding in oil palm cultivated on peat soil improves root zone stability particularly in environments prone to low fertility and structural limitations. This practice enhances soil aeration and root anchorage thereby supporting more effective oil palm root system development. As a result, root growth is improved and nutrient uptake efficiency is enhanced which is clearly reflected in higher root nutrient content. These findings indicate that soil mounding creates a more favorable rhizosphere environment for oil palm on peat soil leading to better root development and improved accumulation of essential nutrients within the roots.

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ASSESSMENT OF OIL PALM FROND BIOMASS REMOVAL ON SOIL NUTRIENT DYNAMICS AND OIL PALM PRODUCTIVITY

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INTRODUCTION

Oil palm cultivation generates substantial quantities of biomass residues throughout its production cycle, including Empty Fruit Bunches (EFB), Palm Oil Mill Effluent (POME), Oil Palm Trunks (OPT), and Oil Palm–Pruned Fronds (OPF) (Pulingam *et al.*, 2022). Among these, OPF is the most abundant plantation biomass, accounting for approximately 50–70% of total field residues generated through routine pruning, with annual production estimated at 8.3–15.6 t ha^{-1} yr^{-1} (Zakaria *et al.*, 2024). Malaysia and Indonesia collectively contribute more than 85% of global palm oil production, resulting in continuous generation of large volumes of biomass residues that require sustainable management strategies (Zakaria *et al.*, 2024). Due to its abundance and continuous production, OPF has become an important biomass resource in sustainable oil palm production systems.

Traditionally, oil palm biomass residues were treated as waste and commonly disposed of through open burning or unmanaged decomposition, contributing to greenhouse gas emissions and environmental degradation. However, increasing emphasis on sustainability and circular economy approaches has shifted the perception of oil palm biomass toward valuable renewable resources (Yeo *et al.*, 2020). Residues such as EFB and POME have been widely explored for biochar, compost, and biogas production, while OPF has gained attention for applications in bioenergy, fibre products, timber substitutes, and animal feed. In addition, retaining and recycling OPF within plantations as an organic nutrient source offers a sustainable alternative to conventional fertilisation, helping to recycle nutrients, maintain soil health, and reduce the risk of soil degradation (Harefa *et al.* 2024). Beyond its role in plantations, OPF has also shown potential as a soil amendment for the remediation of crude oil-contaminated soils by reducing contaminant levels while improving soil pH, moisture content, and total organic carbon (Kingdom *et al.* 2025).

Despite the growing demand for oil palm biomass utilization, excessive residue removal may lead to nutrient depletion and deterioration of soil quality. Retaining pruned fronds within the plantation contributes to nutrient recycling, soil organic matter accumulation, improved soil structure, moisture retention, and reduced runoff and erosion. Conversely, excessive biomass removal may increase dependency on inorganic fertilisers to sustain productivity. Therefore, this study was conducted to evaluate the effects of different frond removal intensities on oil palm productivity and soil nutrient dynamics, with the aim of determining the optimum level of frond removal that can be sustained without adversely affecting yield performance, soil fertility, and long-term plantation sustainability.

MATERIALS AND METHODS

The study was conducted using a randomized complete block design (RCBD) to evaluate the effects of varying levels of oil palm pruned frond removal on oil palm productivity and soil nutrient dynamics at Keratong, Pahang, covering approximately 28 ha. The planting material used was DxP oil palm established on Bungor and Renggam soil series. The experimental site was an oil palm plantation established in 2011, with a planting density of 138 palms ha^{-1}. The mean annual rainfall recorded at the site during the study period (2021–2026) was 1,569.41 mm. Prior to the establishment of the experiment, the area was managed under normal estate practices (NEP), including standard plantation management and fertilisation practices. Five treatments with six replicates were arranged, resulting in 30 experimental plots. Prior to treatment initiation, all existing stacked fronds within the trial plots were removed to standardize field conditions.

The treatments consisted of different levels of pruned frond removal: T1: 0% removal (normal estate practice/control), T2: 25% removal, T3: 50% removal, T4: 75% removal, and T5: 100% removal of pruned fronds from the plantation. For partial retention treatments, remaining fronds were uniformly stacked along designated frond piles. All plots received standard fertiliser management using compound fertiliser at rates ranging from 6 to 10 kg $palm^{-1}$ $year^{-1}$, applied in three split applications depending on palm age. Foliar nutrient analysis was conducted twice yearly using central leaflets sampled from frond 17.

Pre-treatment soil samples were collected once before the commencement of the experiment using a screw auger from the palm circle, frond pile, and avenue at depths of 0–15 cm, 15–30 cm, and 30–60 cm. Soil samples were analysed for pH, macro, and micronutrients. Yield data were recorded from the designated palms at every harvesting round (approximately every 10–15 days), including fresh fruit bunches, bunch number and bunch weight.

Data was analysed to evaluate the effects of frond removal on oil palm growth, yield, and soil properties. Descriptive statistics were used to summarise treatment trends, while a linear mixed-effects model (LMM) was applied to assess treatment effects over time. The use of LMM was appropriate due to the longitudinal nature of the dataset (2021–2025), where repeated observations are not statistically independent. Where significant effects were detected, post-hoc mean comparisons were conducted, and estimated marginal means (EM Means) were used for interpretation and graphical presentation. All statistical analyses were performed using IBM SPSS Statistics version 29 (IBM Corp.), and model assumptions were verified prior to analysis.

RESULTS AND DISCUSSION

For average bunch weight (ABWT), the linear mixed model showed a significant effect of frond removal treatment ($p < 0.001$), while the Treatment × Year interaction was not significant ($p = 0.409$), indicating consistent treatment effects across years. Pairwise comparisons revealed significant differences between T3 and T4, and T4 and T5, with T3 recording the highest ABWT (20.463 kg) (Figure 1). This suggests that moderate frond removal may improve bunch weight relative to other treatments, possibly due to a balance between residue retention and reduced field competition or harvesting interference. Similar observations on the importance of residue management in influencing palm growth and nutrient dynamics have been reported by Khalid *et al.* (2000a, 2000c).

For average bunch number (ABNO), treatment significantly affected bunch production ($p = 0.016$), while the Treatment × Year interaction was not significant, indicating stable treatment responses over time. The Year effect was significant, likely reflecting environmental variation such as rainfall distribution, nutrient availability, and palm physiological cycles. Pairwise comparison showed a significant difference between T1 and T2, with T1 (0% removal; normal estate practice) recording the highest ABNO (10.837), suggesting that full frond retention may support higher bunch production through greater photosynthetic capacity and assimilate supply. Retained fronds also contribute to nutrient recycling and soil organic matter accumulation, which may improve long-term palm performance (Khalid *et al.*, 2000b; Khalid *et al.*, 2000c).

In contrast, fresh fruit bunch (FFB) yield (Figure 2) was significantly affected by Year ($p < 0.001$), but neither treatment ($p = 0.067$) nor the Treatment × Year interaction ($p = 0.695$) was significant. This indicates that overall FFB yield remained comparable across frond removal treatments despite differences in ABWT and ABNO. The absence of significant yield differences suggests a compensatory effect, where increases in bunch weight may be offset by reductions in bunch number. Soil chemical properties, including pH, macro- and micronutrient concentrations, as well as foliar nutrient concentrations, remained statistically comparable across treatments. These findings suggest that the fertiliser regime was sufficient to compensate for potential nutrient losses associated with frond removal, thereby maintaining overall soil fertility and plant nutrient status. Previous studies have shown that oil palm residues contribute substantially to nutrient cycling through decomposition and nutrient release processes (Khalid *et al.*, 2000b), while effective fertiliser management can compensate for nutrient export associated with biomass removal (Khalid *et al.*, 2000a). Furthermore, the uniform application of inorganic fertilisers across all plots likely minimized nutrient limitations and reduced the overall impact of frond removal on total yield. Overall, the findings indicate that frond removal intensity influences specific yield components, but its effect on total productivity is limited under adequate nutrient management conditions.

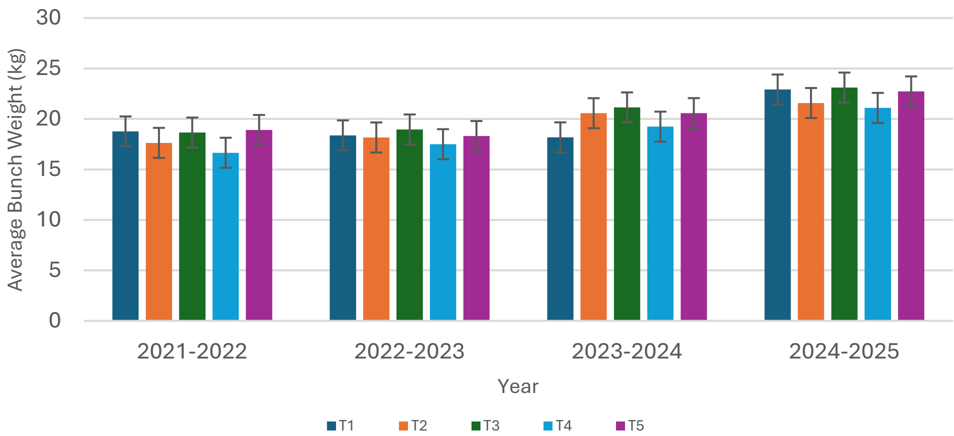

Figure 1 Average Bunch Weight (kg) under different levels of pruned frond removal from 2021–2025. Treatments consisted of T1: 0% removal (normal estate practice/control), T2: 25% removal, T3: 50% removal, T4: 75% removal, and T5: 100% removal of pruned fronds from the plantation. Error bars represent standard error of the mean.

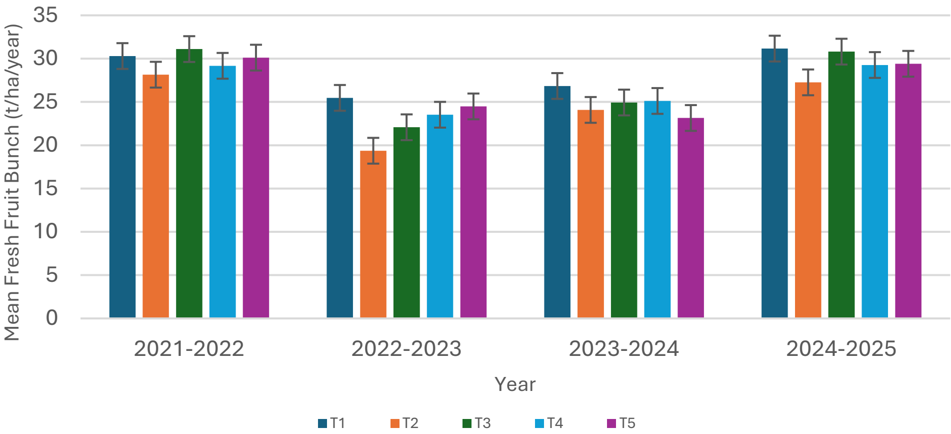

Figure 2 Mean fresh fruit bunch (FFB) yield (t ha^{-1} $year^{-1}$) under different levels of pruned frond removal from 2021–2025. Treatments consisted of T1: 0% removal (normal estate practice/control), T2: 25% removal, T3: 50% removal, T4: 75% removal, and T5: 100% removal of pruned fronds from the plantation. Error bars represent standard error of the mean.

CONCLUSION

Overall, moderate frond removal affected some yield components but did not significantly reduce overall FFB yield under standard fertiliser management. Soil nutrient status also remained stable across treatments throughout the study period. However, continued long-term monitoring is needed to assess the sustainability of different frond removal intensities.

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EFFECT OF RAINFALL INTENSITY ON PHOSPHORUS AVAILABILITY IN A BLACK PEPPER PLANTATION ON BEKENU SOIL, SARAWAK

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INTRODUCTION

Black pepper (*Piper nigrum* L.) in Sarawak is commonly cultivated on sloping land. Under tropical rainfall conditions, these areas are susceptible to surface runoff, soil particle movement, and nutrient redistribution. These processes may influence nutrient availability, particularly in young plantations where soil cover is limited and the soil surface remains exposed.

Bekenu soil series is commonly associated with sandy soil conditions, which have lower nutrient retention capacity compared with finer-textured soils (Paramananthan, 2000). In sandy soils, rainfall intensity may influence nutrient movement through surface processes, especially where land conservation practices are limited. Although phosphorus (P) is generally less mobile than nitrogen (N) in soil solution, it may still be affected by surface mobilisation, sediment-associated transport, and redistribution along slope positions.

Previous studies on black pepper soils have reported variation in nutrient availability under different crop ages, rainfall conditions, and spatial positions in hilly topography (Izzah and Wan Asrina, 2018; Izzah *et al.*, 2022; Izzah *et al.*, 2023). However, field-based evidence on rainfall intensity effects on P availability in sandy black pepper soils remains limited. Therefore, this study evaluated the effect of rainfall intensity on selected soil properties in a black pepper plantation on Bekenu soil series in Samarakan, Bintulu, Sarawak.

MATERIALS AND METHODS

Study Area

The study was conducted in a black pepper plantation located in Samarakan, Bintulu, Sarawak, Malaysia. The study area covered approximately 0.30 ha within a 1.50 ha farm. The plantation had been used for black pepper cultivation for more than 10 years. The study plot consisted of approximately 120 black pepper plants of the *Uthirancotta* cultivar, aged about 16 months, with a planting distance of 2.1 m × 1.8 m. The study site was located on sloping terrain with an average slope of approximately 26°. The farmer's current management practice was maintained during the study. However, the site had exposed soil surface conditions, limited soil cover, and limited land conservation structures. The soil was identified as Bekenu soil series and classified as sandy loam based on the USDA textural triangle, with sand content exceeding 76%.

Soil Sampling and Rainfall Event Selection

Rainfall was monitored using an on-site rain gauge and events lasting more than 60 minutes were considered for post-rainfall soil sampling. Soil sampling was conducted within 12 hours after each selected rainfall event to capture short-term post-rainfall changes in soil properties. Three rainfall intensities were selected to represent low, moderate, and high rainfall conditions:

Low rainfall intensity: 3.30 mm/hr, Moderate rainfall intensity: 13.80 mm/hr, and High rainfall intensity: 21.30 mm/hr. Soil samples were collected from three slope positions, namely upper, middle, and lower slope. For each rainfall intensity, eight replicates were collected from each slope position.

Soil Analysis

Soil pH was determined in water with a ratio of soil to liquid ratio of 1:2 (Tan, 2011). Organic matter (OM) was determined using the loss-on-ignition method (Sutherland, 1998). Soil texture was determined using the hydrometer method (Tan, 2005). Total nitrogen (N) was determined using wet digestion and analysed using AutoAnalyzer 3 (Food and Agriculture Organization, 2021). Available phosphorus (P) and available potassium (K) were extracted using the double acid extraction procedure (Tan, 2005). Available P was determined using the Bray and Kurtz method with a UV–Vis spectrophotometer, while available K was determined using an atomic absorption spectrometer (Bray and Kurtz, 1945).

Statistical Analysis

Mean values were calculated for each soil property under different rainfall intensities. Mean comparison was conducted using Tukey's Honest Significant Difference (HSD) test at $p<0.05$. The analysed soil properties were pH, OM, total N, available P, and available K.

RESULTS AND DISCUSSION

Selected Soil Properties under Different Rainfall Intensities

The results are shown in Table 1. Soil pH ranged from 4.47 to 4.51, indicating acidic soil conditions across the rainfall intensities. Organic matter ranged from 2.50% to 3.81%, while total N ranged from 628.09 to 765.22 mg/kg. Available K ranged from 75.21 to 80.61 mg/kg.

Table 1: Selected soil properties under different rainfall intensities

Rainfall intensity	pH	OM	Total N	Available K
mm/hr		%	mg/kg	
3.30	4.47	2.88	765.22	75.21
13.80	4.51	3.81	720.08	80.61
21.30	4.51	2.50	628.09	78.88

No significant differences were observed among rainfall intensities for pH, OM, total N, and available K

Mean comparison showed that pH, OM, total N, and available K did not differ significantly among rainfall intensities, indicating that these properties were relatively stable over the short-term post-rainfall period examined in this study. Soil pH, OM and total N are commonly used as general soil condition indicators, whereas available nutrient fractions are more directly linked to short-term nutrient cycling and mobility. Therefore, the absence of significant changes in pH, OM and total N in this study suggests that these properties were relatively stable over the short post-rainfall sampling period compared with available P (Abshiba *et al.*, 2025).

Effect of Rainfall Intensity on Available Phosphorus

Available P showed a significant response to rainfall intensity and declined from 5.99 mg/kg under low rainfall intensity to 3.34 mg/kg under moderate rainfall intensity and further decreased to 1.16 mg/kg under high rainfall intensity (Figure 1). Tukey's HSD test indicated significant differences among the rainfall intensity levels, showing that available P was the only measured soil property significantly affected by rainfall intensity.

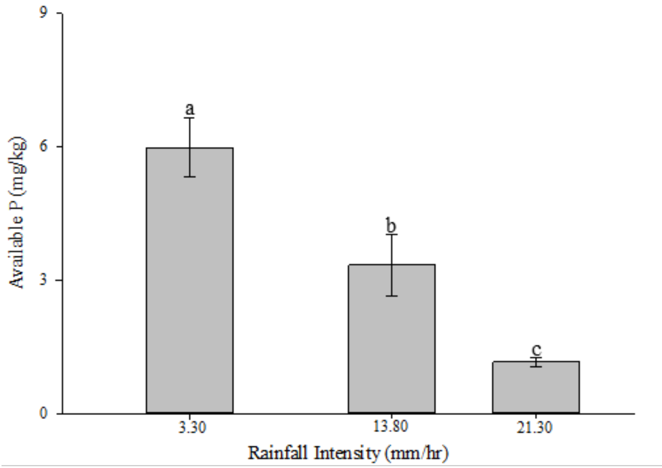

Figure 1 Available P under different rainfall intensities. Error bars represent standard error (mean ± SE, n = 8). Different letters indicate significant differences according to Tukey's HSD test at $p<0.05$

Available P decreased by approximately 81% under high rainfall intensity compared with low rainfall intensity. This reduction was calculated based on the decline from 5.99 to 1.16 mg/kg. The result indicates that available P was more responsive to rainfall intensity than pH, OM, total N, and available K. The decrease in available P may be associated with rainfall-driven mobilisation and redistribution processes in sandy sloping soil. Under higher rainfall intensity, rainfall impact and surface runoff may increase soil particle detachment and downslope movement. Although P is generally less mobile than nitrate in soil solution, it can be transported in dissolved and sediment-associated forms when surface soil materials are mobilised. Therefore, in sandy Bekenu soil with exposed surface conditions, higher rainfall intensity may contribute to lower available P in the sampled surface soil (Yang *et al.*, 2024).

The acidic soil condition in this study may also influence P availability. In highly weathered tropical soils, P availability is often constrained by adsorption and fixation involving aluminium and iron compounds, reducing its availability to plants (Mabagala and Mng'ong'o, 2022). Therefore, the decline in available P under higher rainfall intensity may reflect the combined influence of rainfall-driven redistribution and soil chemical availability processes. However, this study did not directly quantify runoff, sediment-bound P, or leaching losses. Thus, the observed reduction should be interpreted as a decline in available P concentration rather than direct measurement of total P loss.

These findings are consistent with the need to consider rainfall intensity and slope-related processes when managing soil fertility in black pepper plantations. Maintaining soil cover and reducing surface runoff may help improve P retention and fertiliser use efficiency in sandy sloping soils.

CONCLUSION

Rainfall intensity significantly influenced available P in a black pepper plantation on Bekenu soil series in Samarakan, Bintulu, Sarawak. Available P declined from 5.99 mg/kg under low rainfall intensity to 1.16 mg/kg under high rainfall intensity, representing an approximate 81% reduction. In contrast, pH, OM, total N, and available K did not differ significantly among rainfall intensities, indicating relatively stable short-term responses. The findings suggest that available P is more sensitive to rainfall-driven processes than the other measured soil properties.

Higher rainfall intensity may enhance P mobilisation and downslope redistribution in sandy sloping soils. Soil conservation practices, including maintaining soil cover and reducing surface runoff, may help improve P retention in black pepper cultivation systems. Future studies should quantify runoff, sediment movement, and P fractions to better distinguish between P redistribution, fixation, and actual P loss under tropical rainfall conditions.

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