UNIVERSITI TEKNOLOGI MARA

THE GROWTH, YIELD, AND NUTRIENT CONTENT OF HABANERO CHILI (*CAPSICUM CHINENSE*) AS INFLUENCED BY PINEAPPLE LEAF BIOCHAR AND *TRICHODERMA* BIOFERTILIZER IN FERTIGATED COCOPEAT MEDIA

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Thesis submitted in fulfilment
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ABSTRACT

The escalating demand for pineapples has led to a proportional increase in pineapple waste, which is commonly left in the field or openly burned after harvesting, thereby posing significant environmental challenges if not effectively managed. Furthermore, excessive use of chemical fertilizers can cause acidification and mineral depletion in the substrate. In recent years, few studies have explored the conversion of pineapple leaf waste into biochar to promote agricultural sustainability. Biochar has great potential as an organic amendment and can create a more sustainable and environmentally friendly agricultural practices. However, research on using pineapple leaf biochar in cocopeat media remains limited. This study examined the effects of different rates of pineapple leaf biochar (PLB) and *Trichoderma* biofertilizer (TBF) application on the growth, yield, and nutrient content of the *C. chinense* grown in fertigated cocopeat media. The first objective of this study was to determine the optimum pyrolysis temperature to produce a good-quality PLB based on physicochemical characterization. The optimum temperature was subsequently utilized to produce PLB, which was then applied to the *C. chinense* in combination with TBF. Lastly, this study elucidated the adsorption and desorption behavior of nitrogen (N) following the application of PLB and TBF on the *C. chinense*. Conducted in a randomized complete block design (RCBD) under rain shelter conditions equipped with a fertigation system, seven treatments were tested: T0 (Chemical fertilizer - Control), T1 (Organic fertilizer), T2 (Organic fertilizer + 100% PLB), T3 (Organic fertilizer + 100% TBF), T4 (Organic fertilizer + 75% PLB + 25% TBF), T5 (Organic fertilizer + 50% PLB + 50% TBF), and T6 (Organic fertilizer + 25% PLB + 75% TBF). The variables for determining the optimal pyrolysis temperature include the pH, electrical conductivity, surface area, surface morphology, functional group, thermogravimetric analysis, and elemental composition. Meanwhile, the variables for the application of PLB and TBF to *C. chinense* consist of plant height, stem diameter, chlorophyll content, fruit yield, number of fruits, fruit weight, and diameter, total plant biomass, and nutrient content. Lastly, the variable for nutrient retention for this study includes N adsorption and desorption capacity. The findings reveal that PLB produced at 500°C exhibited superior physicochemical properties, including suitable pH (10.80) and electrical conductivity (17.90 dS m^{-1}), higher BET surface area (19.4152 m^2 g^{-1}), well-developed surface morphology, enhanced functional groups, greater thermal stability, and higher carbon (59.90%) and phosphorus content (0.29%). In the application study, T4 significantly improved the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media compared to other organic treatments. In addition, this treatment recorded mean yield (403.69 g), fruit weight (8.87 g), and fruit diameter (2.95 cm) which were comparable to T0. Furthermore, T4 enhanced N retention in the growing media, as evidenced by higher Freundlich adsorption constants (K_F) recorded before planting and after planting. These findings indicate that the combination of 75% PLB and 25% TBF, has potential as an organic amendment for cocopeat media, reducing reliance on chemical fertilizers while sustaining crop productivity. However, further long-term studies are recommended to evaluate the stability of PLB in cocopeat media and its effects on nutrient dynamics under continuous fertigation.

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LIST OF SYMBOLS

Symbols

mm	Millimeter
nm	Nanometer
cm	Centimeter
m	Meter
µg	Microgram
g	Gram
kg	Kilogram
mL	Milliliter
v	Volume
°C	Degree Celsius
pH	Potential Hydrogen
EC	Electrical Conductivity
%	Percentage
M	Molarity
rpm	Revolutions Per Minute
meq%	Milliequivalents Per Percent
mS cm^{-1}	MilliSiemens Per Centimeter
dS m^{-1}	DeciSiemens Per Meter
mg/L	Milligrams Per Liter

$kg\ ha^{-1}$	Kilograms Per Hectare
$cm3\ g^{-1}$	Cubic Centimeters Per Gram
$m2\ g^{-1}$	Square Meters Per Gram
$mg\ kg^{-1}$	Milligrams Per Kilogram
$g\ cm^{-3}$	Grams Per Cubic Centimeter
$\mu g\ g^{-1}$	Micrograms Per Gram
$mg\ L^{-1}$	Milligrams Per Liter
$\mu g\ mL^{-1}$	Micrograms Per Milliliter
$mg\ g^{-1}$	Milligrams Per Gram

LIST OF ABBREVIATIONS

Abbreviations

ANOVA	Analysis of Variance
BET	Brunauer-Emmet-Teller
C	Carbon
Ca	Calcium
CEC	Cation Exchange Capacity
CO_2	Carbon Dioxide
DMRT	Duncan's Multiple Range Test
EC	Electrical Conductivity
Fe	Ferrum
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier-Transform Infrared
H	Hydrogen
H_2SO_4	Sulfuric Acid
K	Potassium
K_2SO_4	Hydrogen Peroxide
KCl	Potassium Chloride
KF	Freundlich Constant
KL	Langmuir Constant
Mg	Magnesium

MP	Malaysia Plan
MPIB	Malaysian Pineapple Industry Board
N	Nitrogen
N_2O	Nitrous Oxide
NaCl	Sodium Chloride
NaOH	Sodium Hydroxide
NH_4Cl	Ammonium Chloride
NH_4OAc	Ammonium Acetate
P	Phosphorus
PLB	Pineapple Leaf Biochar
R^2	Coefficient of Determination
RCBD	Randomised Complete Blocked Design
S	Sulfur
SDGs	Sustainable Development Goals
SHU	Scoville Heat Unit
TBF	*Trichoderma* Biofertilizer
TGA	Thermogravimetric Analysis
UiTM	Universiti Teknologi MARA
UPM	Universiti Putra Malaysia

CHAPTER 1
INTRODUCTION

1.1 Research Background

Under the 12th Malaysia Plan (12MP), the Malaysian Pineapple Industry Board (MPIB) aims to increase the production of MD2 premium pineapples to 50% in order to meet rising domestic and international demand. Pineapple exports are expected to grow at a rate of 5% annually between 2021 and 2025. However, this expansion has led to a significant increase in agricultural waste, particularly pineapple leaf, which are typically left to decompose in the field or discarded into drainage systems after harvest. This practice not only disrupts the natural ecological balance but also creates breeding grounds for pests and contributes to broader agro-environmental challenges.

To foster sustainable agricultural development, it is imperative to transform such biomass waste into value-added products. Pineapple leaf waste offers significant potential for conversion into biochar through pyrolysis, which a thermochemical process that minimizes waste volume while producing a stable, carbon-rich material. Pyrolysis provides an effective and environmentally friendly method for managing agricultural residues, including the abundant biomass generated from pineapple plantations in Malaysia (Mohammad Hariz et al., 2015).

Biochar has been widely recognized for its capacity to improve soil structure, enhance nutrient retention, and immobilize heavy metals (Rawat et al., 2019). Kizito et al. (2019) reported that biochar application enhances soil texture, carbon retention, nutrient retention, and cation exchange capacity, in addition to promoting microbial diversity that facilitates nutrient mineralization. Specifically, pineapple leaf biochar (PLB) is rich in potassium (K), with a high carbon-to-nitrogen (C/N) ratio of 50–70, offering additional benefits for plant nutrition and soil fertility (Bohari et al., 2020; Sánchez-Reinoso et al., 2020).

In line with the Sarawak state government's ambition of adopting the Sustainable Development Goals (SDGs) by 2030, the adoption of organic amendments represents a viable strategy to promote regenerative agriculture. Organic inputs such as biochar and microbial biofertilizers like *Trichoderma* offer sustainable alternatives that

can reduce the dependency on chemical fertilizers while enhancing soil health and crop productivity (Chandini et al., 2019).

Trichoderma is a fungus that known for its role in promoting plant growth and nutrient cycling through microbial activity. Combining biochar with *Trichoderma* biofertilizer (TBF) can improve plant growth and media health, as biochar provides a porous structure that creates a good habitat for *Trichoderma* (Paveen et al., 2025). This helps the microbes work more effectively, which can improve nutrient retention, increase nutrient availability, and support healthy root development, that leading to better crop growth and yield as well as reduce reliance on chemical fertilizer.

In Sarawak, *C. chinense* has emerged as an important cash crop, often cultivated under fertigation systems. However, the expansion of cultivation has increased the use of chemical fertilizers, which in turn raises production costs and environmental concerns (Chiquito-Contreras et al., 2017). Moreover, declining yields have been reported in recent years due to insufficient understanding of suitable growing media and nutrient management (Balraj & Arockiasamy, 2018). The overuse of chemical inputs has also been associated with long-term degradation of soil quality and reduced crop nutritional value (Rawat et al., 2019). The increasing reliance on chemical fertilizers to meet food demand has raised concerns due to their environmental impacts and high costs.

Therefore, this study aims to assess the synergistic effect of application PLB and TBF to the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media. The findings will contribute to improved waste management strategies, reduced reliance on chemical fertilizers, and increased productivity of this economically significant crop.

1.2 Problem Statement

The rapid expansion of pineapple cultivation in Malaysia, particularly of the MD2 variety, has resulted in a substantial increase in agricultural biomass waste, primarily in the form of senescent pineapple leaves, with pineapple plantations now covering more than 17,601 hectares nationwide (Sabri et al., 2025). In the absence of effective waste management practices, these residues are commonly left to decompose on the ground or burned in open fields after harvesting, a practice widely observed among pineapple smallholders in Samarahan, Sarawak (Matius et al., 2022). These raise

concerns about the environmental risks, including CO_2 and N_2O emissions, as well as the sustainability of managing pineapple waste in Malaysia, where a significant portion of pineapples are grown. However, this non-commercial value waste could be potentially produced to become biochar for sustainable agriculture.

In this context, adopting sustainable agricultural practices including the use of organic inputs such as biochar, can reduce or eliminate the negative effects on human health and the environment. Pineapple leaf biochar contains significant macronutrients that are essential for plant growth, including nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca). According to Bohari et al. (2020), PLB produced at low pyrolysis temperatures contained approximately 8.33% N, 0.39% P, and 48.32% K, with Mg and Ca also present, indicating its potential to contribute to soil nutrient supply when applied as a soil amendment. This nutrient-rich composition highlights the potential of PLB as an organic amendment, supporting more sustainable and environmentally friendly agricultural practices. Furthermore, the application of biochar can enhance nutrient adsorption and retention in the growing media, thereby reducing reliance on chemical fertilizers in fertigation systems, which are often associated with substrate degradation and increased production costs.

Chemical fertilizers are manmade soil enhancers that are used to raise the nutrient level in the soil or substrate required by the plant. The availability of nutrients in the soil is low compared to the amount of nutrients required by the plant becomes the main reason why chemical fertilizers need to be applied. Although these chemical fertilizers improve plant growth and give a high yield, they also bring some drawbacks to the soil. For that reason, the application of chemical fertilizer should be reduced.

In this study, *C. chinense* was used as an indicator plant to assess the effects of application PLB and TBF on growth, yield, and nutrient content. The *C. chinense* is recognized as a high-value horticultural crop in Sarawak, widely used in the food industry and contributing significantly to the local agricultural economy. Its consistently strong market demand has made it a popular choice among smallholders, who commonly adopt fertigation systems to maximize productivity. However, the intensive use of chemical fertilizers in such systems can lead to degrade the quality of the growing media over time. To address these challenges, this study was conducted to evaluate the potential and effect of PLB and TBF as sustainable organic amendments on *C. chinense* grown in fertigated cocopeat media while reducing dependence on chemical fertilizer.

1.3 Research Questions

The research questions for this study are as follows:

i) What is the optimum pyrolysis temperature to produce good quality PLB based on physicochemical characterization?
ii) To what extent does the application of PLB and TBF affect the growth performance, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media?
iii) How do PLB and TBF influence nitrogen (N) retention and availability in fertigated cocopeat media before and after planting of *C. chinense* plant?

1.4 Research Objectives

The general objective was to determine the agronomic and nutrient-retention effectiveness of PLB and TBF in enhancing the growth, yield, and nutrient efficiency of *C. chinense* cultivated in fertigated cocopeat media. The specific objectives of the study are shown below:

i) To determine the optimum pyrolysis temperature for producing good quality PLB based on physicochemical characterization.
ii) To quantify the effects of PLB and TBF application on the growth and yield performance, and nutrient content of *C. chinense* plant grown in fertigated cocopeat media.
iii) To elucidate the role of PLB and TBF in relation to nitrogen retention and availability in fertigated cocopeat media

The findings provide new knowledge to develop *C. chinense* plant grown in fertigated cocopeat media and a good prospect for the use of recycled nutrition to reduce the reliance on chemical fertilizer among *C. chinense* smallholders.

1.5 Scope and Limitation of the Study

This study was conducted to evaluate the potential of PLB and TBF as organic amendments for improving the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media. Pineapple leaf waste variety MD2 was collected from smallholders at Kampung Meranek, Samarahan, Sarawak. The standard procedure to produce PLB followed the method by Bohari et al. (2020) with modification. Three different temperatures (300, 400, and 500°C) were used to determine the optimum biochar production to be applied to the *C. chinense* plant. The pyrolysis process was carried out at the Block H Laboratory, University Teknologi MARA (UiTM) Sarawak Branch, Samarahan Campus.

The cultivation of *C. chinense* was conducted at the Farm Unit, UiTM Sarawak Branch, Samarahan Campus. Plants were grown in polybags filled with cocopeat-based media under a net house and supplied with nutrients via a fertigation system using comercial fertilizers. The experimental design focused on evaluating plant performance in terms of growth, yield, and nutrient content for 20 weeks after treatment. Sample preparation for nutrient content analysis was performed at Block H Laboratory, UiTM Sarawak.

For the nitrogen retention analysis, media samples were collected at two time points: before planting at week 0 (pre-treatment) and after planting at week 20 (post planting). Meanwhile, physicochemical characterization and nutrient analysis of growing media were conducted at the Soil Science Laboratory, Universiti Putra Malaysia (UPM) Bintulu Campus, Sarawak.

While this study provide valuables insights into sustainable organic amenements for *C. chinense* cultivation, several limitations should be acknowledged:

i) The source of PLB for this study was from a single variety (MD2), which the findings may not be directly applicable to biochar derived from other pineapple varieties or biomass sources.
ii) The experiment was conducted under controlled net house condition using polybags and cocopeat media, which may limit the extrapolation of results to open-field systems or different environmental conditions.

iii) The evaluation of nutrient retention was focused solely on nitrogen (N), which limiting the comprehensive understanding on how PLB and TBF influenced overall nutrient dynamics in the fertigated cocopeat media.

1.6 Significance of Study

This study aimed to assess the application of PLB and TBF as a strategy to minimizing the reliance on chemical fertilizers and to develop a novel organic amendment mixture. The findings provide knowledge on the ideal combination of PLB and TBF for enhancing the growth, yield, and nutrient content of the *C. chinense*. Moreover, the study supports sustainable agricultural practices by promoting the utilization of agricultural waste and microbial inputs, thereby aligned with current goals for environmental friendly crop production.

CHAPTER 2
LITERATURE REVIEW

2.1 Organic Amendment

Organic amendments such as animal and green manure, organic wastes, compost, and biochar have been advocated as reliable and successful strategies for re-establishing soil fertility (Cesarano et al., 2017). Organic amendments come from something alive, either mined or man-made. According to Ansari et al. (2019), organic amendments are the chief option for soil management that helps to impoverish the soil health. The quality and quantity of organic inputs are assumed to directly affect the soil's physical, chemical, and biological attributes.

Organic amendments are known as supplements to the soil because they are rich in nutrients such as N, P, K, Ca and Mg. One of their roles is to act as a slow-release fertilizer that gradually supplies nutrients to plants over time and can improve the growth and yield of the plant (Abbas et al., 2024). Studies have shown that organic amendments can give various advantages over mineral fertilization, including improved soil structure, enhanced soil fertility, long-term maintenance of soil health, and particularly, similar, or even higher crop yields in certain cases (Luo et al., 2018).

Despite offering numerous advantages, applying organic amendments also brings some disadvantages that can limit their applicability in agricultural environments (Cesarano et al., 2017). The quality of organic amendments varies significantly based on their source as well as the processing ways which lead to unpredictable results in substrate fertility and plant growth performance. Based on a study conducted by Bonanomi et al. (2007), the suppressive capability of organic amendments is sometimes inconsistent, and the study suggests an increase in disease incidence following the application of organic matter. In addition, the excessive application of organic amendments can lead to nutrient imbalances or make the soil become toxic (Ouyang et al., 2022; Paradelo et al., 2024).

Numerous studies about the application of organic amendments on the soil have been explored. However, its application on soilless media such as cocopeat is still in its nascent stage. Therefore, this study was conducted to evaluate the effect of two different

organic amendments, which are PLB and TBF on the growth, yield, and nutrient content of the *C. chinense* grown in fertigated cocopeat media.

2.1.1 Biochar

Biochar is a by-product of pyrolysis of an organic substance at a temperature of 300-1000ºC (Kraska et al., 2016; Ippolito et al., 2020; Joseph et al., 2021). Application of biochar to the soil as an organic amendment potentially improves the soil properties, thus increasing the crop yield and productivity. Recently, it has been reported that biochar obtained from the carbonization of organic wastes can be a substitute that not only influences the sequestration of soil carbon but also modifies its physicochemical and biological properties (Rawat et al., 2019). A study by Anand et al. (2023) reported that biochar can have a wide range of characteristics and stability depending on the feedstock and generation processes employed.

According to Kracmarova-Farren et al. (2024), biochar has been demonstrated to impact soil enzyme activity and the composition and abundance of soil microbial communities. A study by Sánchez-Reinoso et al. (2020) found that adding biochar to the soil improves its physicochemical properties, such as its fertility. In addition, Joseph et al. (2021) ascribe biochar's impacts on crop output primarily to soil chemical and biological responses, including increased plant-available water, increased cation exchange capacity (CEC) and nutrient retention, and increased pH and base saturation. It concludes that the use of biochar will increase germination, building up dry matter, photosynthesis, yield, and quality of crop.

Although biochar is said to bring benefits to the soils, there are also drawbacks caused by the application of biochar. There have been reports of potential detrimental effects of biochar on microbial biomass and activity. The presence of aged biochar in the soil has negative effects on earthworm growth (Anyanwu et al., 2018) and has shown a reduction in the roots and shoots biomass of rice and tomato plants (Alkharabsheh et al., 2021). Low yields could be due to limited nutrient release for plant uptake, biochar application on fertile soils, or a low biochar application rate (Mylavarapu et al., 2013).

Additionally, there is evidence that biochar addition may absorb and retain pesticides for extended periods, which may result in a high weed infestation (Alkharabsheh et al., 2021). In other situations, biochar-amended soils exhibited

decreased Fe and P availability due to their precipitation/sorption (Kim et al., 2016; Joseph et al., 2018). However, the result of the application of biochar may rely on the feedstock sources, pyrolysis temperature, particle size of biochar, and soil texture (Alkharabsheh et al., 2021). Therefore, this study is conducted to determine the potential of PLB as an organic amendment in cocopeat planting media for *C. chinense.*

2.1.2 *Trichoderma* Biofertilizer

Fungi from the genus *Trichoderma* are a very large group of microorganisms that play a significant role in the environment. According to Błaszczyk et al. (2014), several *Trichoderma* positively affect plants by stimulating plant growth and protecting plants from fungal and bacterial pathogens. Moreover, based on the study conducted by Doni et al. (2017), *Trichoderma* can promote the plant's growth, and increase plant height, leaf area, and plant dry weight.

In a study by Halifu et al. (2019), *Trichoderma* is fast-growing and has strong vitality that makes it occupy the plant rhizosphere rapidly and increase the availability of the nutrients needed by the plant. In addition, it is also known for its ability to solubilize phosphate and increase soluble phosphorus for plant nutrient uptake (Nahidan et al., 2019). Based on the study conducted by Harman et al. (2004), *Trichoderma* can increase the growth of rice, wheat, sorghum, tomato, brinjal, soybean, sunflower, gladiolus, opium, chickpea, pea, chili, maize, and many other crops.

Trichoderma is beneficial in enhancing plant growth and development, which is highly desirable in reducing or eliminating the use of chemical fertilizers because harmful residues and their high application are left in the soil. According to Kumar et al. (2019), the application of *Trichoderma* on chili plants can increase the root and shoot length and fruit yield. However, the result might be different to the other chili variety due to their characteristic and requirement. Therefore, in this study, TBF was combined with PLB as an organic amendment and tested to *C. chinense* grown in cocopeat media to evaluate its effects on the growth, yield, and nutrient content.

2.1.3 Overview of Past Research

A critical review of relevant studies over the past decade revealed several research gaps, particularly in biochar feedstock selection (Bohari et al., 2020), degree

of characterization (Abdul Halim et al., 2024), microbial application (Medeiros et al., 2020), crop species, and planting media. Table 2.1 presents a comparative summary of selected studies, highlighting key differences in biochar type and characterization, use of *Trichoderma*, crop species, planting media, and focus on nitrogen related processes.

Most existing studies have examined biochar or microbial biofertilizers as individual amendments, with most experiments conducted under soil-based conditions. Studies involving soilless media, especially cocopeat-based fertigation systems, remain limited. Furthermore, biochar characterization in many studies is partial, often restricted to elemental analysis, which limits the ability to relate material properties to nutrient behavior and plant response.

With respect to nutrient dynamics, previous research has primarily focused on plant growth, yield, or nutrient uptake, while mechanistic investigations of N adsorption and desorption before and after planting are relatively scarce. These observations highlight the diversity and fragmentation of current research on biochar and microbial amendments and provide a foundation for the synthesis of research gaps presented in the final section of this chapter.

Table 2.1
Summary of Previous Studies Related to Biochar and Crop Studied

Biochar type and characterization	**Use of *Trichoderma***	**Crop Studied**	**Tested medium**	**Key Findings**	**Study**
Wheat husk, hardwood and kitchen waste biochar; partially analyzed (lignin, cellulose, hemicellulose, elemental)	Yes	*Cicer arietinum*	Soil	Studied carrier function; not *C. chinense* or cocopeat media	Paveen et al. (2025)
Pineapple waste biochar (550°C); basic nutrient profile	No	*Ananas comosus*	Soil	Biochar + compost for pineapple; lacks *Trichoderma* or cocopeat aspect	Hanyabui et al. (2024)
Pineapple leaf biochar; characterized for elemental	No	N/A	Soil	Assessed pineapple leaf biochar impact on ammonium/nitrate leaching in mineral soil	Jos et al. (2024)
Rice husk biochar (500°C); not characterized	No	*Capsicum annuum* L.	Soil	Microbial synergy but not with *Trichoderma*; no N tracking or cocopeat component	Samyukta et al. (2024)
Pineapple leaf biochar (PLB); characterized for elemental	No	*Ananas comosus*	Soil	Assessed pineapple leaf biochar + fertilizer on growth and nutrient uptake in alluvial soil; no *Trichoderma* or cocopeat component	Jos et al. (2023)
Forestry waste biochar (300–600°C); fully characterized (proximate, elemental, BET, FTIR, SEM);	No	N/A	N/A	Extensive material analysis; no crop testing or N focus	Abdul Halim et al. (2024)
Corncob biochar; characterized for elemental	No	*Capsicum annuum* L.	Soil	High C:N impact tested; lacked biochar interaction with microbes or N dynamics	Jaaf et al. (2022)
No biochar used	Yes	*Capsicum annuum* L.	Soil	Studied *Trichoderma* effects only; no biochar or nutrient dynamics	Tangga et al. (2022)

Biochar type and characterization	**Use of *Trichoderma***	**Crop Studied**	**Tested medium**	**Key Findings**	**Study**
Poultry litter biochar; minimal chemical data (pH, CEC, N)	No	*Capsicum chinense*	Rice husk	Biochar applied in rice husk as media; no microbe or N dynamics examined	Raphael et al. (2022)
Rice husk biochar; not characterized	No	*Amaranthus* sp.	Soil	Biochar applied on soil; no *Trichoderma*, nutrient, or plant species link	Japakumar et al. (2021)
Bean and coffee waste biochar (530°C); not chemically analyzed	Yes	*Citrullus lanatus*	Soil	Soil-based; *Trichoderma* effects only; no biochar characterization; no N study	Medeiros et al. (2020)
Pineapple leaf and sago waste biochar (350°C); full characterization	No	N/A	N/A	Focused on material properties only; no application	Bohari et al. (2020)
Sago bark biochar (350°C); characterized for elemental	No	*Zea mays*	Soil	Compared sago biochar sources on crop yield; no N behavior or *Trichoderma*	Mahdian et al. (2020)
Poultry litter biochar (350°C); characterized for elemental	No	*Capsicum chinense*	Soil	Focused on soil application; no microbial or N study	Tito et al. (2020)
Oil palm waste biochar; no characterized	No	*Zea mays*	Soil	Yield-based corn study with no nutrient interaction tracking	Hasmah et al. (2019)
Chicken litter biochar; characterized for elemental	No	N/A	Soil	Focused on nutrient buffering in mineral soil; no microbe/bio application	Palanivell (2016)
Chicken litter biochar; characterized for elemental	No	*Oryza sativa* L.	Soil	No *Trichoderma*; field-based nutrient enhancement	Yusof et al. (2015)

2.2 Pineapple Leaf Waste

Sarawak is currently in second place behind Johor as the largest producer with a pineapple planting area of 9,782 hectares, capable of producing 181,000 metric tonnes of pineapple a year (Malaysia Pineapple Industry Board, 2022). With the higher production of pineapple, it will generate higher waste production. The generation of waste from the growing pineapple plantation industry will especially disturb the environmental balance and contribute to environmental pollution. Being a lignocellulose-rich biomass, pineapple leaf waste could be a potential raw material to produce biofuel, biochemicals, and other value-added products (Saini et al., 2022). Malaysia produces 335,488 tons of pineapple in addition to 67,098 and 137,550 tons of leaf and peel wastes (Ahmad Zamri et al., 2020). About 13 tonnes per hectare of pineapple waste are generated for every growing season (Choo et al., 2021). Processing of pineapple generates about 60% of the original pineapple fruit in the form of peel, core, crown end, and pomace that can be converted into bioenergy sources like bioethanol, biobutanol, biohydrogen, and biomethane along with animal feed and vermicompost (Sarangi et al., 2022). About 80% of parts, including the crown, peels, leaf, core, and stems, are discarded during pineapple processing, transportation, and storage and end as waste (Roda & Lambri, 2019; Nahrul Hayawin et al., 2020).

The abundance of these wastes means they often remain relatively unexploited and are often subjected to landfills (Jehan et al., 2017) which causes severe environmental problems since this waste inhibits the biological and chemical oxygen demand of ecosystems (Zaki et al., 2017), site contamination and increase the risk of infectious diseases (Roda & Lambri, 2019). Typically, pineapple waste, especially pineapple leaf is left on the ground or burned after harvesting. In situ burning of pineapple wastes has little effect on macronutrient intake or yield, but it does reduce pest and disease outbreaks (Choo et al., 2021). In Samarahan, most pineapple was planted on peat soils and burning activities became common practice in the pineapple industry. Burning the pineapple leaf wastes before replanting raises concerns about the hazards of peat fires (Choo et al., 2021). Thus, producing value-added products like biochar from pineapple leaf waste can help to reduce pollution and build a more sustainable agriculture industry by transforming waste into wealth.

2.2.1 Pineapple Leaf Characteristics and Composition

The pineapple leaf possesses specific characteristics and composition that make it suitable for conversion into biochar. Pineapple leaf contains more lignin and cellulose than other plants which is essential for biochar production. According to Banerjee et al. (2017), pineapple leaf contains 13.05% lignin, 21.02% hemicellulose, and 41.15% cellulose. Each component undergoes distinct thermal degradation processes during pyrolysis, affecting the resulting biochar's characteristics. Aside from that, carbonyl, carboxyl, and hydroxyl groups from pineapple leaf can be utilized as a precursor in the production of activated carbon (Astuti et al., 2019). The results of an investigation by Pardo et al. (2014) into the protein, ash, and fiber content of various pineapple parts revealed that pineapple pulp contains the most protein and fiber. While the leaf contains the least amount of protein, it is rich in ash.

According to Bohari et al. (2020), the higher fiber content in pineapple leaf contributes to the structural integrity of the resulting biochar and enhances its porosity and surface area, which are critical for nutrient retention and microbial activity in the substrate. The pineapple leaf has a significant capacity for water retention due to its thick structure. This characteristic aids in maintaining moisture during the pyrolysis process, which is beneficial for producing biochar that can improve soil moisture retention when applied.

Pineapple leaf also has a stable carbon structure when transformed into biochar. This can persist in the soil for extended periods, contributing to long-term soil health and carbon sequestration efforts. According to a study by Mansor et al. (2018), the MD2 pineapple leaf contains 43.43% carbon while the stem contains 41.09% carbon. This makes the pineapple leaf more suitable for biochar production as the higher carbon ceontent typically yields more biochar during pyrolysis and contributes to the formation of stable, aromatic carbon structure. These structures enhance the long-term stability of biochar in soil, allowing it to persist for decades or even centuries (Lehmann & Joseph, 2009). Therefore, in this study, pineapple leaf from the MD2 variety was used to produce biochar, which was subsequently applied to *C. chinense* grown in fertigated cocopeat media to evaluate its effects on growth, yield, and nutrient content.

2.2.2 Pineapple Leaf Biochar

In recent years, transforming pineapple leaf waste into biochar has captured the world's attention due to its characteristics. It has emerged as a promising agriculture by-product that has significant potential for improving soil health and promoting sustainable agricultural practices. Bohari et al. (2020) reported that the high N and P content of PLB, at 8.33% and 48.32%, respectively, and a high C/N ratio (50-70), supplement the plant's nutrition and increase the fertility of the medium. Application of PLB was found to significantly improve N availability which can enhance N retention by up to 20%, which is crucial for crops that require substantial N for optimal yield (Jos et al., 2023, 2024).

Supported by Ch'ng et al. (2016), PLB contains a high amount of N (2.30%), P (0.46%), and K (2.67%). As compared to biochar derived from the fruit peel and crown, PLB consists of high K content (Sánchez-Reinoso et al., 2020). A recent study found by Hanyabui et al. (2024), that the application of PLB as soil amendment can increase pineapple yield and improve fruit quality. Hence, this study is conducted to evaluate the potential of PLB in the planting media for organic habanero chili plants in response to plant growth, yield, and nutrient status. The outcomes from this study will identify possible ways to manage pineapple waste without negatively affecting the quality of the environment by converting this waste into a value-added product.

2.3 Habanero Chili (*Capsicum chinense*)

Capsicum chinense or the common name habanero chili belongs to the family Solanaceae and originates from the Amazon region of South America. The *C. chinense* is well-known for its elevated spiciness level compared to other chili varieties with the Scoville Heat Unit (SHU) ratings ranging from 100 000 to 350 000 (Septiana et al., 2023). The *C. chinense* fruit is green when immature and turns to shades of orange and red when mature and ready to harvest. The size of the *C. chinense* fruit is small, with a length of about 2 to 6 centimeters. For the physical characteristics of *C. chinense* plants, it typically grows as an erect, multi-stemmed shrub, reaching about 0.5 to 1.5 meters tall with a life cycle of up to 12 months (Department of Agriculture Sarawak, 2022).

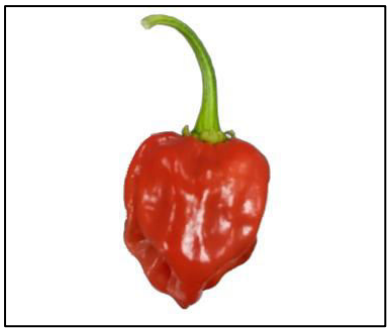


Figure 2.1 The *C. chinense* Fruit

The *C. chinense* is becoming a significant crop due to increasing demand in national and international markets. According to Balraj & Arockiasamy (2018), the yield of chili production is reduced year to year. In 2018, the domestic demand for chili was 55,420 tons. Meanwhile, the domestic production is 24,428 tons. This figure shows that the total chili production is not reaching the domestic demand. About 34,855 tons of chili have been recorded for the export demand, and only 3,863 tons have been exported.

According to the Department of Statistics Malaysia, domestic chili production remains insufficient to meet market demand despite its economic and cultural significance. In 2020, Malaysia produced an estimated 28,264 tons of red chili, representing a decline of approximately 54.75% compared with production in 2016, which totaled 43,738 tons. To address this shortfall, Malaysia increasingly relied on imports from neighboring countries such as China, India, and Thailand. Consequently, chili imports rose from 49,069 tons in 2016 to 66,295 tons in 2020 (Tan et al., 2023).

The whole chili production including *C. chinense* is not reaching the domestic demand. Most farmers are not producing at the optimum production due to a lack of information about the medium suitability. In recent years, the use of beneficial soil microorganisms has been studied as an alternative to chemical fertilizers. Therefore, in this study, the *C. chinense* plant was used as an indicator plant to determine the suitable cultivation conditions that may affect its growth, yield, and nutrient content.

2.3.1 Macronutrient Requirement of *C. chinense*

The balanced nutrition supplement for *C. chinense* is the most crucial factor that ensures better growth and yield performance. Similar to the other crops, the macronutrients required by *C. chinense* are N, P, K, Ca, and Mg. Meneses-Lazo et al.

(2020) indicate that numerous nutrient solutions for *C. chinense* were formulated empirically without assessing concentration and nutrient sources, with the predominant formulation used being 125-100-150 kg ha-1 N-P-K. On the other hand, González-Cortés et al. (2023) suggest a quantity of 130-120-160 of N-P-K. Table 2.2 below summarizes the macronutrients required by the *C. chinense* plant as suggested by the Department of Agriculture Sarawak.

Table 2.2
Macronutrient Requirement by *C. chinense* Plant

Nutrient	Total Requirement (kg/ha)
Nitrogen	145
Phosphorus	300 – 400
Potassium	140 – 150
Calcium	19 – 190
Magnesium	12 – 48

Sources: Department of Agriculture Sarawak, 2022.

The yield production of *C. chinense* is greatly influenced by the fertilizer schedule and management. As a common practice, the producer fertilization practices are not based on balanced nutrient solutions for the optimal nutrient use, rather they often rely on empirical information (Meneses-Lazo et al., 2020). Poor nutrition received by the plant is one of the reasons for low yield produce because by applying an adequate amount of nutrients will enable the plant to execute fundamental metabolic processes. Therefore, it is crucial to know the required amount of fertilizer needed by the plant and implement the agronomic practices to ensure sustainable agriculture management.

2.3.2 Economic Importance of *C. chinense*

Agriculture is the anchor sector of the Sarawak Digital Economy. The objectives are to improve the productivity and efficiency of the agricultural sector and access to new markets for agricultural produce and products. The Sarawak government aims to shape the Revolution 4.0 agricultural economy and promote modern agriculture as a business for the rural community. In line with this, *C. chinense* cultivation using a fertigation system became popular and preferred among the smallholders due to the high-profit income. For the gross income of 4,000 polybags *C. chinense* plants, it is

expected about RM65,800 will be gained by smallholders (per cycle), which requires 1 acre of land (Department of Agriculture Sarawak, 2022).

The growing demand for *C. chinense* in Sarawak and around the world has been shown to strengthen the economic sustainability of its production through value-added processing. Besides being freshly consumed, *C. chinense* can also be processed into downstream products such as sauces, purees, and chili powder, which can reduce the risk of loss if the fresh fruit is not sold in the local market. Besides being used in culinary, *C. chinense* also brings health benefits due to the presence of capsaicin which is widely used in anti-inflammatory products. Overall, *C. chinense* plays a crucial role in Sarawak's agricultural economy through its contributions to production, employment, exports, and culinary traditions.

2.4 Current Practices on *C. chinense* Cultivation

In Sarawak, the cultivation of *C. chinense* has become increasingly important in both smallholder and commercial agricultural due to its high demand and profitability. The region’s warm and humid tropical climate provides an ideal environment for *C. chinense* production throughout the year. Two primary methods that commonly used by local farmer are conventional soil-based cultivation and fertigation systems.

2.4.1 Conventional Cultivation

Conventional methods involve traditional soil cultivation techniques without the use of advanced irrigation systems and are commonly practiced by home growers. For this method, fertilizers are manually applied in a solid form, often using basal and top-dressing methods. The irrigation is typically performed through surface or sprinkler methods, which widely practiced among smallholders due to low initial cost. However, conventional cultivation method suffers from inefficiencies in water and nutrient use. As mentioned in a study by Tanaskovik et al. (2016), fertilizers may leach into the soil, reducing nutrient availabilty to plants and increasing environmental risks. In addition, uneven distribution of water and nutrients may result in inconsistent crop growth and yield production. Tan et al. (2023) highlighted that low yield and high susceptibility to pests and diseases are the challenges commonly faced by growers when using this method. Due to this challenges and limitations, fertigation has become the preferred

choice among smallholders, as it offers better control over water and nutrient management, leading to improved crop performance and resource efficiency.

2.4.2 Fertigation System

Fertigation system is the modern approach that combines fertilization with irrigation, which ensures the application of nutrients is more precise. According to Tan et al. (2023), application through fertigation systems has shown enhancement in plant growth and yield significantly up to 130% more as compared to conventional methods. In Sarawak, for commercial purposes, *C. chinense* was planted using fertigation systems under a greenhouse condition (Department of Agriculture Sarawak, 2022). The fertigation system significantly outperforms traditional fertilization methods in terms of chili yield. A study by Subiksa et al. (2019), indicates that fertigation could improve chili yields by approximately 115% to 130% compared to conventional methods, which typically yield around 2,527 kg/ha. Conversely, commercial AB-mix fertilizer application via fertigation can enhance yields to about 5,436 kg/ha or more (Subiksa et al., 2019; Tan et al., 2023). Additionally, fertigation improves nutrient uptake efficiency and reduces labor costs, making it a more cost-effective choice for smallholders (Dixon & Liu, 2022).

Balanced nutrition is the most crucial factor that ensures chili growth and yield performance. The fertigation system continuously supplies macro and micronutrients to the chili plants thus improving the growth and yield compared to conventional NPK fertilizers (Subiksa et al., 2019). However, fertilizer cost becomes the main challenge among chili growers as water-soluble fertilizers are relatively high cost compared to conventional fertilizers (Rajput et al., 2007; Reddy & Hebbar, 2018).

Besides bringing numerous benefits, the fertigation system that relies on chemical fertilizer can not only increase the cost of production but also may reduce substrate quality over time. According to Chiquito-Contreras et al. (2017) the increase in the cultivation area of *C. chinense* has increased the use of chemical fertilizers, hence causing high costs and adverse effects on the soil and water. On the other hand, in a study by Stan et al. (2021), the combined use of organic and chemical fertilizers with biofertilizers successfully improved the plants' growth and obtained a better yield of chili.

Nevertheless, the research on the utilization of organic fertilizer with organic amendments remains in its nascent stages. Therefore, this study was implemented to evaluate the response of the *C. chinense* plant toward the application of organic fertilizer combined with two organic amendments, which are PLB and TBF.

2.4.2.1 Chemical Fertilizer

Crop yields have steadily increased globally, and food security has improved as a result of increased chemical fertilizers inputs and the introduction of new technologies (Wang et al., 2018). Chemical fertilizers are known as the main source of nutrients for plants, and they can be defined as manmade soil enhancers used to raise the nutrient level in the soil or substrate. The availability of nutrients in the soil usually is at a lower rate as compared to the amount that plants require. This becomes the main reason why chemical fertilizers need to be applied to gain high-yield production. Nevertheless, this chemical fertilizer increases the plant growth and vigor, thereby ensuring global food security, plants grown in this manner do not develop good plant characteristics such as strong root and shoot systems, and nutritional characteristics and do not have enough time to grow and mature properly (Chandini et al., 2019).

According to Wang et al. (2018), crops can only absorb 30-50% of chemical fertilizers, thus a substantial percentage of the applied components is lost in the soil, causing pollution to groundwater. The world population is expected to increase by 2.3 billion in 2020 and double by the year 2050 (Chandini et al., 2019). This projection directly affects global food security and thus could increase the utilization of chemical fertilizer to meet high-yield production. Therefore, to reduce and eliminate the negative effects of chemical fertilizers on human health and the environment, a new agricultural practice known as organic agriculture, sustainable agriculture, or ecological agriculture has gained global recognition (Chandini et al., 2019).

In this study, the *C. chinense* plant was planted in a polybag, equipped with a fertigation system, and placed under a net house. Organic commercial fertilizer as the main source of nutrients and two different organic amendments which are PLB and TBF were applied at different rates to evaluate their effects on the growth, yield, and nutrient content of the *C. chinense*.

2.4.2.2 Cocopeat as Soilless Media

The global population continues to grow, significantly impacting agriculture and food security. As of 2024, the world population is about 8 billion, expected to reach 9.5 billion by 2050 (Lal, 2015). This increase in population heightens pressure on land resources, leading to land scarcity and soil degradation. Deforestation, unsustainable farming practices, and climate change contribute to soil degradation, characterized by a diminution in soil quality, and pose major challenges to agricultural productivity and food security (Nauman et al., 2023). As an alternative to conventional soil-based farming, soilless planting media are commonly used, including cocopeat, peat moss, rock wool, perlite, vermiculite, and hydroponic systems.

In Malaysia, cocopeat has gained popularity as an intensive production technique, especially for greenhouse cultivation (Yaseer Suhaimi et al., 2018) because of its superior physical properties such as the capacity to hold onto water and essential nutrients like calcium, magnesium, potassium, sodium, and phosphorus (Kusparwanti et al., 2023). Due to this characteristic, cocopeat gradually releases nutrients to plants over time. Recent studies by Felle et al. (2023) and Ruli et al. (2023) have shown the effectiveness of cocopeat in achieving higher yields under limited and adverse conditions, offering ideal growing conditions and protection against soil-borne diseases.

The use of cocopeat as soilless media in Malaysia represents a shift towards more sustainable agricultural practices due to its ability to retain moisture, improve aeration, and provide a nutrient-rich environment making it an attractive option for the smallholders. According to Kusparwanti et al. (2023), cocopeat considerably increases melon yields compared to conventional techniques. Consequently, many growers in Sarawak choose to cultivate *C. chinense* commercially using cocopeat. However, there is limited research on the effect of PLB and TBF application on the cocopeat. Therefore, this study was conducted to evaluate the response of the *C. chinense* plant toward the composition of the growing media.

2.5 Nutrient Retention

Nutrient retention refers to the ability of a soil or soilless planting media to hold and maintain essential plant nutrients in a form available for uptake over time. It is a critical factor influencing crop productivity, nutrient use efficiency (NUE), and overall

soil or substrate health (Borchard et al., 2019; Liao et al., 2020). In soilless media such as cocopeat, nutrient retention plays a central role in preventing nutrient losses through leaching, thereby ensuring a consistent supply to plants throughout their growth cycle. Efficient nutrient retention reduces the need for frequent fertilizer applications, enhances economic returns, and minimizes negative environmental impacts such as groundwater contamination and eutrophication (Khan et al., 2024).

The capacity of a planting media to retain nutrients is determined by various factors, including its physical and chemical characteristics, application of organic amendments, and environmental conditions. Media with high surface area, porosity, and water-holding capacity promote physical nutrient retention, while chemical properties such as CEC, pH, and EC influence the strength and stability of nutrient binding (Ighalo et al., 2025). Organic amendments such as biochar, compost, and biofertilizers can significantly improve nutrient retention by providing additional binding sites, enhancing nutrient cycling, and supporting beneficial microbial activity (Bohari et al., 2020; Murtaza et al., 2023). Environmental factors such as moisture, temperature, and aeration also play a role by affecting nutrient mobility, microbial activity, and reaction rates within the planting media (Alkharabsheh et al., 2021).

Nutrient retention is governed by physical, chemical, and biological mechanisms that operate in combination to sustain nutrient availability. Physically, nutrients may be adsorbed onto particle surfaces or trapped within micropores, thereby reducing their loss from the medium (Skic et al., 2024). Chemically, retention can occur through electrostatic attraction via ion exchange processes or through incorporation into insoluble compounds formed by precipitation or complexation (Strawn, 2021). Biologically, microorganisms can immobilize nutrients during their growth and subsequently release them upon decomposition, while plant roots contribute by exuding organic compounds that influence nutrient binding and availability (Medeiros et al., 2023). Acting synergistically, these mechanisms maintain a consistent nutrient supply that supports optimal plant growth and yield performance.

2.5.1 Nitrogen Retention in Planting Media

Nitrogen retention is a key component of overall nutrient retention, as nitrogen is one of the most mobile and easily lost nutrients in agricultural systems. In planting media, nitrogen is retained primarily through adsorption to solid surfaces and gradual

desorption back into the soil or soilless solution. These processes determine both the short-term availability of nitrogen for plant uptake and the prevention of nutrient losses through leaching, thereby directly influencing nutrient use efficiency (NUE) and crop productivity.

2.5.1.1 Nitrogen Adsorption

Nitrogen adsorption is the process by which nitrogen-containing ions—mainly ammonium (NH_4^+) and nitrate (NO_3^-)—become bound to particle surfaces within the planting medium. This binding, achieved through electrostatic attraction to negatively charged surfaces or physical entrapment within substrate pores, functions as a temporary nitrogen storage mechanism that minimizes leaching losses and ensures gradual release to plants (He et al., 2023; Kohira et al., 2025). The efficiency of this process is influenced by factors such as surface area, pore size distribution, pH, and the presence of functional groups like hydroxyl and carboxyl (Thao et al., 2021: Bolan et al., 2023).

Biochar, with its high porosity and abundant reactive sites, significantly enhances nitrogen adsorption capacity, making it a valuable amendment for improving nitrogen retention (Khan et al., 2024). Studies using rice husk, water hyacinth, and agricultural residue biochars have shown that adsorption data often fit Langmuir or Freundlich isotherm models, providing insight into the number and strength of adsorption sites (Thao et al., 2021). These models help predict how effectively different substrates can store and release nitrogen, which is particularly relevant in soilless media where nutrient losses through leaching are a concern.

2.5.1.2 Nitrogen Desorption

Nitrogen desorption is the release of previously adsorbed nitrogen back into the planting medium solution, making it available for plant uptake. Controlled desorption is essential for maintaining a consistent nitrogen supply that aligns with plant growth demands, supporting nutrient retention by ensuring steady availability while minimizing leaching losses (Ibrahim et al., 2020; Banik et al., 2023).

Microbial activity plays a pivotal role in regulating desorption rates—beneficial microorganisms like *Trichoderma* spp. enhance nutrient cycling by decomposing

organic matter and facilitating the gradual release of adsorbed nitrogen. The combination of biochar and biofertilizers containing such microbes yields a synergistic effect: biochar enhances adsorption capacity, while microbial activity drives-controlled desorption, maximizing nitrogen retention, reducing nutrient losses, and promoting long-term crop nutrition in soilless media (Paveen et al., 2025).

2.5.1.3 Nitrogen Adsorption Isotherms

Nitrogen (N) adsorption isotherms play a key role in understanding how N interacts with solid surfaces in soils or soilless substrates like cocopeat, influencing its availability and mobility in plant root zones, particularly after the application of organic amendments such as biochar. These interactions are governed by several factors, including surface area, porosity, functional groups, and microbial activity (Eissa et al., 2024; Wu et al., 2025), as well as environmental variables like pH, reaction time, and initial N concentration (Gong et al., 2019). Biochar, especially when derived from pyrolyzed biomass such as pineapple leaf waste, possesses a high surface area and rich functional groups like carboxyl and hydroxyl, that enhance N adsorption.

Research by Li et al. (2023) indicates that biochar amendments can significantly improve N retention through both physical adsorption and chemical bonding with NH_4^+ and NO_3^-. Furthermore, biochar supports microbial activity, thereby boosting the effectiveness of microbial fertilizers and enriching the nutrient profile of the soil (Wang et al., 2022; Wang et al., 2023). Notably, based on study by Jos et al. (2024), PLB has been shown to reduce N leaching and improve N retention, particularly when used in combination with compound fertilizers.

On the other hand, biofertilizers also contribute to dynamic N cycling by enhancing microbial activity and enzyme production, which promotes greater N mineralization and retention within substrates. The interaction between microbial biomass and biochar surfaces can also facilitate N desorption, making it more gradually available to plants over time (García-Jaramillo et al., 2021; Sharifi & Hajiaghaei-Kamrani, 2023).

Commonly used models to describe N adsorption include the Langmuir and Freundlich isotherms (Lv et al., 2021; Eissa et al., 2024). The Langmuir model assumes monolayer adsorption onto a homogenous surface, indicating a finite number of adsorption sites. It is particularly useful when quantifying the maximum N adsorption

capacity (Q_m) of substrates like cocopeat that enriched with organic amendments. In contrast, the Freundlich isotherm accounts for multilayer adsorption on heterogeneous surfaces, which is often more realistic in biologically active systems such as those treated with TBF. In this study, Langmuir and Freundlich isotherm models were used as it effective in describing N adsorption on various biochars (Eissa et al., 2024; Lv et al., 2021).

The N adsorption data for the samples tested were fitted to Langmuir and Freundlich adsorption isotherms as given in equation 2.1 and 2.2, while the list of adsorption isotherms models used in this study showed in Table 2.3.

The linear form of the Langmuir isotherm is reported as:

$$C_e/q_e = C_e/q_m + 1/(q_m K_L) \quad (2.1)$$

where: C_e is the equilibrium concentration in a liquid phase (mg L^{-1}); q_e is the maximum amount of the 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:

$$\log(q_e) = \log(K_F) + 1/n \log (C_e) \quad (2.2)$$

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 2.3
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	$\log(q_e) = \log(K_F) + \frac{1}{n}\log(C_e)$	$\log(q_e)\ vs. \log(C_e)$	$K_F = antilog\ (intercept)$ $\frac{1}{n} = slope$

Source: Palanivell et al. (2020)

Understanding the N adsorption and desorption dynamics in cocopeat media enriched with PLB and TBF is crucial for optimizing nutrient use efficiency and improving the growth and yield of *C. chinense*. This knowledge also contributes to the sustainable utilization of agricultural waste, especially pineapple leaf waste and TBF as organic amendments in cocopeat medium. Since the interplay between adsorption and desorption directly affects the fertility of the growing medium and overall plant productivity, a clear understanding of these processes is essential for advancing sustainable agricultural practices and boosting crop performance.

2.5.2 Role of Biochar and Biofertilizers in Nutrient Retention

Biochar is increasingly recognized as a promising amendment for improving nutrient retention due to its high surface area, porosity, and cation exchange capacity (Khan et al., 2024; Kozioł et al., 2024). When derived from feedstocks such as pineapple leaf waste, biochar contributes to sustainable waste management and enhances soil nutrient dynamics. Previous research shows that PLB significantly increases soil CEC and nutrient content (Bohari et al., 2020). In addition to its physical and chemical retention mechanisms, biochar provides habitat for beneficial microorganisms, fostering long-term nutrient cycling (Murtaza et al., 2023).

Biofertilizers containing beneficial fungi such as *Trichoderma* spp. enhance nutrient retention through microbial immobilization, raised enzymatic activity, and improved nutrient solubilization. The integration of biochar with *Trichoderma* creates a synergistic effect, where biochar serves as both carrier and protective environment for

microbes, while the microbes enhance nutrient turnover and release in alignment with plant needs (Medeiros et al., 2020; Paveen et al., 2025).

2.5.3 Implications for Sustainable Agriculture

Enhancing nutrient retention in planting media offers multiple benefits for sustainable agriculture. It increases nutrient use efficiency, reduces dependency on chemical fertilizers, and mitigates environmental risks such as nutrient leaching (Schmidt et al., 2021; Sharma et al., 2025). For high-value crops like *C. chinense*, optimizing nutrient retention through amendments such as biochar and biofertilizers can lead to improved yield and quality while supporting environmentally responsible farming practices (Kebede et al., 2023).

2.6 Summary of Literature Review and Research Gaps

Based on the critical review of studies summarized in this chapter, several important research gaps were identified, particularly in relation to the combination of PLB and TBF in fertigated cocopeat media. While biochar and microbial biofertilizers have been widely studied, no research has specifically examined their combined application for the cultivation of *C. chinense* in fertigated cocopeat media. Most existing studies have focused on soil-based media, single amendments, or biochars with limited physicochemical characterization.

In addition, a limited number of studies have evaluated N adsorption and desorption behavior before and after planting. Despite N being the most dynamic and loss-prone macronutrient in fertigated cocopeat media, it is continuously required by plants from the vegetative stage through to flowering and fruit development, as nitrogen plays a central role in chlorophyll synthesis, photosynthetic capacity, enzyme activity, and the formation of proteins and nucleic acids that support both vegetative growth and reproductive development (Chawla & Sharma, 2024; Wang et al., 2024). Frequent irrigation and low buffering capacity of cocopeat media further increase the risk of N leaching, leading to reduced fertilizer use efficiency. Biochar can influence NH_4^+ and NO_3^- retention through surface functional groups, while *Trichoderma* plays a key role in N mineralization and microbial immobilization–remobilization processes. Therefore, nitrogen was selected as the focus of this study as it represents the most critical and

responsive nutrient for evaluating adsorption–desorption behavior and nutrient use efficiency in fertigated cocopeat media.

To address these gaps, this study integrates well-characterized PLB with TBF in a fertigated cocopeat media for the *C. chinense* plant, while systematically evaluating N adsorption and desorption behavior across the planting cycle. This approach provides new insights into biochar–microbe interactions in cocopeat media and supports sustainable nutrient management through the valorization of pineapple leaf waste.

CHAPTER 3
OPTIMIZATION OF BIOCHAR PRODUCTION FROM PINEAPPLE LEAF WASTE

3.1 Introduction

Sarawak, Malaysia is the second-largest producer, with a pineapple cultivation area of 9,782 hectares, and can produce 181,000 metric tons of pineapple annually (Malaysia Pineapple Industry Board, 2022). The pineapple industry in Sarawak supplies both domestic and international markets, contributing to the state's export earnings. Pineapple is typically harvested in fields by eliminating its inedible components, such as leaves and crowns. According to a study by Anukwah & Gadzekpo (2024) Malaysia produces approximately 500,000 tons of pineapple leaf waste annually. This substantial waste poses environmental challenges and calls for sustainable waste management strategies. The abundant and underutilized waste has the potential to be converted into value-added products such as biochar.

Biochar is a carbon-rich substance produced at temperatures above 300-400°C in an environment with limited or low oxygen levels (Basu, 2018). It has emerged as a potential solution for various environmental challenges, including soil degradation, carbon sequestration, and waste management. Converting pineapple leaf waste into biochar is sustainable and environmentally friendly and has gained significant attention in recent years. The PLB is an abundant and low-cost agricultural waste material that is rich in carbon and possesses unique physicochemical properties, such as high porosity and surface area. These properties make it an attractive material for various applications, particularly in agriculture and environmental remediation. There have been several studies on the characterization of biochar. However, the study on PLB characterization at different temperatures is still limited. According to Rodriguez Ortiz et al. (2020), the heating temperature during carbonization affects biochar yield, textural properties, functional groups, and elemental composition.

Given these circumstances, this study was to determine the optimum temperature to produce good quality PLB based on characterization. To assess the quality of PLB, it is necessary to characterize its properties through various analytical

analyses which consist of Brunauer-Emmet-Teller (BET) surface area, surface morphology, thermal stability, functional groups, and element composition. These analyses provide valuable information about the composition and structure of PLB, which can be used to determine its suitability as organic amendments in cocopeat media and understand its behavior.

3.2 Materials and Methods

3.2.1 Pineapple Leaf Sample Preparation

The raw biomass of pineapple leaf waste variety MD2 was obtained from small-scale farmers located in Kampung Meranek, Samarahan, Sarawak. The samples were washed and subsequently sun-dried and subjected to oven drying at a temperature of 60°C until they achieved a constant weight (Zainuddin et al., 2014). The sample was then crushed into a size of about 2 mm using a heavy-duty grinder (Claoston et al., 2014).



Figure 3.1 Sun Dried Pineapple Leaf Waste



Figure 3.2 Cut Pineapple Leaf

3.2.2 Pineapple Leaf Biochar Production

The production of PLB was done at Block H Laboratory, UiTM Sarawak Branch, Samarahan Campus, according to Jos et al. (2023) with modification. The samples were placed into ceramic crucibles with fitting lids and pyrolyzed in a large chamber muffle furnace (Daihan Scientific FH-14, Korea) at 300°C, 400°C, and 500°C for 2 hours. The moderate temperature (300-500°C) optimizes PLB yield and qualities, minimizing energy consumption while producing PLB with favorable structural and chemical attributes that can be used as an organic amendment (Lehmann & Joseph, 2009). Finally, the pyrolyzed samples were ground to a particle size that could pass through a 1 mm sieve and kept at room temperature before analysis (Bohari et al., 2020). After carbonization, the samples were reduced by 60-70% in weight. Figure 3.3 showed PLB produced at three different temperatures.

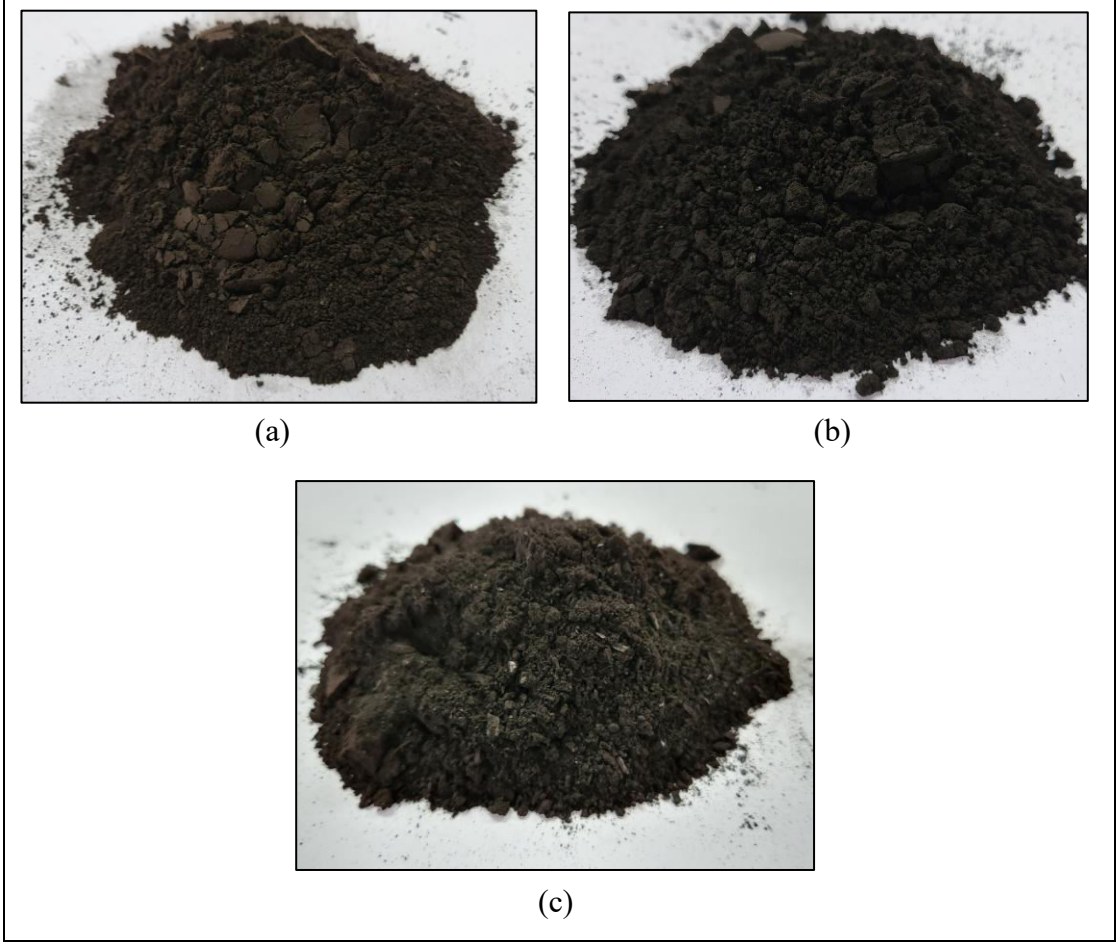


Figure 3.3 Pineapple Leaf Biochar Produced at (a) 300, (b) 400, and (c) 500°C

3.2.3 Moisture Content and Yield of Pineapple Leaf Biochar

For the moisture content, the PLB sample was oven-dried at 105°C for 24 hours (Abdul Halim et al., 2024). The moisture content (wet basis) of the PLB sample was calculated according to Gupta (2007). The moisture content was calculated as follows:

$$\text{Moisture content (\%)} = \frac{(Initial\ weight - Dried\ weight)\ g}{Initial\ weight\ (g)} \times 100\% \qquad (3.1)$$

The yield of the PLB sample was measured to determine the produced recovery after being pyrolyzed under different temperatures. The yield of PLB sample was calculated as follows:

$$\text{Biochar yield (\%)} = \frac{Mass\ of\ biochar\ (g)}{Mass\ of\ raw\ material\ after\ oven\ dry\ (g)} \times 100\% \quad (3.2)$$

3.2.4 pH and Electrical Conductivity Analysis

The pH value of the PLB was measured according to Abdul Halim et al. (2024). The ratio was 10 g of biochar to 25 mL of distilled water (1:2.5). The sample was shaken for 60 minutes at 245 rpm on a Digital Orbital Shaker (Daihan SHO-1D, SHO-2D, Korea). The pH electrode (Hanna Instruments HI-83141-1, UK) was placed in the supernatant solution to measure the pH. The pH value was recorded.

For electrical conductivity (EC) values of the samples, the Bohari et al. (2020) method was used. The 10 g PLB sample was immersed in 50 mL of distilled water (ratio of 1:5), and the mixture was shaken for 60 minutes at 245 rpm on Digital Orbital Shaker (Daihan SHO-1D, SHO-2D, Korea). An EC meter (Mettler Toledo, USA) was used to measure and record the EC. The EC electrode was placed into the supernatant solution to obtain the EC value. The EC value was recorded.

3.2.5 Pineapple Leaf Biochar Characterization

Pineapple leaf biochar characterization was conducted before the application to *C. chinense* plants based on methods adopted by Abdul Halim et al. (2024). The physicochemical properties of PLB were assessed based on the following analysis: Brunauer-Emmet-Teller (BET) surface area; surface morphology using Field Emission Scanning Electron Microscopy (FESEM); functional groups using Fourier-transform Infrared Spectroscopy (FTIR); thermal stability using Thermogravimetric Analysis (TGA); and element composition using CHNS analyzer.

3.2.6 Surface Area

The BET surface area, pore size, surface area distributions, micropore volume, and surface area of PLB were determined using N adsorption at 77 K with a 3 Flex Surface Characterization Analyser (Micromeritics Instrument Corporation; Norcross, GA). Before analysis, the biochar was degassed at 300°C under inert conditions for 24 hours.

3.2.7 Surface Morphology

Biochar surface morphologies are performed using Field Emission Scanning Electron Microscopy FESEM((Hitachi SU8220, Japan). The sample was prepared by applying carbon to the sample's outer layer, and the elemental components were identified using microscopy (Bohari et al., 2020).

3.2.8 Functional Groups

The functional group characterization in the 400–4000 cm^{-1} range was identified using a Fourier-transform Infrared (FTIR) Spectroscopy (Spectrum 100, Perkin Elmer, USA). A 1% sample pellet was produced using spectrophotometric potassium bromide (KBr) to prepare the sample.

3.2.9 Thermal Stability

Thermogravimetric analysis (TGA) is conducted to understand how the weight of material changes as it is subjected to a controlled temperature increase. This method assists in identifying the characteristics and behaviors of materials, such as their composition, moisture content, decomposition temperature, and thermal stability. Thermogravimetric Analyzer (TGA 4000, Perkin Elmer, USA) was used to perform the TGA. The samples were heated to a temperature of 550°C in an aluminum pan.

3.2.10 Element Composition

The elements C, N, and S of PLB were analyzed using a CHNS analyzer (LECO Corporation, CHNS 628, St. Joseph, MI, USA). Samples were degassed at 200 for 12 hours. The P and K content in PLB were determined using a sulfuric acid digestion spectrophotometer and flame photometric respectively.

3.2.11 Statistical Analysis

Statistical analysis was conducted using Minitab 21 (Version 2.1) to perform an analysis of variance (ANOVA). The significant difference between means was

determined at $p<0.05$, and Tukey's Test ($\alpha = 0.05$) was employed for means comparison.

3.3 Results and Discussion

3.3.1 Moisture Content and Yield of Pineapple Leaf Biochar

The mean moisture content of pineapple leaf was calculated using equation (3.1). The mean moisture content recorded was 70.92% (wet basis) and 11.46% (dry basis), indicating that pineapple leaf has a high moisture biomass. Although the dry-basis moisture content observed in this study was higher than values reported by Zainuddin et al. (2014), who documented moisture contents of 9.42%, 7.87%, and 7.23% for Josapine, MD2, and Moris varieties, respectively, the difference can be attributed to variations in cultivar, leaf maturity, harvesting conditions, and post-harvest handling prior to analysis. Nevertheless, both studies consistently demonstrate that pineapple leaf possess relatively high moisture content, which is a key characteristic influencing their suitability for thermochemical conversion processes. As for the yield of PLB, Table 3.1 showed the data for biochar yield that produced at three different temperatures (300, 400, and 500°C).

Table 3.1
Pineapple Leaf Biochar Yields at Different Temperatures

Temperature (°C)	Yield (%)
300	47.84 ± 1.38^{a}
400	41.17 ± 0.30^{b}
500	37.24 ± 0.57^{c}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant difference ($p>0.05$) according to Tukey's Test ($\alpha = 0.05$).

The statistical analysis observed a significant difference ($p<0.05$) in PLB yield produced at different temperatures. The PLB yield was highly produced at a temperature of 300°C (47.84%), followed by 400°C (47.17%), and the lowest was recorded at 500°C (37.24%). This finding aligns with a study by Nuwarapaksha et al. (2024), reported that biochar yield produced from *Gliricidia sepium* decreased from 38.17% at 325°C to 27.43% at 700°C. Coconut flesh waste biochar reduced from 23.54% at 350°C to 13.97% at 600°C (Noor et al., 2019).

The reduction in biochar yield at higher temperatures is mainly due to increased thermal decomposition and volatilization of biomass components. At lower temperatures, a larger fraction of fixed carbon remains in the solid phase. As the temperature increases, greater degradation of hemicellulose and cellulose, along with continued lignin breakdown, releases more volatile compounds and gases, thereby reducing the remaining solid biochar. In addition, secondary cracking reactions at higher temperatures further convert solid carbon into gaseous products, resulting in lower biochar yield.

Compared to other studies that use similar feedstock, Hanyabui et al. (2024) found that the output of pineapple waste biochar was 54% (550°C) decreased by 46%. Bohari et al. (2020) stated that the yield of PLB produced was reduced by 48.57% when pyrolyzed at 350°C. However, this study reduced the PLB produced by 50 to 65% in weight after pyrolysis. The findings emphasize the sustainability of pineapple leaf waste as a significant feedstock for biochar production with relatively high yields. Pineapple leaf biochar can be considered as one of the prospective resources for substrate enhancement and agricultural uses.

3.3.2 pH and Electrical Conductivity Analysis of Pineapple Leaf Biochar

The study on pH and EC analysis of the PLB is important to determine the acidity and alkalinity of the samples as it is associated with the presence of functional groups on its surface (Abdul Halim et al., 2024). The statistical analysis of the pH and EC values are significantly difference ($p<0.05$) among different temperatures. Based on Table 3.2, the PLB produced at lower temperatures exhibited lower pH and EC values, whereas higher pyrolysis temperatures resulted in increased alkalinity and salinity.

Table 3.2
The pH and EC of PLB Pyrolyzed at Different Temperatures

Temperature (°C)	pH	Electrical conductivity (dS m^{-1})
300	8.57 ± 0.03^{c}	8.12 ± 0.94^{c}
400	10.17 ± 0.03^{b}	16.00 ± 0.67^{b}
500	10.80 ± 0.15^{a}	17.90 ± 0.51^{a}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant difference ($p>0.05$) according to Tukey's Test ($\alpha = 0.05$).

The PLB pyrolyzed at 300°C showed significantly lower pH (8.57) and EC (8.12 dS m^{-1}) than other temperatures. In contrast, PLB pyrolyzed at a higher temperature of 500°C gave a high pH (10.80) and EC (17.90 dS m^{-1}). All the PLB samples were classified under the alkaline group (pH > 7). A study by Leng et al. (2017) found pineapple leaf residues char produced by controlled combustion and by open burning show high pH (>9) and salinity (>7 mS cm^{-1}). Bohari et al. (2020) reported that the pH value of PLB is 8.78, while the EC value is 7.38 (mS cm^{-1}). Moreover, Hanyabui et al. (2024) observed that the pH of PLB is under an alkaline group, 9.8.

The increase in pH and EC with increasing pyrolysis temperature is consistent with well-established biochar formation mechanisms. Higher pyrolysis temperatures promote the thermal decomposition and removal of acidic surface functional groups, such as carboxyl and phenolic groups, while simultaneously concentrating inorganic ash constituents that are generally alkaline in nature (Wystalska & Kwarciak-Kozlowska, 2021). Although specific base cations were not directly quantified in this study, previous studies have demonstrated that biochar produced at elevated temperatures typically contain higher proportions of basic mineral elements, including Ca, Mg, K, and Na, present in the form of carbonates, oxides, or hydroxides. These inorganic components are known to contribute to increased alkalinity and salinity when biochar is in contact with water (Yuan et al., 2011).

Similarly, the higher EC values observed at elevated temperatures are likely associated with the increased concentration of soluble inorganic salts following the loss of organic matter during pyrolysis. As volatile organic fractions are removed, remaining mineral ions become more concentrated and readily soluble, resulting in increased electrical conductivity (Méndez et al., 2013; Guo et al., 2025). Therefore, the observed increases in pH and EC reflect temperature-driven changes in biochar chemistry and mineral concentration, consistent with established biochar behavior.

The alkaline pH and high EC value suggest that PLB could be impactful as a organic amendment, significantly raising substrate pH. The alkaline nature of PLB makes it beneficial for amending acidic soil as it acts as a liming material that can help to neutralize acidic soil, especially highly weathered soils such as Oxisols (Jos et al., 2024). Enhancing substrate pH is essential as it directly boosts fertility and promotes plant growth. The availability of specific nutrients is affected by the pH level. Therefore, for acidic substrate, applying PLB can help to release nutrients that may be bound or unavailable due to low pH conditions (Bohari et al., 2020).

3.3.3 Surface Area of Pineapple Leaf Biochar

The analysis of surface area as well as pore properties of PLB at three different temperatures, are shown in Table 3.3. Observations indicate that the PLB's BET surface area, total pore volume, as well as micropore volume, significantly increased with rising temperature.

Table 3.3
Pore Properties of PLB Pyrolized at Different Temperatures

Pore property	Single point surface area ($m^2 g^{-1}$)	BET surface area ($m^2 g^{-1}$)	Langmuir surface area ($m^2 g^{-1}$)	t-plot external surface area ($m^2 g^{-1}$)	Total pore volume ($cm^3 g^{-1}$)	t-plot micropore area ($cm^3 g^{-1}$)	Mean pore diameter (nm)
300°C	6.9559	7.6595	8.7952	8.4323	0.0028	0.0027	3.5855
400°C	8.0200	8.1494	9.0540	14.7590	0.0069	0.0033	2.0202
500°C	19.2267	19.4152	21.4702	17.5377	0.0098	0.0069	1.3782

The BET surface area of PLB increased from 7.6595 $m^2 g^{-1}$ at 300°C to 8.1494 $m^2 g^{-1}$ at 400°C, and rose sharply to 19.4152 $m^2 g^{-1}$ at 500°C, indicating substantial structural reorganization and pore development at higher temperatures. A similar trend was observed for Langmuir surface area, confirming the formation of a more developed porous structure at elevated pyrolysis temperatures.

Total pore volume increased steadily from 0.0028 $cm^3 g^{-1}$ (300°C) to 0.0098 $cm^3 g^{-1}$ (500°C), accompanied by an increase in micropore area from 0.0027 to 0.0069 $cm^3 g^{-1}$, suggesting that higher pyrolysis temperatures promoted the formation of finer pores. This enhancement in microporosity is attributed to the progressive release of volatile matter and the aromatization of the carbon matrix, which generate new pore channels and enlarge the internal surface area of the biochar.

In contrast, the average pore diameter decreased consistently from 3.5855 nm at 300°C to 2.0202 nm at 400°C and 1.3782 nm at 500°C, indicating a shift from wider pores towards a micropore-dominated structure as pyrolysis temperature increased. This inverse relationship between pore diameter and surface area reflects the increased formation of micropores due to volatilization of organic components and aromatization of the carbon matrix.

This finding aligned with Bakhtiar et al. (2019), who observed that BET surface area, total pore volume, as well as micropore volume increased with temperature during EFB biochar production. A comparable trend was also reported by Mohamed et al. (2010), who observed that increasing pyrolysis temperature led to a reduction in mean pore diameter of activated carbon samples, resulting in enhanced micropore formation and higher surface area. Similar trends in BET surface area, mean pore size and pore volume were also examined for biochar derived from acorn shell (Saka, 2012) and forestry waste that produced at higher temperatures (Abdul Halim et al., 2024). These consistent trends support the structural evolution observed in PLB produced at elevated temperatures.

The surface area of PLB directly influences the adsorption capacity of the substrate, where the larger surface area will provide more sites for the adsorption of various substances, for example, nutrients, water, organic compounds, heavy metals, and pollutants (Zhao et al., 2019). This characteristic makes PLB with a large surface area functional with regard to substrate improvement and environmental remediation (Skic et al., 2024; Zhou et al., 2024).

Application of PLB on the substrate can improve fertility, as it may enhance the properties, which include increasing the water holding, nutrient retention, as well as cation exchange capacity (Skic et al., 2024). Furthermore, the porous nature of PLB with a large surface area provides a favorable habitat for various beneficial soil microorganisms, directly enhancing the substrate biological activities. Determining the PLB surface area is crucial in assessing the effectiveness and potential application to the substrate, as it influences the effectiveness in various applications.

Overall, PLB produced at 500°C exhibited the most developed pore structure, characterized by the highest surface area, greatest pore volume, and smallest average pore diameter. These properties are particularly favorable for nutrient retention and adsorption processes, supporting the potential application of PLB as a functional biochar amendment in fertigated cocopeat media.

3.3.4 Surface Morphology of Pineapple Leaf Biochar

Field Emission Scanning Electron Microscopy (FESEM) was used to investigate the surface morphology of PLB. It is a powerful tool for biochar characterization as it provides high-resolution images of the biochar's surface

morphology, to observe the physical structure of the biochar, such as its pore size and distribution, surface roughness, and presence of impurities or mineral deposits. Regarding surface texture and pore size distribution, there are general distinguishable differences in PLB produced as shown in Figure 3.4.

According to Bohari et al. (2020), the pore structure of raw pineapple leaf was well-established and smaller than that of PLB. After carbonization, it was observed that the biochar produced had large pores that exhibited a variety of pore shapes, appeared fractured due to its thin walls, and was quickly destroyed by pyrolysis. This finding supported the study of Ahmad et al. (2012), which found that removing volatile material at high pyrolysis temperatures causes an increase in surface area and decreases micropore volume.

As illustrated in Figure 3.4. (a), the development of micropores on the surface of PLB became more obvious but still barely noticeable as carbonization began at 300°C. During 400°C, the pore size expanded, and the development of macropores in PLB became more prominent, as illustrated in Figure 3.4. (b). Simultaneously, upon reaching a pyrolysis temperature of 500°C, numerous macropores were observed on the surface of PLB, together with visible micropores, as shown in Figure 3.4. (c).

Large pores in PLB allow increased water and nutrient retention in medium when used as an organic amendment. The pores act as reservoirs, holding onto water and nutrients and releasing them slowly over time, promoting optimal plant growth and reducing the need for frequent irrigation and fertilization. In addition, the presence of large pores has a greater surface area which enhances its absorption capability, allowing it to effectively capture and remove contaminants from medium (Horák et al., 2021). These large pores also create a network of pathways through which water and other substances can flow, facilitating the movement and distribution of nutrients in the medium. This is particularly beneficial for plants, as it ensures they access a consistent water supply and nutrients (Zhao et al., 2022).

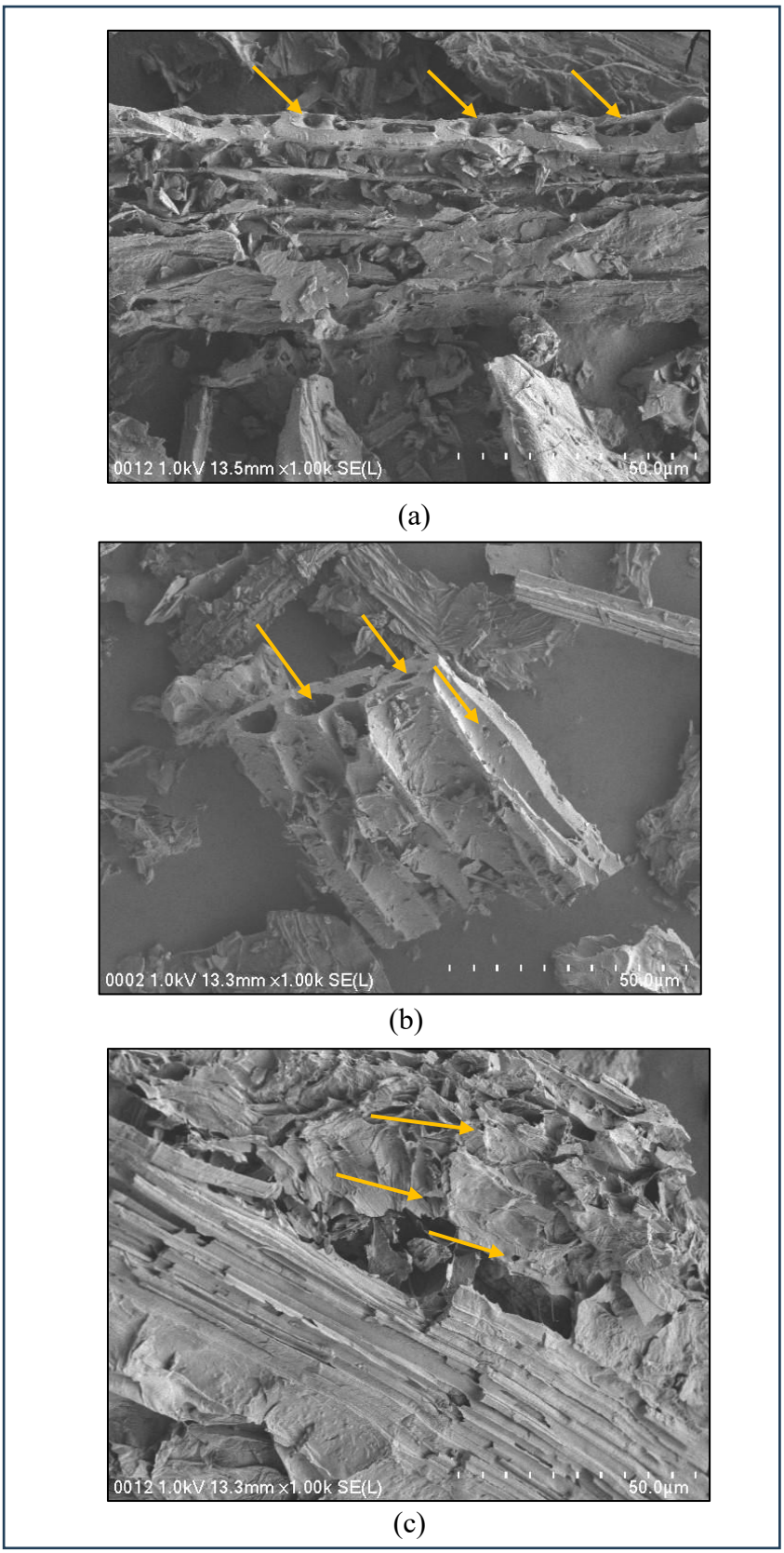


Figure 3.4 Surface Morphology of PLB Pyrolyzed at (a) 300, (b) 400, and (c) 500°C Respectively

3.3.5 Functional Groups of Pineapple Leaf Biochar

Fourier-Transform Infrared Spectroscopy (FTIR) was used to identify the effect of activation on the surface chemistry of the PLB samples produced at different temperatures. The summary of functional groups for PLB based on adsorption peak from FTIR spectra is shown in Table 3.4.

Table 3.4
Summary of Major Functional Groups of PLB Identified by FTIR Spectroscopy

Temperature	Wave number (cm^{-1})	Functional group
300	3306.25	Hydroxyl (-OH) stretching (alcoholic and phenolic groups)
	2925.54	Aliphatic C-H stretching
	779.74	Aromatic C–H bending (out-of-plane)
	612.10	Inorganic / mineral-related vibration
	1570.00	Aromatic C=C stretching
	1407.30	Aromatic C=C / carboxylate vibration
	1113.43	C–O stretching (phenols/alcohols/ethers)
400	3306.49	hydroxyl (-OH) stretching (alcoholic and phenolic groups)
	2164.69	Weak C≡C / possible inorganic-related vibration
	1568.44	Aromatic C=C stretching
	1400.07	Aromatic C=C / possible carboxylate vibration
	1119.53	C–O stretching (phenols/alcohols/ethers)
	872.68	Aromatic C–H bending
	755.97	Inorganic / mineral-related vibration
	595.66	Inorganic / mineral-related vibration
500	3181.04	Hydroxyl (-OH) stretching (alcoholic and phenolic groups)
	2164.81	Weak C≡C / possible inorganic-related vibration
	1405.15	Aromatic C=C / possible carboxylate vibration
	1130.20	C–O stretching (phenolic groups)
	873.05	Aromatic C–H bending
	821.11	Aromatic C–H bending
	692.20	Aromatic C–H bending
	590.43	Inorganic / mineral-related vibration

*Note: Functional group assignments are based on characteristic FTIR absorption regions commonly reported for biomass-derived biochar. Minor peaks in the low wavenumber region may also include contributions from inorganic or mineral-related vibrations.

Regarding Table 3.4, for PLB produced at 300°C, a broad adsorption band at 3306.25 cm^{-1} was observed and attributed to the O-H stretching vibrations, representing hydroxyl functional groups associated with alcoholic and phenolic structures. Bands at 2925.54 cm^{-1} correspond to aliphatic C-H stretching, while the absorption at 779.74 cm^{-1} is attributed to aromatic C-H out-of-plane bending. The low wavenumber band at 612.10 cm^{-1} may include contributions from inorganic or mineral-related vibrations, as commonly reported for biomass-derived biochar (Claoston et al., 2014). The adsorption bands at 1570.00 cm^{-1} and 1407.30 cm^{-1} are attributed to aromatic C=C stretching and possible carboxylate-related vibrations within the aromatic framework (Bohari et al., 2020). In addition, the band at 1113.43 cm^{-1}corresponds to C-O stretching associated with phenolic, alcoholic, or ether functional groups.

As for PLB produced at 400°C, a broad O–H stretching band remained evident at 3306.49 cm^{-1}, indicating the persistence of hydroxyl (alcoholic and phenolic) groups. A weak band at 2164.69 cm^{-1} may be associated with weak C≡C vibrations or inorganic-related contributions. The prominent bands at 1568.44 cm^{-1} and 1400.07 cm^{-1} are assigned to aromatic C=C stretching and possible carboxylate vibrations, reflecting increased aromatization with temperature. The C–O stretching band at 1119.53 cm^{-1} suggests the continued presence of phenolic and alcoholic functionalities, while the band at 872.68 cm^{-1} is attributed to aromatic C–H bending. Minor absorptions at 755.97 cm^{-1} and 595.66 cm^{-1} are interpreted as inorganic or mineral-related vibrations rather than specific halogenated groups.

Finally, for PLB produced at 500°C, the broad absorption peak at 3181.04 cm^{-1} indicates O–H stretching from residual hydroxyl (alcoholic and phenolic) groups. A weak band at 2164.81 cm^{-1} may reflect C≡C or inorganic-related vibrations. The absorption at 1405.15 cm^{-1} is attributed to aromatic C=C stretching and possible carboxylate vibrations, consistent with enhanced carbonization and aromaticity at higher pyrolysis temperatures. The band at 1130.20 cm^{-1} corresponds to C–O stretching of phenolic or alcoholic groups. Additional bands at 873.05 cm^{-1} and 821.11 cm^{-1} are assigned to aromatic C–H bending, while low-wavenumber features at 692.20 cm^{-1} and 590.43 cm^{-1} are likely associated with inorganic or mineral-related vibrations.

The chemical functional groups on the surface of PLB play an important role in its adsorption behaviors. Overall, the FTIR spectra exhibit similar band patterns across pyrolysis temperatures, with changes mainly in band intensity rather than the appearance of new functional groups, in agreement with Bakhtiar et al. (2019). The

dominance of hydroxyl-related bands is associated with cellulose and hemicellulose components in the original pineapple leaf biomass (Wafti et al., 2017; Bakhtiar et al., 2019). With increasing temperature from 300 to 500°C, enhanced aromatization and changes in C–H-related bands reflect progressive carbonization of the biochar matrix (Song et al., 2024).

These observations indicate degradation and depolymerization of cellulose, hemicellulose, and lignin during pyrolysis, leading to a more aromatic and thermally stable biochar structure (Cantrell et al., 2012; Zainuddin et al., 2014; Bohari et al., 2020). Overall, FTIR analysis provides information on the chemical composition of PLB by analyzing the infrared spectra of biochar to identify the types and abundance of functional groups present, which are closely related to its potential reactivity and adsorption–desorption behaviour (Kirmizakis et al., 2020).

3.3.6 Thermal Stability of Pineapple Leaf Biochar

Thermogravimetric analysis (TGA) is an instrument commonly used to characterize PLB in term of thermal stability. It involves subjecting the PLB sample to a controlled temperature increase while continuously monitoring its weight loss. This allows determining the PLB's thermal stability, decomposition behavior, and volatile matter content. The thermal stability of biochar is an important factor as it influences its suitability for different applications. For example, biochar with high thermal stability would be desirable for applications such as organic amendment, which needs to retain its structure and properties over time. This information is crucial in determining the optimal temperature range for applying biochar in various fields. Figure 3.5 illustrates the thermal analysis for PLB.

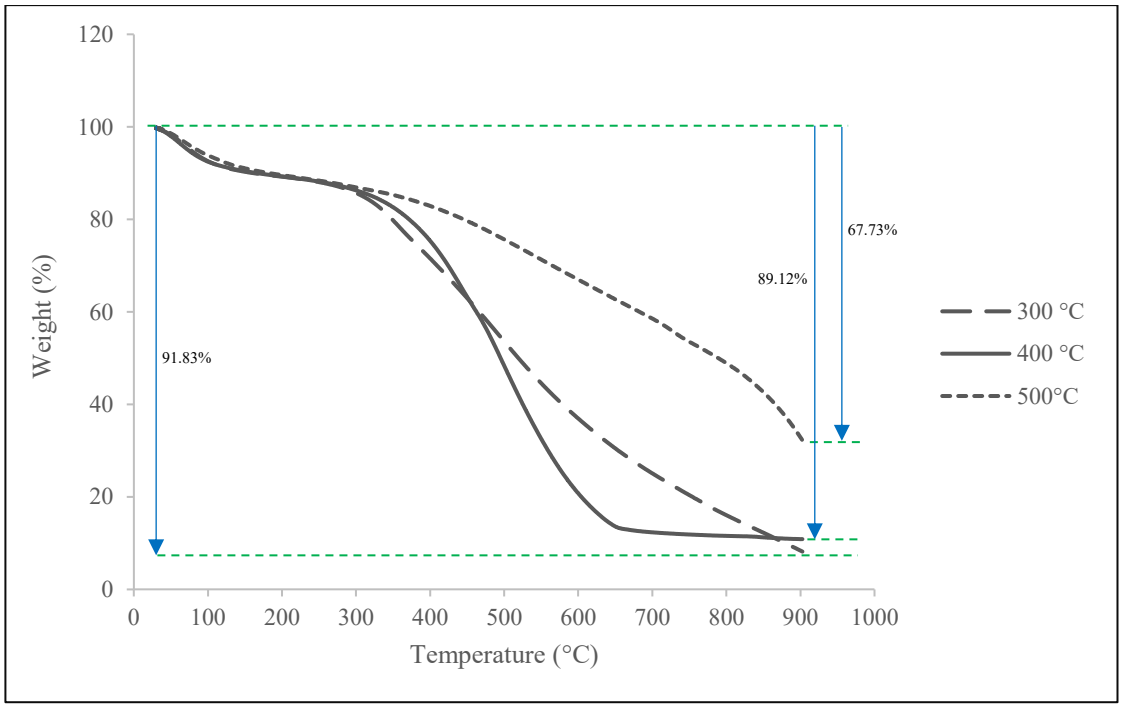


Figure 3.5 Thermal Analysis of PLB Pyrolyzed at (a) 300, (b) 400, and (c) 500°C, Respectively

The TGA graph of PLB in Figure 3.5 demonstrated a weight reduction from 30 to 900°C. The thermogram indicates that the highest total weight loss occurred at 300°C, reaching 91.83%. At a temperature of 500°C, the PLB exhibited the lowest weight loss, recorded at 67.73%. A temperature of 400°C was noted to result in a loss of 89.12%. The weight loss at 400 and 500°C is significantly slower than at 300°C, suggesting that biochar produced at higher temperatures is more stable (Song et al., 2024). Corroborate with Călin et al. (2024), who discovered that weight loss rates consistently decrease at elevated temperatures, suggesting the development of more stable carbon structures.

Based on the thermogram presented, the active pyrolysis stage occurs between 200 to 600°C, during weight loss resulting from the volatilization of cellulose and hemicellulose, while at the final stage, from 600 to 900°C, weight loss is due to the decomposition of lignin (Reza et al., 2023; Abdul Halim et al., 2024). Md Yunos et al. (2012) identified three stages of thermal degradation in biochar samples, including moisture removal, hemicellulose decomposition, and degradation of cellulose and lignin. Hemicellulose is the component that is most easily decomposed when subjected to thermal processes, with cellulose and lignin following in terms of thermal stability (Yang et al., 2007). The decomposition of hemicellulose and cellulose took place in the

ranges of 200 to 315°C and 315 to 400°C, respectively, whereas lignin decomposition was observed within the range of 160 to 900°C (Zainuddin et al., 2014).

In comparison with the finding by Călin et al. (2024), hemicellulose decomposed at temperatures within 200 to 260°C, cellulose decomposed at temperatures between 240 to 350°C, and lignin decomposed at temperature range 280 to 500 °C or higher. The decomposition of the primary components is represented by a significant weight loss in the TGA graph for PLB, which usually occurs between 300 to 500°C. It is crucial to demonstrate TGA analysis as it helps in understanding the thermal stability and composition of the biochar, which is vital for its potential applications in agriculture and environmental management.

3.3.7 Element Composition of Pineapple Leaf Biochar

The pyrolysis temperature in preparation for PLB determines the content of the N, S, P, and K, as well as C in it. Chemical analysis has determined that these elements in PLB are produced at 300, 400, and 500°C. The result of the elemental composition of PLB at variation pyrolysis temperatures is outlined in Table 3.5.

Table 3.5
Selected Chemical Characteristics of PLB at Different Pyrolysis Temperatures

Element	C (%)	N (%)	S (%)	P (%)	K (%)
300°C	55.00 ± 0.13^{c}	2.19 ± 0.02^{a}	0.20 ± 0.01^{a}	0.23 ± 0.01^{b}	2.10 ± 0.14^{b}
400°C	57.80 ± 0.16^{b}	2.11 ± 0.04^{ab}	0.22 ± 0.03^{a}	0.27 ± 0.01^{ab}	2.46 ± 0.01^{a}
500°C	59.90 ± 0.31^{a}	1.85 ± 0.10^{b}	0.14 ± 0.02^{a}	0.29 ± 0.01^{a}	2.23 ± 0.01^{ab}

*Note: Mean ± standard deviation of mean was analyzed by ANOVA.

Data in Table 3.5 showed that the C and P content increases with increased temperatures (Song et al., 2024). The higher C content results from the incomplete pyrolyze of organic matter at low temperatures, while the organic matter undergoes progressive pyrolyzed at high temperatures. Note that the PLB's C content rose 8.91% from 55.00% (300°C) to 59.90% (500°C). In contrast, the P content increased from 0.23% (300°C) to 0.29% (500°C), with an increment of 26.09%. As for the N, content decreased gradually with increased temperatures (Song et al., 2024). The N content decreased by 15.53% from 2.19% (300°C) to 1.85% (500°C). Meanwhile, for S and K, the content was fluctuated. Temperature 400°C records the highest content for both S

(0.22%) and K (2.46%). From the data, PLB contains a high K, followed by N, P, and S.

These results supported Ch'ng et al. (2016), that PLB contains a high amount of K (2.67%), followed by N (2.30%) and P (0.46%), which can improve plant yield as C, N, S, P, and K are the crucial elements for healthy plant growth and development. Potassium is an essential nutrient for *C. chinense* as it is involved in numerous physiological processes crucial for overall plant health, which aids in the uptake of water and other nutrients, ensuring the plants have the necessary resources for growth and development. It also plays a key role in photosynthesis, which by activating enzymes involved in photosynthesis, K helps optimize the plant's ability to produce energy and thus enhances its overall productivity.

A comparable result was stated by Bohari et al. (2020) that the high N (8.33%) and K (48.32%) content of PLB and a high C/N ratio (50-70%) supplement the plant's nutrition and increase the fertility of the substrate. The higher C/N ratio of PLB can improve soil structure and boost microbial activity, enhancing overall soil health. The pyrolysis procedure increased the nutrient content of PLB, while its porous structure improved nutrient retention and availability. In addition, the alkaline properties of PLB can help to raise the soil pH, enhancing nutrient availability. Therefore, the slow-release characteristics of PLB ensure a consistent supply of nutrients over the growth period, minimizing nutrient loss and improving overall plant nutrition. These findings indicate that combining PLB and TBF in cocopeat medium can improve the growth performance and yield production of *C. chinense* due to the higher K content in both organic amendments.

3.4 Conclusion

This study successfully optimized the production of PLB from underutilized MD2 pineapple leaf waste, identifying 500°C was the most suitable pyrolysis temperature. At this temperature, PLB exhibited superior physicochemical properties, including a high pH (10.80), elevated EC (17.90 dS m^{-1}), substantial BET surface area (19.4152 m^2 g^{-1}), notable total pore volume (0.0098 cm^3 g^{-1}), and enriched carbon (59.90%), and phosphorus (0.29%) content. Scanning electron microscopy revealed well-developed macro and micropores, while enhanced aromaticity and stablility futher confirmed the structural and chemical advantages of PLB produces at this temperature.

Given these attributes, 500°C is recommended as the optimal condition for producing high quality PLB. This optimized biochar was subsequently applied in combination with TBF to evaluate its effect on the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media.

CHAPTER 4
THE EFFECTS OF PINEAPPLE LEAF BIOCHAR AND *TRICHODERMA* BIOFERTILIZER APPLICATION ON THE GROWTH, YIELD, AND NUTRIENT CONTENT OF *CAPSICUM CHINENSE* PLANT GROWN IN FERTIGATED COCOPEAT MEDIA

4.1 Introduction

Currently, *C. chinense* is a popular cash crop cultivated by smallholders due to the high demand from the local market and abroad. *Capsicum chinense* is known for its high spiciness level compared to other chili types (Septiana et al., 2023). The current demand for *C. chinense* in Malaysia and globally is steadily increasing. This can be seen from the growing popularity of spicy foods and the increasing number of restaurants and food businesses incorporating *C. chinense* into their menu items. Besides being consumed fresh, *C. chinense* can be processed into different products, contributing to its economic sustainability in Malaysia. Value-added processing techniques are key in transforming *C. chinense* into sauces, purees, powders, and seasonings, offering diverse avenues for its utilization and marketability. This increases its shelf life, expands farmers' opportunities to cater to different consumer preferences, and expands their market reach.

Furthermore, Malaysia's tropical climate provides favorable conditions for *C. chinense* production, in which warm and humid weather allows for year-round cultivation, ensuring a continuous supply of fresh *C. chinense*. The Sarawak government aims to shape the Revolution, 4.0 agricultural economy, and promote modern agriculture as a rural community business, *C. chinense* planting utilizing fertigation techniques gained popularity and preference among smallholders because of the high-profit income. However, the expansion of the *C. chinense* growing area has resulted in a rise in the usage of agricultural inputs, primarily chemical fertilizers, resulting in harmful impacts on the planting medium and water (Chiquito-Contreras et al., 2017).

Chemical fertilizers are crucial in *C. chinense* production, providing the necessary nutrients for the plants to thrive and produce high yields. Most of the growers have been utilizing the fertigation method to apply fertilizer to their crops. This method is highly effective in increasing agricultural output, particularly in terms of yield Halifu et al. (2019). One key advantage of fertigation is its ability to ensure efficient nutrient management by simultaneously delivering water and essential nutrients.

However, it is worth noting that the use of chemical fertilizers in fertigation is not without its drawbacks. According to Rawat et al. (2019), the widespread use of chemical fertilizers decreases the nutrient composition of crops and medium fertility over time. The fertigation system commonly used to plant *C. chinense* relies on chemical fertilizer that can increase the cost of production and may reduce the medium quality. Additionally, uncontrolled use of chemical fertilizers in unbalanced circumstances has been shown to cause loss of fertility, plant medium health, multiple nutrient deficiencies, and microbial activity loss, which reduce crop productivity and quality. Therefore, chemical inputs should be reduced, and regenerative farming methods must be implemented to revitalize the planting medium and ensure a sustainable future.

In recent years, organic amendments such as biochar and biofertilizers have been introduced as stable and effective methods to restore medium fertility. Biochar is a porous, carbon (C)-rich material resulting from the pyrolysis of various organic wastes without oxygen. The primary goals of biochar production are to reduce waste, recycle nutrients, and convert beneficial bio waste into carbon-rich goods for the environment. There have been publications on producing and characterizing biochar from various agro waste. However, the environmental benefits of pyrolysis and the PLB as a feedstock are still in their infancy. Based on its physio-chemical properties and nutritional analysis as a fertility index indicator, the present study was designed to comprehensively assess the influence of PLB potential in cocopeat medium as soil amendments instead of conventional soil media.

A Sánchez-Reinoso et al. (2020) study stated that PLB has a high potassium content. Supported study by Bohari et al. (2020) the high N and P content of PLB, at 8.33% and 48.32%, respectively, and a high C/N ratio (50-70), supplement the plant's nutrition and increase the fertility of the medium. Pineapple waste production averages 13 tonnes per hectare per season (Choo et al., 2021). Although in situ burning of pineapple residues is commonly practiced to suppress insect and disease outbreaks, this

approach provides limited benefits in terms of improving macronutrient availability or crop yield. In contrast, converting pineapple leaf waste into biochar enables the recycling of nutrients, reduces environmental pollution associated with open burning, and supports more sustainable agricultural practices. Furthermore, the use of pineapple leaf biochar enhances the economic value of agricultural waste (Rabiu et al., 2018), while improving soil nutrient availability, acidity regulation, and sorption capacity (Rawat et al., 2019).

In addition to biochar, the application of beneficial soil microorganisms such as *Trichoderma* has been widely studied as an alternative to chemical fertilizers due to their roles in enhancing nutrient availability and plant health. Previous studies by Halifu et al. (2019) and Nahidan et al. (2019), *Trichoderma* is fast-growing and has strong vitality that makes it occupy the plant rhizosphere rapidly and increase the availability of the nutrients needed. Moreover, *Trichoderma* species are well known for their antagonistic activity against soil-borne plant pathogens through mechanisms such as competition for space and nutrients, mycoparasitism, and the production of antifungal metabolites, making them effective biological control agents in various cropping systems (Kaewsalong et al., 2019).

The combined application of PLB and TBF is believed can be more effective compared to a single application of organic amendment. Biochar improves the physical and chemical properties of the media, particularly structure, nutrient retention, and sorption capacity, while *Trichoderma* enhances biological processes such as nutrient cycling nutrient mobilization, disease suppression, and root health. Through these complementary mechanisms, their combination may improve nutrient use efficiency, reduce reliance on chemical fertilizers, and promote plant growth and yield more effectively than either amendment applied alone. Therefore, this study evaluated the effect of combining PLB and TBF on the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media, with the aim of reducing reliance on chemical fertilizers in commercial *C. chinense* production.

4.2 Materials and Methods

4.2.1 Site Description

The field study was conducted at Farm Unit, UiTM Sarawak Branch Samarahan Campus, Sarawak, Malaysia, at latitude “1°26'46.5" N” and longitude “110°27'08.3" E” (1.446256, 110.452313), under the rain shelter equipped with a fertigation system, similar condition to small-scale holder setting in Rampagi, Kuching. The temperature at the study site range from 30 to 40ºC, with the relative humidity of 60 to 80%, and the duration of the study was from April – September 2022 (20 weeks).



Figure 4.1 Aerial View of the Experimental Site at the Farm Unit, UiTM Sarawak



Figure 4.2 Rain Shelter Used as the Experimental Site at the Farm Unit, UiTM Sarawak

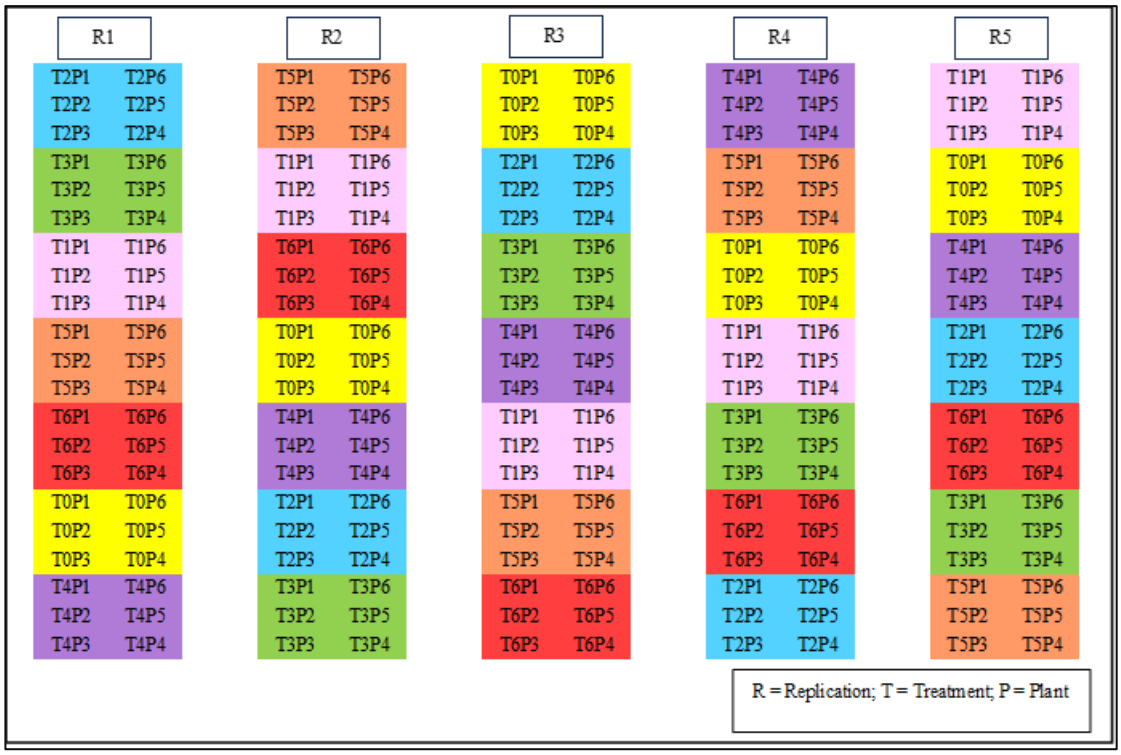


Figure 4.3 Experimental Layout



Figure 4.4 Actual Experimental Layout

4.2.2 Plant Materials

The *C. chinense* variety used in this study was the F1 (First Filial Generation) progeny of Cili Geronong Sarawak, a locally cultivated chili variety. Two-months-old seedlings were commercially sourced from HFE Agro Resources Sdn. Bhd

(1225962D/201701011797), Kuching, Sarawak, Malaysia, a recognized supplier of *C. chinense* planting materials for commercial cultivation and research purposes. Cocopeat was used as the growing medium throughout the experiment and was obtained from the same supplier.



Figure 4.5 The 2-months-old *C. chinense* Seedlings

4.2.3 Pineapple Leaf and *Trichoderma* Biofertilizer

Pineapple leaf biochar (MD2 cultivar) used in this study was produced from pineapple leaf sourced from a local grower in Kampung Meranek, Samarahan, Sarawak, Malaysia. *Trichoderma* biofertilizer was obtained from Sungei Marong Agri Farm Company, Kota Samarahan, Sarawak, Malaysia. As this was a commercially formulated product, detailed information on the inert carrier materials was not disclosed by the manufacturer, and the product was applied according to the manufacturer's recommended rate.

4.2.4 Fertilizer and Fertigation Management

Chemical (AB) fertilizer were sourced from HFE Agro Resources Sdn. Bhd., while the commercial organic fertilizer (Indusol Premium) was obtained from the State

Farmers' Organization Sarawak. The nutrient compisition of the chemical (AB) fertilizer and Indusol Premiun organic fertilizer is outlined in Table 4.1.

Table 4.1
Nutrient Composition of Chemical (AB) Fertilizer and Indusol Premium Organic Fertilizer used in the Study

Fertilizer type	**Component / Nutrient source**	**Nutrient supplied**	**Form / Approximate content**
AB fertilizer (A solution)	Calcium nitrate [$Ca(NO_3)_2$]	Ca, NO_3^-–N	Water-soluble; Ca and nitrate N
AB fertilizer (B solution)	Potassium nitrate (KNO_3)	K, NO_3^-–N	Water-soluble
	Mono-potassium phosphate (KH_2PO_4)	P, K	Water-soluble
	Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	Mg, S	Water-soluble
	Micronutrient mix	B, Mn, Zn, Cu, Mo	Trace elements
Indusol Premium organic fertilizer	Organic matter	—	~75% organic matter
	Total nitrogen (N)	N	~8–9%
	Phosphorus (as P_2O_5)	P	~3–5%
	Potassium (as K_2O)	K	~2–3%
	Secondary nutrients	Ca, Mg, S	Present
	Micronutrients	Fe, Zn, Mn, Cu, B, Mo, Co	Trace amounts

Table 4.2 presents the schedule of commercial fertilizer application for *C. chinense*, in which fertilizer was supplied through a controlled fertigation system that was adjusted according to crop age and growth demand. Fertilizer concentration, expressed as electrical conductivity (EC), was gradually increased from 1.50 to 2.50 dS m^{-1} as the cultivation period progressed, reflecting the increasing nutrient requirements of the plants from early establishment to the reproductive stage. The daily fertilizer requirement per plant increased from 500 mL during the first 30 days to 2,000 mL from 91 days onward, with corresponding increases in the volume of fertilizer solution applied per event and the duration of each application. Fertigation was carried out five times daily at fixed intervals, specifically at 8:00 am, 10:00 am, 12:00 pm, 2:00 pm, and 4:00 pm, to ensure a consistent supply of nutrients and to minimize nutrient leaching in

the cocopeat media. This frequent, low-volume fertigation strategy was designed to maintain stable nutrient availability in the root zone and to support optimal growth and yield of *C. chinense* under fertigated cocopeat conditions.

Table 4.2
Commercial Fertilizer Application Schedule for *C. chinense* Grown in Fertigated Cocopeat Media

Month	Days		EC reading dS m^{-1}	Fertilizer requirement for each plant per day (mL)	Frequency application per day	Amount of fertilizer applied at one time (mL)	Duration of each application (minutes)
	Start	End					
1	1	30	1.50	500	5	100	2
2	31	60	1.75	1000	5	200	2
3	61	90	2.00	1500	5	300	2
4	91	120	2.50	2000	5	400	2
5	121	150	2.50	2000	5	400	2

Source: Department of Agriculture Sarawak, 2022.

4.2.5 Growth Condition of the Seedlings

The procedure for seed planting followed the Department of Agriculture Research Station Rampangi, Kuching, Sarawak. The healthy and uniform seedlings were transplanted into polybags (40 × 40 cm) filled with cocopeat and arranged on the research site with a 60 × 90 (cm) planting distance. The seedlings were acclimatized for seven (7) days before transplanting.



Figure 4.6 The *C. chinense* Seedlings Transplanted in a Polybag Arranged according to Experimental Design

4.2.6 Experimental Design

The research was conducted using a Randomized Complete Block Design (RCBD). The experiment comprised seven (7) treatments consisting of six (6) plants per treatment with five (5) replications, which gave a total of 210 experimental units. The composition of treatments is shown in the Table 4.3 below:

Table 4.3
Composition of Treatments

Treatment	Description	Fertilizer (per polybag)	PLB (g/polybag)	TB (g/polybag)
T0	Chemical fertilizer (Control)	500 mL*	0	0
T1	Organic fertilizer	50 g**	0	0
T2	Organic fertilizer and PLB	50 g**	50	0
T3	Organic fertilizer and TBF	50 g**	0	50
T4	Organic fertilizer, 75% PLB and 25% TBF	50 g**	37.5	12.5
T5	Organic fertilizer, 50% PLB and 50% TBF	50 g**	25	25
T6	Organic fertilizer, 25% PLB and 75% TBF	50 g**	12.5	37.5

*Note. PLB = Pineapple leaf biochar; TBF = *Trichoderma* biofertilizer; *= applied daily following the standard recommended by the Department of Agriculture Sarawak; ** = applied biweekly following the standard recommended by State Farmers' Organization Sarawak.

Through a fertigation system, 500 mL of commercial chemical fertilizer was applied daily to T0, as the common practice by local growers. The recommendation from the Department of Agriculture Sarawak's (Personal communication, Shafik, 2021) was followed by diluting the commercial chemical fertilizer with water to achieve the required electrical conductivity (EC) level. Following the recommendations of the State Farmers' Organization Sarawak (Personal communication, Seraphina, 2021), 50 g of commercial organic fertilizer was administered every two weeks to the organic treatments (T1-T6). The quantities of nutrients applied to *C. chinense* seedlings were modified from the findings of Rivitra et al. (2021). Meanwhile, the treatments consisting of PLB and TBF were applied on the second, seventh and tenth week after transplant.

4.2.7 Physicochemical Properties of Cocopeat, Pineapple Leaf Biochar, and *Trichoderma* Biofertilizer

The determination of physicochemical properties of cocopeat, PLB, and TBF were performed at Block H Laboratory, Faculty of Plantation and Agrotechnology, and Block B, Faculty of Applied Science, UiTM Sarawak Branch. The analysis was conducted on the 1st (pre-treatment) month after planting. Thereafter, the sample was oven-dried at a temperature of 60ºC until it reached a constant weight and sieved to pass 1 to 2 mm before being stored in a labeled plastic bag (Patiram et al., 2007). The cocopeat sample was analysed for pH, cation exchange capacity (CEC), organic carbon, N, P, K, Ca, and Mg as described by Tarmizi & Tayeb (2006). In contrast, PLB and TBF samples were analysed for pH, N, P, and K.

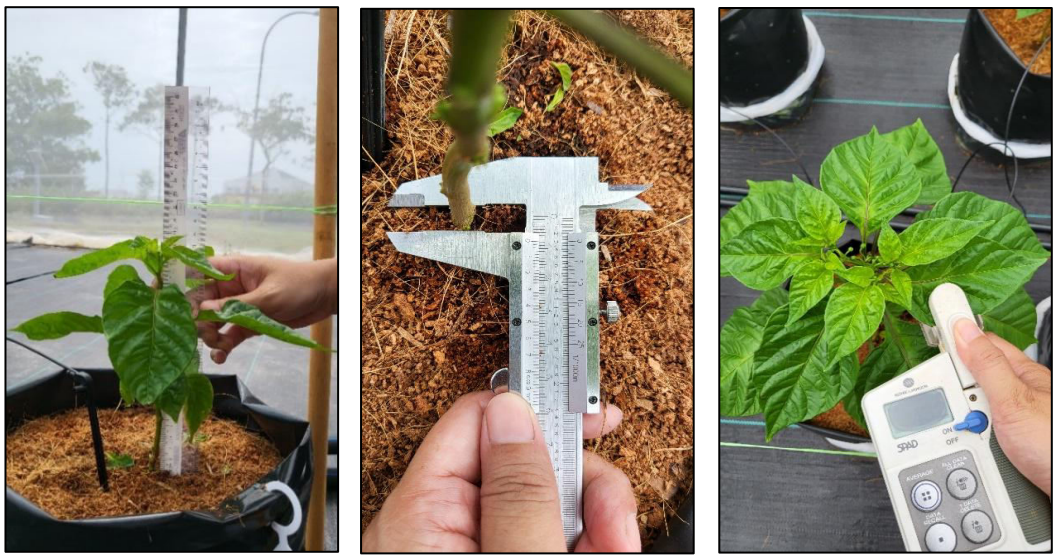
The pH values of cocopeat, PLB, and TBF were measured according to Abdul Halim et al. (2024). The ratio was 10 g of sample to 25 mL of deionised water (1:2.5). The sample was shaken for 90 minutes at 245 rpm on a Digital Orbital Shaker (Daihan SHO-1D, SHO-2D, Korea) to ensure sample and solution equilibration, thus, obtaining accurate pH readings. The pH value was determined by using a digital pH meter (Hanna Instruments HI98103 Checker, UK).

For the determination of the EC values, the Bohari et al. (2020) method was used. The 10 g sample was immersed in 50 mL of distilled water (ratio of 1:5), and the mixture was shaken for 60 minutes at 245 rpm on a Digital Orbital Shaker (Daihan SHO-1D, SHO-2D, Korea). An EC meter (Mettler Toledo, USA) was used to measure and record the EC. The EC electrode was placed into the supernatant solution, and the value was recorded.

As for the chemical analysis, total N was analyzed using a CHNS analyzer (Elementar Excellence, Elements). Available P was determined spectrophotometrically following the development of a blue color using the Murphy & Riley (1962) method. Available K was measured using Atomic Absorption Spectroscopy (AAS) (Perkin-Elmer 5100 PC). All the analyses were conducted at the laboratories in Block H, Faculty of Plantation and Agrotechnology, and Block B, Faculty of Applied Sciences, UiTM Sarawak Branch.

4.2.8 Growth Performance Measurement

Three plant growth parameter under studied, included plant height, stem diameter, and chlorophyll content, were recorded once biweekly to evaluate the effects of treatment application. Plant height was recorded in centimeters from the plant's base to the plant's apical point. Meanwhile, the stem diameter was measured using a digital caliper (Fisherbrand TM TraceableTM Digital Caliper, USA) three centimeters above the ground (Jaaf et al., 2022). As for chlorophyll content, SPAD Chlorophyll Meter (SPAD-502 Konica Minolta, Japan) was used (Japakumar et al., 2021). The chlorophyll content measurements were taken from three fully expanded leaves on the apical shoot of each chili plant (Yuan et al., 2016). Thirty plants per treatment were sampled, with readings recorded from three leaves per plant. The average value per plant was calculated to enhance accuracy and ensure reliable treatment comparisons. All growth parameters including plant height, stem diameter, and chlorophyll content were measured on samples of 30 plants per treatment. This sample size exceeds the commonly accepted range of 15 to 20 plants for surpasses the typical use of 10 plants for accurately assessing agronomic growth traits such as plant height and stem diameter (Elsahookie & Dawood, 2024), and achieving ~5% precision in SPAD reading (Costa et al., 2003).



(a) (b) (c)

Figure 4.7 Measurement of the (a) Plant Height, (b) Stem Diameter, and (c) Chlorophyll Content of *C. chinense*

4.2.9 Plant Biomass Measurement

The *C. chinense* plants were destructively sampled for total plant biomass 20 weeks after treatment and partitioned into shoots, stems, and roots as the method of Jaaf et al. (2022). Figure 4.8 showed the partition for *C. chinense* plant at 20 weeks after treatment. For fresh weight, the samples were washed under tap water to remove the debris, then with distilled water, dried with a paper towel, and weighed separately as fresh weight. For dry weight, all fresh samples were placed into an oven and dried in an oven at 60°C until constant weight. Total plant biomass were recorded and subjected to a nutrients analysis to determine the N, P, and K content.

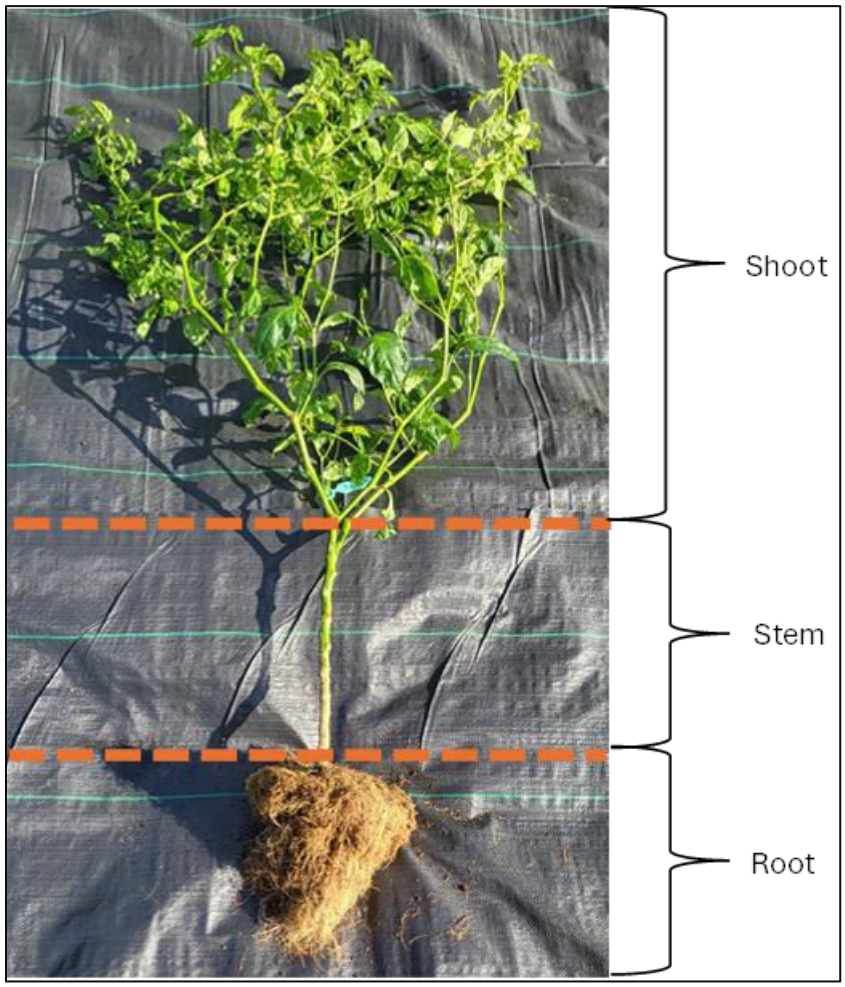


Figure 4.8 Plant Partitioned at 20 Weeks After Treatment

4.2.10 Yield Parameter

C. chinense fruit weight was recorded as the yield. The fully ripe red color *C. chinense* fruit was harvested manually by hand-picking. Thirty fruit samples from each treatment were randomly picked to determine the individual fruit weight and diameter. The fruit weight (gram) and yield were measured based on the total fruit weight (gram) using an electronic balance (Mettler Toledo SB16001, USA). The fruit diameter was measured using a digital caliper (Fisherbrand TM TraceableTM Digital Caliper, USA). The number of fruits per treatment were counted and recoeded manually. The yield parameters were recorded weekly for 10 weeks harvesting period.



(a) (b)

Figure 4.9 Measurement of the (a) Weight and (b) Diameter of *C. chinense* Fruit

4.2.11 Media and Plant Nutrient Analysis

The partitioned parts of *C. chinense* plant which included shoot, stem, and root. Media samples gathered at the harvest stage were subjected to a chemical analysis to determine N, P, and K content. The samples were analysed for N, P, and K content in plant tissues following the method of Mohidin et al. (2015), with the digestion step

modified by employing a hot plate rather than a block digester due to equipment availability, while maintaining the same digestion reagents and temperature conditions.



Figure 4.10 Preparation of Samples for Nutrient Analysis

4.2.12 Statistical Analysis

All data were analyzed using the statistical software of Minitab 21 (Version 2.1). The data average of the mean from all replications of each treatment was used to correlate the related parameters. Analysis of variance (ANOVA) was conducted using individual data points from all replicates to assess the effects of different treatments. Tukey's Test ($\alpha = 0.05$) was applied for mean separation.

4.3 Results and Discussion

4.3.1 Initial Cocopeat Analysis

Based on Table 4.4, the initial physicochemical analysis of cocopeat showed a slightly acidic pH value of 5.26. Its CEC was 93.13 cmol kg^{-1}, indicating a strong ability to retain and supply essential cations like K, Ca, and Mg. The bulk density was 0.14 g cm^{-3}. The cocopeat was also composed of 42.71% organic C, 0.60% N, 0.05% P, 0.30% K, 0.09% Ca, and 0.09% Mg.

Table 4.4
Physicochemical Characterization of the Cococopeat Material

Properties	Cocopeat (Values)
pH	5.26
CEC (cmol kg^{-1})	93.13
Bulk density (g cm^{-3})	0.14
Organic carbon (%)	42.71
N (%)	0.60
Total P (%)	0.05
Total K (%)	0.30
Total Ca (%)	0.09
Total Mg (%)	0.09

*Note: Values represent measurements obtained from a single composite sample.

Measuring the pH of the planting media is fundamental as it directly influences the growth and development of plants by affecting nutrient availability and microbial activity (Ferrarezi et al., 2022). Due to slightly acidic conditions, when cultivating plants that prefer neutral or slightly alkaline conditions, minor pH adjustments through the application of lime and balanced fertilization are recommended for cocopeat. As the *C. chinense* thrives in slightly acidic to neutral soils with an ideal pH range of 6.0 to 7.5 pH adjustment is necessary (Li & Harper, 2020). The application of dolomite lime at a rate of 2 to 4 g/L cocopeat is recommended to gradually increase the pH (Lee et al., 2016). Proper pH regulation enhances the availability of essential nutrients such as P, Ca, and Mg, preventing nutrient lock-up and promoting healthier growth and development of *C. chinense*. Based on a study conducted by Hussain & Farooq (2023), it is concluded that cocopeat is an efficient growth medium, which makes it promising for growing chilies due to its favourable physical properties and nutrient-retaining capacity.

In addition to pH, the CEC value of growth media also needs to be measured as it affects nutrient retention and supply capacity. According to the findings outlined in Table 4.4, the higher CEC of cocopeat would allow a nutrient reservoir throughout time, reducing the frequency of fertilization and supporting optimal plant growth (Xiong et al., 2017; Khan et al., 2019). The high CEC of cocopeat helps meet the nutrient needs of *C. chinense* at different growth stages by retaining and gradually releasing essential nutrients. This is especially important during flowering and fruiting, when the plant requires more K, as well as Ca and Mg for healthy growth. By holding nutrients for

longer periods, cocopeat reduces the need for frequent fertilization while ensuring a steady supply of nutrients. This supports strong vegetative growth, improves fruit formation, and enhances yield and quality. According to Ilahi & Ahmad (2017), for the bulk density of cocopeat, the value is under the general range of 0.09 – 0.2 g cm^{-3}. The bulk density depends on the composition and processing method for cocopeat production. With a bulk density of 0.14 g cm^{-3}, the cocopeat is considered a suitable medium for various crops. It's generally offering good physical structure that can support the overall growth of the plant, such as good aeration, high water retention and nutrient holding capacity, and good compatibility with other amendments (Ahn et al., 2016; Fitriadi et al., 2022; Wu et al., 2025).

The high organic C content of cocopeat significantly benefits *C. chinense* by enhancing root development, nutrient uptake, and stress tolerance. Organic C improves the physical properties of the growing medium, such as aeration and water-holding capacity, which are crucial for healthy root growth (Bhogal et al., 2009). Enhanced root systems facilitate more efficient nutrient absorption, leading to robust plant development. Furthermore, incorporating TBF into cocopeat further amplifies these benefits is known to promote plant growth by increasing nutrient availability and enhancing soil microbial activity. A study by Zhang et al. (2018) demonstrated that applying TBF led to improved plant biomass, likely due to altered soil chemistry and microbial community structures that favour nutrient cycling. The interaction between high organic C content and TBF creates a synergistic effect, enhancing nutrient retention and promoting beneficial microbial populations. This synergy supports optimal nutrient uptake and improves stress resilience in *C. chinense*, leading to healthier plants and potentially higher yields.

Despite organic C, N is one of the essential nutrients required by plants, which are involved in photosynthesis and protein synthesis. The findings revealed that the cocopeat contains a moderate N (0.60%). Minor adjustments with additional fertilizer could be performed to meet the requirements for *C. chinense*. The P content (0.05%) in cocopeat was relatively low, which may limit root development, flowering, and fruit setting. For *C. chinense* cultivation, additional fertilizer is required to promoting early root development and enhancing flowering, as P is essential for energy transfer, cell division, and root formation. Meanwhile, the K content (0.30%) is at moderately high level, which plays a crucial role in regulating water balance, enzyme activation, and photosynthesis, that are vital for fruit development and stress tolerance. As cocopeat

naturally provides N, P, and K, it serves as a suitable growing media for *C. chinense*, supporting plant structure and metabolic functions. Additionally, the incorporation of PLB can further enhance nutrient availability by improving P retention and K release, ensuring a steady supply throughout different growth stages (Srikhaow et al., 2023; Song et al., 2024). This optimized nutrient balance promotes stronger root systems, improved flowering, higher fruit yield, and better resilience to environmental stress. Nevertheless, based on the result outlined, the Ca and Mg were almost two times higher than the K content. Ca is vital in cell wall formation and stability, while Mg is a crucial nutrient of chlorophyll, which is necessary for plant photosynthesis. The balanced availability of these nutrients in cocopeat promotes the growth and development of the plants, and this finding is supported by Kusparwanti et al. (2023).

4.3.2 Pineapple Leaf Biochar and *Trichoderma* Biofertilizer Chemical Analysis

The chemical analysis on pH, N, P, and K content in PLB and TBF samples are outlined in Table 4.5.

Table 4.5
Chemical Properties of PLB and TBF

Nutrient elements	PLB	TBF
pH	10.80	5.70
N (%)	1.85	2.20
P (%)	0.29	2.14
K (%)	2.23	3.64

*Note: Values represent measurements obtained from a single composite sample.

The PLB had a pH of 10.8, which indicates a highly alkaline causes nutrient lockout, where the essential nutrients become less available to plants. Alkaline stress particularly can limit the nutrient availability for plant growth and physiological processes like Fe, Mn, and P, which play important roles in metabolic functions (Li et al., 2023), especially for the *C. chinense* plant. However, when the PLB was applied to cocopeat, which is slightly acidic, it helped to improve the pH of the cocopeat to become near neutral that favourable for nutrient solubility and uptake, thereby enhancing the ability of plant to absorb essential nutrients efficiently. On the other hand, N (1.85%) in PLB provided a moderate amount of this essential macronutrient, which is involved in

protein synthesis and chlorophyll production. However, the high pH may limit N uptake (Hawkins & Robbins, 2010). The P (0.29%) content was relatively low, which potentially limits plant growth and productivity because it is vital for energy transfer and root development. Meanwhile, the K (2.23%) content was relatively higher than P, which is beneficial for various plant physiological processes, including enzyme activation and water regulation. However, the high pH may affect K uptake for the *C. chinense* plant (Chen & Barber, 1990).

As for the TBF, the results showed the pH (5.7) was slightly acidic and fell within the optimal range for most plants as it improves the availability of essential nutrients and supports a healthy rhizosphere microbial community, enhancing nutrient uptake and overall plant health (Deng et al., 2021). The N (2.20%), P (2.14%), and K (3.64%) content in TBF was higher than in PLB. Higher N provides a better nutrient supply for vigorous vegetative growth. While P is essential during the flowering and fruiting stages. The slightly acidic pH enhances P availability, making it more accessible to plants (Hauck et al., 2022). The high content of K supports stronger stem and root development, improved drought resistance, and enhanced overall plant health. The slightly acidic pH facilitates better K availability, making it suitable for *C. chinense* growth. However, the application of TBF alone in cocopeat would not be the right decision as the pH of the cocopeat itself was slightly acidic. Therefore, applying PLB in cocopeat would help to increase and buffer pH levels to an optimal range for plant growth. This combination ensures consistent nutrient availability and reduces the need for frequent pH adjustments.

4.3.3 Effect of Pineapple Leaf Biochar and *Trichoderma* Biofertilizer in Growth Performance of *C. chinense* Plant

Figure 4.11 illustrate the monthly changes in plant height, stem diameter, and chlorophyll content of *C. chinense* under different treatments over the 20 weeks study period.

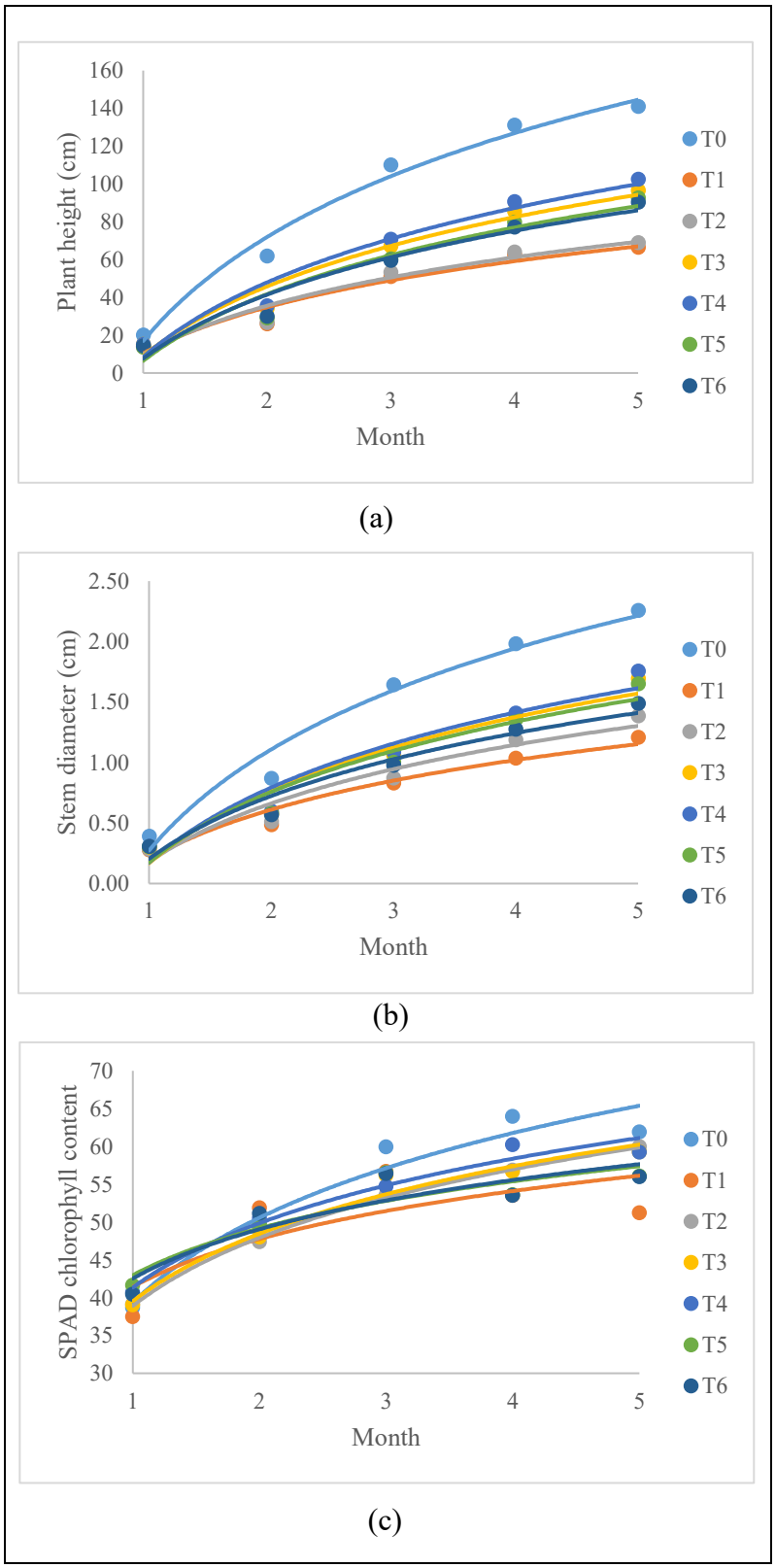


Figure 4.11 Monthly Changes in (a) Plant Height, (b) Stem Diameter, and (c) Chlorophyll Content of *C. chinense* under Different Treatments over the 20-week Study Period. T0= Commercial Chemical Fertilizer (Control), T1= Commercial Organic Fertilizer, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

All treatments show positive responses in all parameters measured with the increments in each month. For Figure 4.11 (a), T0 recorded the highest increment in plant height from 20.08 cm in the first month to 141.02 cm in the fifth month. Treatment T1 exhibited the least growth, starting at 14.23 cm and reaching 66.43 cm by the fifth month. However, treatment T4 demonstrated superior performance among the organic treatments (T2-T6) with an initial height of 15.13 cm in the first month, growing to 102.52 cm in the fifth month. The result suggests this treatment combination may offer optimal nutrients for promoting vertical growth.

Regarding Figure 4.11 (b), data reveals that all treatments showed an increase in stem diameter over time. The degree of stem diameter varied significantly among the treatments with T0 increasing steadily from 0.39 cm in the first month to 2.26 cm in the fifth month. Meanwhile, for T1, the stem diameter was the lowest among the treatments, starting at 0.28 cm in the first month and reaching only 1.21 cm in the fifth month. Treatment T4 showed the highest stem diameter among the organic treatments (T2-T6), with an initial height of 0.31 cm in the first month, culminating at 1.75 cm in the fifth month. This finding suggests that the treatment combination supports greater plant height and enhances stem diameter.

As for the chlorophyll content, Figure 4.11 (c) shows the variable data recorded for chlorophyll content in the *C. chinense* plant. These results indicate that the chlorophyll content in the *C. chinense* plant changes and does not consistently increase over time. Based on the data presented, T0 and T4 showed a similar trend, where these two treatments record a steady increase in chlorophyll content from the first four months and then start to decrease in the fifth month. In contrast, for T1, the chlorophyll content was increased in the first three months and started to decrease in the fourth month. For T5 and T6, the chlorophyll content increases in the first three months, decreases in the fourth month, and then increases again in the fifth month. Interestingly, as for T2 and T3, the chlorophyll content steadily increased from the first month until the fifth month. This shows that the single application of either PLB or TBF could improve the chlorophyll content. The findings conclude that the combination of PLB and TBF has a similar trend and effect with chemical fertilizer. This is in line with findings by Japakumar et al. (2021), Jaaf et al. (2022), and Hanyabui et al. (2024).

The findings provided deeper insights beyond the expected trend of increasing plant growth parameters over time by identifying specific time points where certain treatments exhibit superior performance. Notably, while all treatments showed growth

increments, T4 consistently outperformed other organic treatments (T2-T6) in both plant height and stem diameter, particularly from the third to fifth month, indicating its effectiveness in supporting sustained vegetative growth. Additionally, the chlorophyll content trends revealed distinct patterns among treatments, with T0 and T4 showing a steady increase up to the fourth month before declining, while T2 and T3 displayed continuous improvement over five months. This suggested that single applications of PLB or TBF might have provided prolonged benefits in chlorophyll content compared to combination treatments. These variations highlighted the differential impact of treatments at various growth stages, emphasizing the importance of selecting optimal nutrient combinations for maximizing plant development at critical periods.



Figure 4.12 Comparison of Plant Height of *C. chinense* between T0 and T4 at 4 Weeks After Treatment. T0= Commercial Chemical Fertilizer (Control), T1= Commercial Organic Fertilizer, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

The findings revealed that the application of PLB and TBF in cocopeat enhanced the growth performance of *C. chinense*, particularly in terms of plant height and stem diameter. As shown in Figure 4.12, during the 4 weeks after treatment, the growth

performance of *C. chinense* grown in fertigated cocopeat media under treatment T4 was comparable to that of T0. This could be due to the synergistic interaction between PLB and TBF that improved nutrient retention and availability in cocopeat. Specifically, the characteristics of PLB such as the porous structure, high surface area, and functional groups provided adsorption sites for essentials nutrients, as well as reducing leaching losses and maintaining a more stable nutrient pool. Concurrently, TBF contributed through microbial colonization of PLB pores, secretion of organic acids, enzymes, and polysaccharides, which facilitated nutrient solubilization, improved root-rhizosphere interactions, and enhanced plant uptake efficiency. These mechanisms collectively created a biologically active media that promoted sustained plant growth.

To summarize the overall treatment effects across the entire study period, the mean values of growth parameters averaged over 20 weeks after treatment are presented in Table 4.6. The analysis of variance (ANOVA) for the plant height, stem diameter, and chlorophyll content showed significant differences ($p<0.05$) among the treatments. Treatment T0 (92.86 cm, 1.43 cm, 54.48) produced the highest mean values for all parameters, followed by T4 (62.93 cm, 1.03 cm, 53.10), and T1 (44.06 cm, 0.77 cm, 50.18) illustrating the lowest mean value respectively. This indicates that chemical fertilizer resulted in superior growth compared to commercial organic fertilizer.

Table 4.6
Effect of PLB and TBF Application on Mean Plant Height, Stem Diameter, and, Chlorophyll Content of *C. chinense* over 20 weeks after Treatment

Treatment	Plant height (cm)	Stem diameter (cm)	Chlorophyll content
T0	92.86 ± 1.54^{a}	1.43 ± 0.03^{a}	54.84 ± 0.44^{a}
T1	44.06 ± 2.63^{d}	0.77 ± 0.03^{d}	50.18 ± 0.63^{c}
T2	45.35 ± 2.24^{cd}	0.85 ± 0.05^{cd}	51.38 ± 0.60^{bc}
T3	59.75 ± 2.15^{b}	1.00 ± 0.03^{b}	51.86 ± 0.78^{bc}
T4	62.93 ± 2.94^{b}	1.03 ± 0.03^{b}	53.10 ± 0.68^{ab}
T5	55.14 ± 2.02^{b}	0.92 ± 0.03^{bc}	51.54 ± 0.69^{bc}
T6	54.30 ± 2.47^{bc}	0.98 ± 0.02^{b}	51.53 ± 0.86^{bc}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant differences at $p>0.05$ according to Tukey's Test ($\alpha = 0.05$). T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

The highest mean value of T0 may be due to the soluble fertilizer used, which the *C. chinense* plant can easily absorb. Although T0 had the highest mean value for all parameters, PLB and TBF also boosted *C. chinense* plant growth. The application of PLB and TBF outperformed T1, with T4 having the second-highest mean value. Several studies found that biochar and biofertilizers can increase plant height and leaf count (Hanyabui et al., 2024), besides increasing soil carbon (C), aggregation, macro porosity, and penetration resistance, improving plant growth (Japakumar et al., 2021). *Trichoderma* promotes plant growth, increases leaf area, height, and dry weight, and protects against fungal and bacterial pathogens (Harman, 2011; Doni et al., 2017). The findings corresponded to Jaaf et al. (2022) results that biochar and poultry litter interacted significantly with plant height. Maru et al. (2015) also found that co-applicating poultry litter biochar and urea increased soil nutrient availability and improved most rice plant growth parameters.

The combination of PLB and TBF also affects the chlorophyll content of the *C. chinense* plant. Based on the data presented in Table 4.6, there is a relationship between the chlorophyll content with plant height and stem diameter. Chlorophyll is a pigment that is responsible for the photosynthesis process and important in plant growth performance. The higher chlorophyll content in the plant will lead to an increase the photosynthetic efficiency. This will result in higher energy production, that influences the rapid cell division and elongation, thus promoting faster growth and an increase in plant height and stem diameter. Supported by the data, T0, and T4 were recorded as the two highest treatments with the highest plant height, stem diameter, and chlorophyll content.

The importance of chlorophyll content in plant leaves indicates photosynthetic activity. Plants with higher chlorophyll content will be able to absorb more energy from the sun to undergo the process of photosynthesis. Chlorophyll is related to the N content found in green plants, and it also plays a significant role in evaluating plant response to fertilizer application and soil nutrient levels (Japakumar et al., 2021). The findings reported by Danish & Zafar-ul-Hye (2019) were in good agreement with the results. The researchers reported an increment of 114% of the total chlorophyll content of wheat through the combination application of *Bacillus amyloliquefaciens* + biochar compared to the untreated Control. In addition, a study by Abid et al. (2017) found that applying biochar improved the production of photosynthetic and accessory pigments of tomato plants under various irrigation waters.

Figure 4.13 showed the comparisons of the growth performance of *C. chinense* under each treatment at 20 weeks after treatment. Based on the findings, T0 showed superior growth in all parameters measured. However, the application of PLB with TBF has shown significant potential in enhancing the growth performance of the *C. chinense* plant in terms of plant height, stem diameter, and chlorophyll content. Based on the observations, the addition of these organic amendments can help to improve the structure and aeration of cocopeat. As the bulk density of cocopeat is lightweight and porous, adding these amendments can help to improve its physical structure. Moreover, it can improve the water-holding capacity, and nutrient retention capacity, promoting root growth, and enhancing microbial activity which leads to better nutrient cycling and nutrient uptake by the *C. chinense* plant, thus resulting in better plant growth performance. This result shows that a combined application of PLB and TBF is better than a single application.



Figure 4.13 Comparison of the Growth Performance of *C. chinense* under Each Treatment at 20 Weeks After Treatment. T0= Commercial Chemical Fertilizer (Control), T1= Commercial Organic Fertilizer, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

4.3.4 Effects of Pineapple Leaf Biochar and *Trichoderma* Biofertilizer on Yield Parameters

4.3.4.1 Yield and Fruits Number of C. chinense

Table 4.7 presented the comparison of the effect application PLB and TBF on the mean yield and fruits number of *C. chinense* grown in fertigated cocopeat media over 20 weeks after treatment. Analysis of variance (ANOVA) indicated that both yield and fruits number differed significantly ($p<0.05$) among the seven treatments, demonstrating that the application of PLB and TBF significantly influenced the yield performance of *C. chinense*.

Table 4.7
Comparison of the Effect PLB and TBF on the Mean Yield and Fruits Number of *C. chinense* for 20 Weeks After Treatment

Treatment	Mean yield (g)	Fruits number
T0	493.71 ± 41.06^{a}	329.00 ± 2.33^{a}
T1	84.43 ± 6.43^{c}	72.20 ± 0.87^{e}
T2	193.69 ± 16.69^{b}	166.00 ± 1.80^{d}
T3	198.81 ± 18.94^{b}	170.40 ± 0.49^{cd}
T4	403.69 ± 27.21^{a}	269.00 ± 1.39^{b}
T5	186.87 ± 13.21^{b}	160.20 ± 0.60^{d}
T6	212.63 ± 17.07^{b}	182.20 ± 0.72^{c}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant differences at $p>0.05$ according to Tukey's Test ($\alpha = 0.05$). T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

Based on Table 4.7, statistical analysis confirms that T0 (493.71 g) and T4 (403.69 g) illustrate mean total yields that were significantly higher than other treatments, reinforcing the efficacy of the treatments. These mean values showed a significant difference compared to other treatments, notably T1 (84.43 g) demonstrated the lowest mean value. The highest mean value for the yield recorded by T0 might be influenced by the chemical fertilizer used for T0, which is in liquid form and easily absorbed by the plant. Although T0 recorded the highest mean value for total yield based on statistical analysis, there is no significant difference with T4 by an 18.23% difference. This finding indicated that the application of organic fertilizer with 75%

PLB and 25% TBF has been shown to positively affect the total yield per cycle of *C. chinense*. Based on nutrient analysis for PLB in this study, K (2.23%) was higher compared to N (1.85%) and P (0.29%). The higher K content in PLB will probably improve the nutrient content of the media, thus increasing the yield of *C. chinense*.

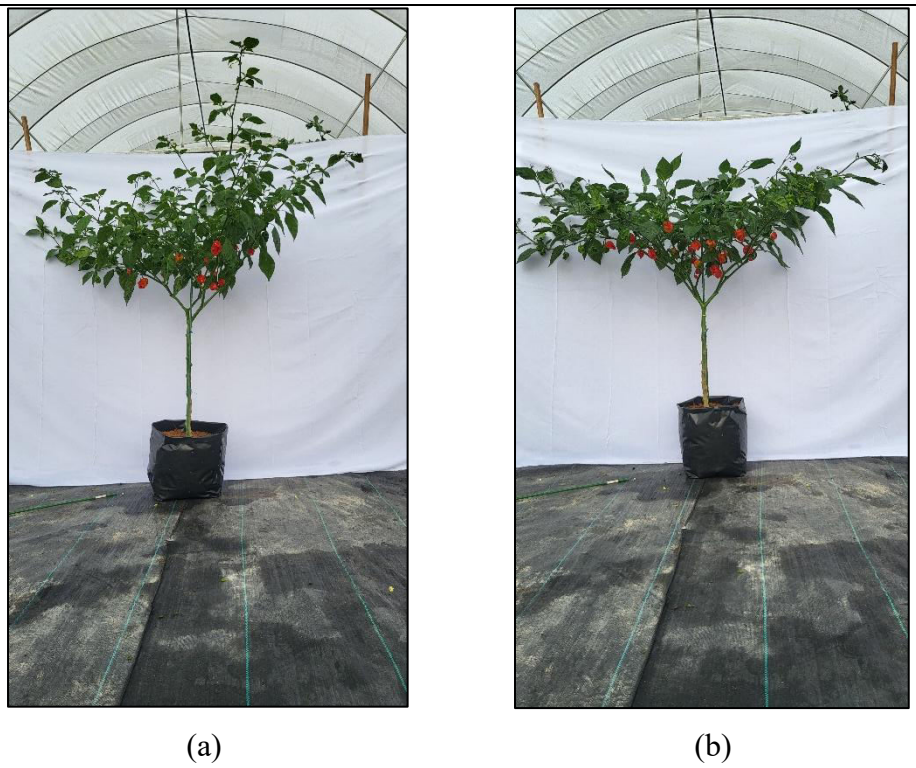
Potassium is essential for enzyme activation, water balance, and photosynthesis, which directly impact fruit development and overall plant productivity (Medina-Lara et al., 2008). It enhances the movement of sugars from leaves to developing fruits, promoting higher fruit yield and quality. Additionally, K improves plant resistance to abiotic stresses such as drought and temperature fluctuations, ensuring steady growth under varying environmental conditions (Hasanuzzaman et al., 2018). Compared to N and P, which primarily support vegetative growth and root development, respectively, K is particularly important during the reproductive stage, ensuring optimal flowering and fruit set. Moreover, the main role of PLB is to improve the physical properties of the substrate, which includes enhancing the nutrient retention capacity. Meanwhile, the purpose of the addition of TBF is to enhance nutrient uptake by promoting root growth, thus increasing the efficiency of nutrient adsorption. Therefore, the presence of PLB can enhance the effectiveness of TBF to give better results in the yield produced than a single application of organic amendment.

Findings reported by Sifton et al. (2023) found that biochar combined with biofertilizers significantly increase the growth and nutrient uptake in silver maple grown in urban soil, enhancing both macronutrient and micronutrient availability, and although this study was using cocopeat as media, the effects aligning with the high yields observed in T4 treatments for the *C. chinense*, which might reflect optimal nutrient conditions. Irawan et al. (2023) and Yan et al. (2023) clarified that the benefit of *Trichoderma* sp. inoculum was found to significantly increase the decomposition rate of pineapple litter, resulting in better compost quality with lower organic C content and C/N ratio and partial substitution of chemical fertilizers with TBF improved N use efficiency and plant growth in wolfberry, indicating enhanced N stabilization and carbon fixation respectively. Thus, demonstrated that possibly explaining the superior yields seen in T4, which combines organic fertilizer with 75% PLB and 25% TBF, can significantly enhance substrate health, nutrient availability, and plant growth, providing a sustainable alternative. The results indicated that T4 might be used as a potential combination for long-term agronomic strategies.

The highest mean value for the number of fruits was recorded by T0 (329), as shown in Table 4.7. This might be influenced by the chemical fertilizer used for T0 that is in the liquid form and easily absorbed by the plant. As for the organic treatments (T1-T6), T4 (269) recorded the highest mean value. This result reveals that the combined application was better than the single application of the organic amendment, as both have characteristics that complement each other and thus give better results in the total number of fruits produced. A study by Arthanawa et al. (2022) also found that the co-application of biochar and compost significantly increased the number of fruits in red chili plants. Based on nutrient analysis for PLB in this study, K (2.23%) is higher compared to N (1.85%) and P (0.29%). The higher K content in PLB will probably improve the nutrient content of the medium, thus increasing the total number of fruits. The study by Ch'ng et al. (2016) showed that PLB content significant proportions of K (2.67%), N (2.30%), and P (0.46%) that could potentially enhance plant growth. Bohari et al. (2020) also mentioned that plant nutrition and soil fertility were influenced by N (8.33%), and K (48.32%) as major elements with a higher C/N ratio (50-70%) in PLB. On the other hand, the findings indicate that the combined application of PLB and TBF can significantly improve yield on *C. chinense* as compared to organic fertilizer alone (T1). The results indicated that T4 might be used as a potential combination for long-term agronomic strategy.

The findings suggest that application of PLB (75%) and TBF (25%) gave better result as compared to the other organic treatments (T2, T3, T5, T6) that received PLB or TBF. The mean yield value of *C. chinense* as presented in Table 4.7 also showed that the T4 was comparable to T0, which treated with chemical fertilizer. Figure 4.14 showed the comparison of the effect different treatment, which are T0 and T4 on the growth performance of *C. chinense* at 12 weeks after treatment. The improved growth observed under T4 can be attributed to the complimentary roles of both organic amendments. The role of PLB provide a large surface area and diverse functional groups that trapped and stored essential nutrients such as N, P, and K, thereby minimizing nutrient losses. Moreover, its porous structure also created microhabitats that supported *Trichoderma* colonization. Once established, the fungus secreted organic acids, enzymes, and polysaccharides that helped dissolve bound P and release nutrients retained on PLB surfaces. These interactions enriched the rhizospere environment, promoted efficient nutrient cycling, and facilitated greater root access to essential elements. Although *C. chinense* treated with T0 appeared more robust due to the rapid

nutrient uptake from chemical fertilizer, plant treated with T4 benefited from a more sustainable nutrient supply system that combined physical adsorption, chemical retention, and biological colubilization mechanisms, which not only support healthy plant growth but also indicated the potential to reduce reliance on chemical fertilizer.



(a) (b)

Figure 4.14 Comparison of the Effect of Different Treatment (a) T0 and (b) T4 on the Growth Performance of *C. chinense* at 12 Weeks After Treatment

The weekly mean yield of C. chinense for seven different treatments over 10 weeks harvesting period was presented in Figure 4.15.

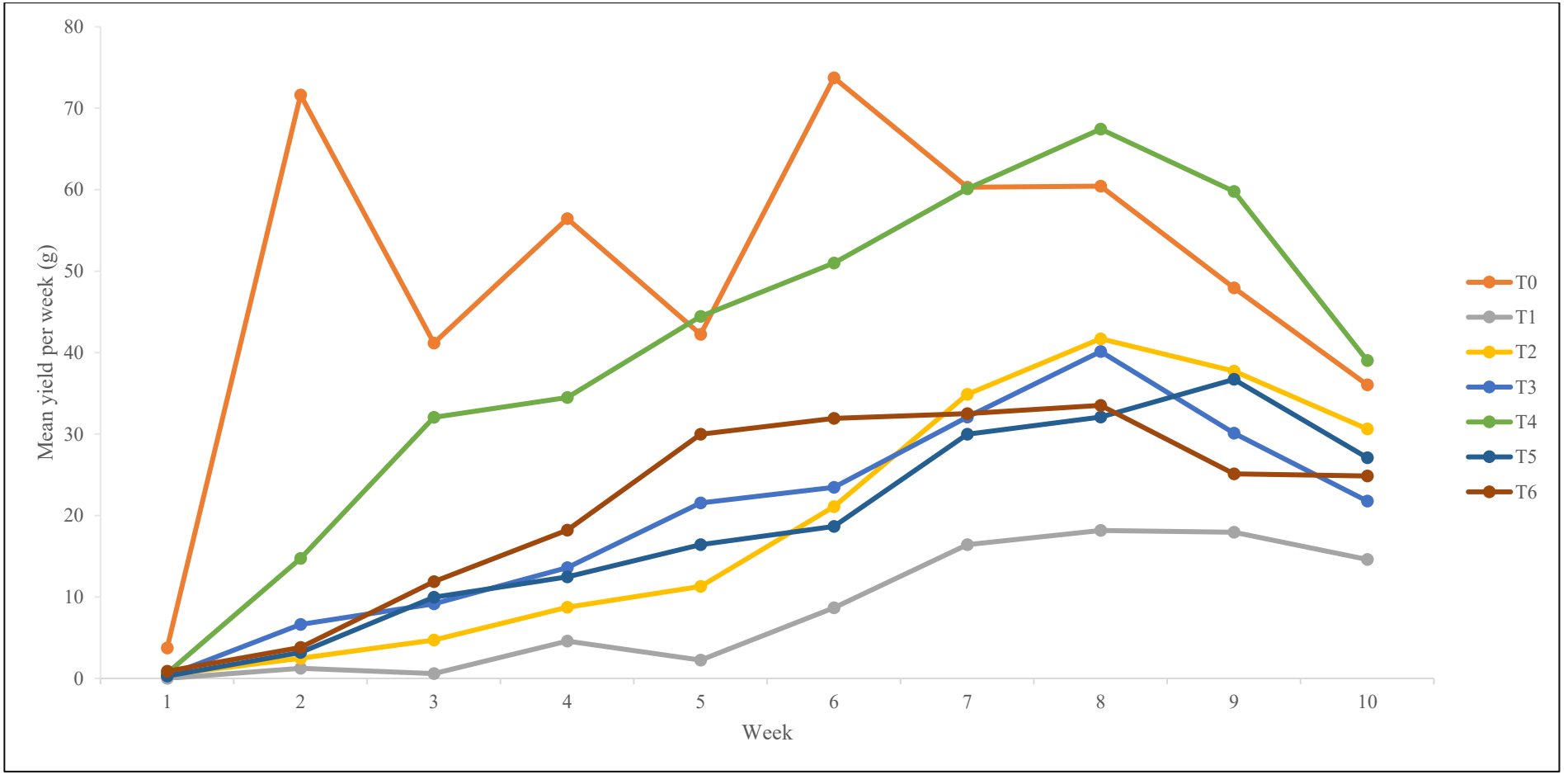


Figure 4.15 Weekly Mean Yield of *C. chinense* for Seven Different Treatments over 10 Weeks Harvesting Period. T0= Chemical fertilizer (Control), T1= Organic Fertilizer, T2= Organic Fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic Fertilizer + 75% PLB + 25% TBF, T5= Organic Fertilizer + 50% PLB + 50% TBF, and T6= Organic Fertilizer + 25% PLB + 75% TBF.

In the study, general trends were observed. For the first week, T0 showed the highest initial yield, 3.75 g, compared to other treatments with negligible yields, which were close to 0 g. This indicates that the *C. chinense* plant supplied with chemical fertilizer was initially more favourable for yield production than the other treatments that received organic fertilizer. Meanwhile, for the subsequent weeks, T0 consistently exhibited high yields, particularly noticeable in the second (71.6 g), third (41.17 g), fourth (56.43 g), sixth (73.74 g), and seventh (60.31 g) week. Nonetheless, T4 often outperformed T0 in yield, particularly notable in the fifth (44.45 g), eighth (67.44 g), ninth (59.78 g), and tenth (39.03 g) week, indicating potentially high efficacy of the treatment used. Meanwhile, T1 consistently showed the lowest yields among all treatments throughout the study period, suggesting the treatment was the least beneficial. This finding aligned with a study by Hanyabui et al. (2024) that applying PLB and compost as organic amendments can increase pineapple yield and improve fruit quality.

As for specific observations, there was a significant fluctuation in yield for T0 compared to other treatments, with yields in T0 jumping from 3.75 g in the first week to 71.6 g in the second week and then dropping to 41.17 g in the third week. A similar trend was recorded in the fourth to eighth weeks, and it began to decline in the ninth week. However, the yield for T4 consistently increased from the first week until the eighth week and started to decrease in the ninth week. This result suggested that the combination of organic fertilizer with PLB and TBF released nutrients gradually over time, and it was affirmed by the response of *C. chinense* when the yield produced was delayed. In addition, it showed an effective response to the treatment when it resulted in consistency-increasing yield production. The other treatments, like T2, T3, T5, and T6, also showed improvements but not as consistently or significantly as T4. Overall, T0 recorded a high yield most in the week of harvesting, indicating that the chemical fertilizer was consistently favourable as the week progressed from the first to the seventh week. Finally, in the eighth, ninth, and tenth weeks, both T0 and T4 showed high yields, with T4 often exceeding T0 results in consistency-increasing.

The weekly yield data of *C. chinense* collected in this study provides actionable insights for optimizing agricultural management practices, particularly in nutrient application timing and harvest optimization. By analyzing yield fluctuations over time, growers can identify critical periods when nutrient application may have the greatest impact on crop productivity. For instance, if yield trends indicate a significant increase

following specific fertilization events, this could inform the best practices for nutrient scheduling. Additionally, these findings can aid in determining the optimal harvest window by identifying peak yield periods, thereby maximizing both yield quantity and quality.

4.3.4.2 Fruit Weight snd Diameter

The analysis for mean comparison between fruit weight and diameter is shown in Table 4.8. Treatment T4 has the highest mean value for fruit weight (8.87 g) indicating a significant difference from T1 (5.85 g) which recorded the lowest. In addition, the fruit diameter T4 resulted in the largest mean value of 2.95 cm, indicating a significant difference from T1. However, T1 exhibited the smallest fruit diameter of 2.16 cm that significant compared to other treatments. These findings indicate that T4 was significantly better at enhancing fruit weight and diameter as compared to other treatments, notably T1.

Table 4.8
Effect of PLB and TBF Application on the Fruit Weight and Diameter of *C. chinense* for 20 Weeks After Treatment

Treatment	Fruit weight (g)	Fruit diameter (cm)
T0	8.50 ± 0.10^{ab}	2.68 ± 0.05^{a}
T1	5.85 ± 0.10^{c}	2.16 ± 0.02^{b}
T2	8.44 ± 0.13^{ab}	2.86 ± 0.03^{a}
T3	8.34 ± 0.08^{ab}	2.88 ± 0.03^{a}
T4	8.87 ± 0.13^{a}	2.95 ± 0.02^{a}
T5	8.41 ± 0.15^{ab}	2.89 ± 0.02^{a}
T6	7.28 ± 0.05^{b}	2.70 ± 0.03^{a}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant differences at $p>0.05$ according to Tukey's Test ($\alpha = 0.05$). T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

Based on the findings, T4 showed promising results in the production of *C. chinense*. The combination of organic fertilizer with PLB at 75% and TBF at 25% has shown significant effects on the fruit weight and diameter results. These findings were supported by Arthanawa et al. (2022), who found that the application of biochar and

compost significantly increased the fruit weight in red chili plants. The results are also in agreement with a study by Hanyabui et al. (2024) that applying PLB and compost as organic amendments can increase pineapple yield and improve fruit quality. The availability of essential nutrients provided by PLB and TBF has been shown to enhance fruit quality in terms of fruit weight and diameter. Overall, the use of PLB and TBF as organic amendments has shown promising results in improving the weight and diameter of *C. chinense* fruits. Therefore, incorporating PLB and TBF into *C. chinense* cultivation practices can be a beneficial strategy for producing the best quality of *C. chinense* in terms of fruit weight and diameter.



(a) (b)

Figure 4.16 Measurement of *C. chinense* Fruit Weight from (a) T0 and (b) T4



(a) (b)

Figure 4.17 Measurement of *C. chinense* Fruit Diameter from (a) T0 and (b) T4

In all parameters measured, the *C. chinense* plant treated with chemical fertilizer (T0) gave excellent results among other treatments. Although this chemical fertilizer improves plant growth performance, it also brings some drawbacks to the environment and human health. Therefore, a regenerative farming method should be practiced for a sustainable future. There is considerable evidence that regenerative agricultural approaches can help minimize fertilizer use and have been shown to benefit medium quality and nutrient retention, hence promoting plant growth. In this research, the *C. chinense* plant treated with organic fertilizer, PLB, and TBF positively impacted the plant growth performance compared to the plant treated with organic fertilizer only (T1). The result indicates that T4 is the most promising treatment combination and could be adopted as a sustainable agronomical strategy. Thus, the findings from this study suggest that the integration of organic fertilizer with PLB and TBF into *C. chinense* cultivation practices can lead to significant improvements in yield production.

4.3.5 Effects of Pineapple Leaf Biochar and *Trichoderma* Biofertilizer on Total Plant Biomass Parameters

Table 4.9 shows the mean value for dry shoot, stem, and root biomass. Results showed significant differences ($p<0.05$) between treatments with T0 gave the highest mean values for dry shoot weight (329.53 g), dry stem weight (35.20 g), and dry root weight (66.87 g). This was followed by T4, with a mean value of 94.00 g, 20.33 g, and 41.80 g, respectively. However, T1 gave the lowest mean values with 46.73 g, 8.20 g, and 22.67 g respectively. This finding indicates *C. chinense* plants that are supplied with chemical fertilizer have superior growth performance with a total plant biomass of 431.60 g as compared to the ones that are supplied with organic fertilizer. However, the *C. chinense* plant that was amended with a treatment combination of organic fertilizer with PLB and TBF has shown a good response in total plant biomass as T4 (156.13 g) recorded as the second highest after T0.

Table 4.9
Effect of PLB and TBF on Plant Biomass Parameters

Treatment	Dry shoot (g)	Dry stem (g)	Dry root (g)	Total plant biomass (g)
T0	329.53 ± 16.56^{a}	35.20 ± 2.33^{a}	66.87 ± 6.32^{a}	431.60 ± 20.02^{a}
T1	46.73 ± 2.98^{d}	8.20 ± 0.85^{d}	22.67 ± 2.00^{c}	77.60 ± 5.29^{c}
T2	54.07 ± 7.61^{cd}	10.13 ± 1.97^{cd}	25.80 ± 4.77^{bc}	90.00 ± 14.03^{c}
T3	93.00 ± 8.07^{bc}	17.07 ± 1.66^{bc}	40.67 ± 3.49^{b}	150.73 ± 12.30^{b}
T4	94.00 ± 7.70^{b}	20.33 ± 1.88^{b}	41.80 ± 3.97^{b}	156.13 ± 11.83^{b}
T5	82.00 ± 9.85^{bcd}	14.13 ± 1.08^{bcd}	33.73 ± 2.30^{bc}	129.87 ± 10.65^{bc}
T6	69.93± 7.17^{bcd}	13.87 ± 1.32^{bcd}	32.13 ± 2.28^{bc}	115.93 ± 8.86^{bc}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant differences at $p>0.05$ according to Tukey's Test ($\alpha = 0.05$). T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

As for T0, the *C. chinense* plant was supplied with commercial chemical fertilizer in a liquid form through a fertigation system as a standard practice by smallholders in Kuching, Sarawak. Using this type of fertilizer could contribute to the highest total plant biomass in T0 because the nutrient was in a form that was readily available for the plant roots to absorb. In addition, liquid chemical fertilizer is the most popular commercial fertilizer because it can be easily monitored for nutrient supply (Lai et al., 2019). Therefore, the amount of nutrients supplied to the *C. chinense* plant is sufficient as the liquid chemical fertilizer contains a balanced mixture of essential macro and micronutrients that are crucial for their growth and biomass accumulation. Compared to organic fertilizer that is supplied in solid form, the nutrient was slowly released and uptake by the plant. Thus, it leads to lower total plant biomass for the *C. chinense* plant.

Although this chemical fertilizer improves plant growth and gives a high total yield, it also brings some drawbacks to the medium. The application ratio of the three fertilizer components varies by crop and medium (Arthanawa et al., 2022), and repeated fertilization in monoculture systems can worsen the medium's N, P, and K imbalance, causing ecosystem disturbances (Eo & Park, 2016). According to Wang et al. (2018), crops can only absorb 30-50% of chemical fertilizers, so a lot of them are lost in the medium and pollute groundwater. Compared to organic fertilizer, it is supplied in solid form, acts as a slow-release fertilizer, and requires a longer time for the nutrient to be readily available for plant uptake, thus reducing medium and water pollution. This

statement aligns with Chatterjee et al. (2021) finding that organic fertilizer releases nutrients slower than chemical fertilizer. Assefa & Tadesse (2019) conclude that organic fertilizer that derives from natural materials can help to minimize chemical runoff and pollution and protect groundwater, besides promoting soil biodiversity and reducing reliance on chemical fertilizer. Therefore, it is crucial to shift towards organic fertilizer and adopt sustainable agriculture practices.

Regarding the data presented in Table 4.9, T0 has higher total plant biomass than the other treatments, with a difference of 63.82% in total compared to T4, however the mean yield result revealed no significant difference between T0 and T4. As for T4, applying organic fertilizer with PLB and TBF could have improved plant growth and yield because both acts as organic amendments that boost medium fertility and increase total plant biomass. These findings are supported by Lehmann & Joseph (2009), who reported that the addition of biochar could be done to increase plant growth so that it can grow optimally due to biochar's ability to bind carbon, produce extremely porous fiber and charcoal, and hold nutrients and water in the medium. Situmeang et al. (2019) also found that applying biochar can increase C levels, retain water and nutrients, and restore medium fertility. The higher total plant biomass for T0 may be related to the fact that all the nutrients were utilized to produce plant leaves, stems, and roots, whereas, for T4, it was assumed that the plant's uptake of the nutrient was used to produce the yield. This can be seen in Figure 4.18, where the growth performance of *C. chinense* treated with T0 appeared more vigorous compared to T4. The superior growth in T0 can be attributed to the immediate availability of nutrients supplied through chemical fertilizer in solution form, which ensured a continuous and balanced nutrient supply to the *C. chinense* plants. In contrast, the nutrient released in T4 was more gradual as slow release fertilizer was used, and it also strongly influenced by adsorption desorption processes and microbial activity. While this slow release mechanism enhance nutrient retention and reduce leaching losses, it was less efficient in meeting the high and immediate nutrient demand by *C. chinense* plants, particularly for their growth. Nevertheless, T4 highlights a more sustainable approach, offering improved nutrient use efficiency, reduced reliance on chemical fertilizer, and long term benefits for media health.



(a) (b)

Figure 4.18 Comparison of *C. chinense* Growth Performance in Treatment (a) T0 and (b) T4

4.3.6 Effects of Pineapple Leaf Biochar and *Trichoderma* Biofertilizer on Nutrient Content in *C. chinense* Plant

The mean comparisons for N, P, and K in the *C. chinense* plant in Table 4.10 indicated significant differences ($p<0.05$) among the treatments.

Table 4.10
Nitrogen, P, and K Content in *C. chinense* Plant According to Treatments

Treatment	N (%)	P (%)	K (%)
T0	9.64^{a}	3.03^{a}	15.13^{a}
T1	6.58^{g}	1.07^{f}	7.67^{g}
T2	7.30^{f}	1.31^{e}	8.75^{f}
T3	7.78^{e}	1.33^{e}	9.25^{e}
T4	9.33^{b}	1.68^{b}	13.20^{b}
T5	8.90^{c}	1.54^{c}	11.05^{d}
T6	8.18^{d}	1.44^{d}	11.12^{c}

*Note: Means with the same letter within each column indicate no significant difference ($p>0.05$) according to Tukey's Test ($\alpha = 0.05$). T0= Commercial chemical fertilizer (Control), T1= Commercial organic fertilizer, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

The results showed that T0 (9.64%) and T4 (9.33%) exhibit the highest N content in *C. chinense* plants, suggesting that these treatments are most effective in promoting N absorption. In contrast, T1 shows the lowest N content (6.58%), indicating its limited effectiveness. Similarly, the absorption of P is highest in T0 (3.03%) and T4 (1.68%), and lowest in T1 (1.07%), highlighting the greater capacity of T0 to improve P absorption. Potassium content follows a similar trend, with T0 (15.13%) and T4 (13.20%) being the most effective, while T1 again displays the lowest content (7.67%), further suggesting its inefficiency in nutrient uptake. Table 4.11 showed the detailed of the nutrient content in shoots, stems, and roots of *C. chinense*.

Table 4.11
Nitrogen, P, and K Content in Shoots, Stems, and Roots of *C. chinense* Plant According to Treatments

Treatment	Shoot			Stem			Root		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
T0	5.34^{a}	0.44^{a}	4.65^{a}	1.20^{a}	0.54^{a}	6.35^{a}	3.10^{a}	2.05^{a}	5.33^{a}
T1	3.38^{g}	0.28^{d}	2.90^{g}	0.80^{d}	0.22^{e}	2.08^{f}	2.40^{d}	0.57^{f}	2.69^{d}
T2	3.60^{f}	0.33^{c}	3.06^{f}	0.80^{d}	0.22^{e}	2.89^{d}	2.90^{c}	0.76^{e}	3.00^{c}
T3	3.98^{e}	0.32^{c}	3.36^{e}	0.90^{c}	0.25^{d}	2.69^{e}	2.90^{c}	0.76^{e}	3.00^{c}
T4	5.03^{b}	0.38^{b}	3.76^{b}	1.20^{a}	0.40^{b}	5.23^{b}	3.10^{a}	0.90^{b}	4.21^{b}
T5	4.90^{c}	0.38^{b}	3.51^{c}	1.00^{b}	0.29^{c}	3.40^{c}	3.00^{b}	0.87^{c}	3.00^{c}
T6	4.28^{d}	0.36^{b}	3.45^{d}	0.90^{c}	0.27^{cd}	3.40^{c}	3.00^{b}	0.81^{d}	4.21^{b}

*Note: Means with the same letter within each column indicate no significant difference ($p>0.05$) according to Tukey's Test ($\alpha = 0.05$). T0= Commercial chemical fertilizer (Control), T1= Commercial organic fertilizer, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

Analysis of the nutrient content in shoots of *C. chinense* indicates that T0 (5.34%) and T4 (5.03%) have the highest N content, reflecting significant nutrient uptake. Conversely, treatments T1 (3.38%) and T2 (3.60%) exhibit the lowest N content, suggesting that commercial organic fertilizer and single organic amendment are less effective. In terms of P, T0 (0.44%) has the highest content, closely followed by T4 (0.38%) and T5 (0.38%). Contrastingly, T1 (0.28%) and T3 (0.32%) show the lowest P content, indicating lesser P uptake. The K content is highest in T0 (4.65%) and T4 (3.76%), while T1 (2.90%) and T2 (3.06%) have the lowest K uptake.

As for the nutrient content in the stem of *C. chinense*, T0 (1.20%) and T4 (1.20%) show the highest N content, with T1 and T2 (0.80%) exhibiting the lowest N content. For P, the highest levels are again recorded in T0 (0.54%) and T4 (0.40%), while T1 and T2 (0.22%) have the lowest P content. Treatment T0 (6.35%) and T4 (5.23%) also show the highest K content, with T1 (2.08%) and T3 (2.69%) recording the lowest K levels. Lastly, for the nutrient content in the roots of *C. chinense*, T0 (3.10%) and T4 (3.10%) exhibit the highest N content, while T1 (2.40%) T2 (2.90%), and T3 (2.90%) have the lowest nitrogen levels. In terms of P, T0 (2.05%) and T4 (0.90%) have the highest phosphorus content, and T1 (0.57%), T2 (0.76%), and T3 (0.76%) are the lowest. For K, T0 (5.33%) and T4 (4.21%) exhibit the highest, whereas T1 (2.69%), T2(3.00%), and T3 (3.00%) have the lowest K content.

Treatment T0 exhibits the highest nutrient content in *C. chinense* shoot, stems, and roots among all parameters that were measured. The higher mean values of N, P, and K content in the T0 plant are probably due to nutrient availability as water-soluble rather than solid fraction. Nevertheless, T4 exhibited promising results, as it recorded the highest N content for the stem and root, and the second highest for the other parameters. The results suggest that the treatment utilizing a combination of PLB and TBF (T4, T5, T6) exhibits superior nutrient content compared to the single treatments (T1, T2, T3). This emphasizes the synergistic effect of utilizing both organic amendments. Consequently, these results suggest that the combined application of organic fertilizer with 75% PLB and 25% TBF (T4) significantly enhanced nutrient uptake by *C. chinense* compared with other treatments.

These findings were congruent with studies by Japakumar et al. (2021) and Hanyabui et al. (2024), who state that the co-application of biochar with compost enhances nutrient uptake by the plant. In the study, co-application use of PLB and TBF treatments was found to enhance the nutrient uptake in *C. chinense* plants, with T0

giving the highest plant nutrient content followed by T4. These results indicated that the use of 75% PLB combined with 25% TBF application is the most effective combination to improve nutrient uptake by *C. chinense*. A recent study conducted by Atluri et al. (2021), states that the co-application of biochar along with biofertilizer showed better performance of crops and nutrient uptake. This study indicates that the incorporation of PLB with TBF could improve nutrient retention in the soil. These additions can directly mitigate nutrient leaching and increase the availability of nutrients required for growth as well as yield production. Furthermore, this study aligns with findings by Lehmann et al. (2003) on the potential of biochar as a plant growth promoter and nutrient retention agent in medium by reducing rapid nutrient leaching during irrigation, especially organic N, and finally increasing yields. Therefore, this study shows that using T4 as an alternative to chemical fertilizer could improve soil fertility as sustainable agricultural practices.

4.3.7 Effect of Pineapple Leaf Biochar and *Trichoderma* Biofertilizer on the Media Nutrient Content

The mean comparison for N, P, and K in the cocopeat outlined in Table 4.12 . The analysis of variance (ANOVA) for N, P, and K indicates significant differences ($p<0.05$) among the treatments. Based on data presented, T0 (0.77%; 0.94%) recorded the lowest N and P content respectively, while T4 recorded the lowest K (1.05%) content, indicating the nutrients were highly absorbed by the plant. Furthermore, T1 (2.20%) showed the highest N content, indicating poor plant uptake. Treatment T3 (1.52%) showed the highest P content, suggesting reduced absorption by the plants, while T2 (6.22%) showed the highest K, also indicating decreased plant absorption.

Table 4.12
Nitrogen, P, and K Content in Cocopeat According to Treatments

Treatment	N (%)	P (%)	K (%)
T0	0.77^{g}	0.94^{e}	1.44^{f}
T1	2.20^{a}	1.15^{c}	4.93^{c}
T2	1.86^{b}	1.23^{b}	6.22^{a}
T3	1.82^{c}	1.52^{a}	5.82^{b}
T4	0.86^{f}	1.11^{d}	1.05^{g}
T5	0.90^{e}	1.11^{d}	3.23^{d}
T6	1.61^{d}	1.15^{c}	2.74^{e}

*Note: Means with the same letter within each column indicate no significant difference ($p>0.05$) according to Tukey's Test ($\alpha = 0.05$). T0= Commercial chemical fertilizer (Control), T1= Commercial organic fertilizer, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

According to the result, T0 consistently shows the highest nutrient levels in plants however the nutrient levels in cocopeat are relatively low. This finding indicates effective plant uptake. Treatment T1 generally shows the lowest nutrient content in plants but higher levels in cocopeat, indicating inefficient nutrient uptake by plants. Treatment T4 stands out as an effective treatment for promoting nutrient uptake, particularly for N and K. Its relatively lower nutrient levels in cocopeat suggest efficient absorption by plants. The findings indicate that the co-application of PLB and TBF improves nutrient uptake compared to a single organic amendment. This finding was similar to the results from studies by Japakumar et al. (2021) and Hanyabui et al. (2024). Employing a combination of treatments that balance nutrient availability, and uptake can lead to better plant health and yields. An integrated approach ensures all essential nutrients are adequately supplied and utilized. The addition of both organic amendments into the medium positively impacts nutrient retention, minimizing nutrient leaching while making it continuously available to plants. Furthermore, this finding aligns with a study by Lehmann et al. (2003), which stated that the ability of biochar as a growth trigger for plant growth and maintaining nutrient content in the medium so that nutrients are not easily lost during leaching which eventually affects yield increase. Based on the overall findings, T4 is recommended to preserve soil fertility and ensure a sustainable future for people.

4.3.8 Pearson's Correlation

The correlation analysis, Figure 4.19, among morphological and yield-related parameters revealed several notable associations.

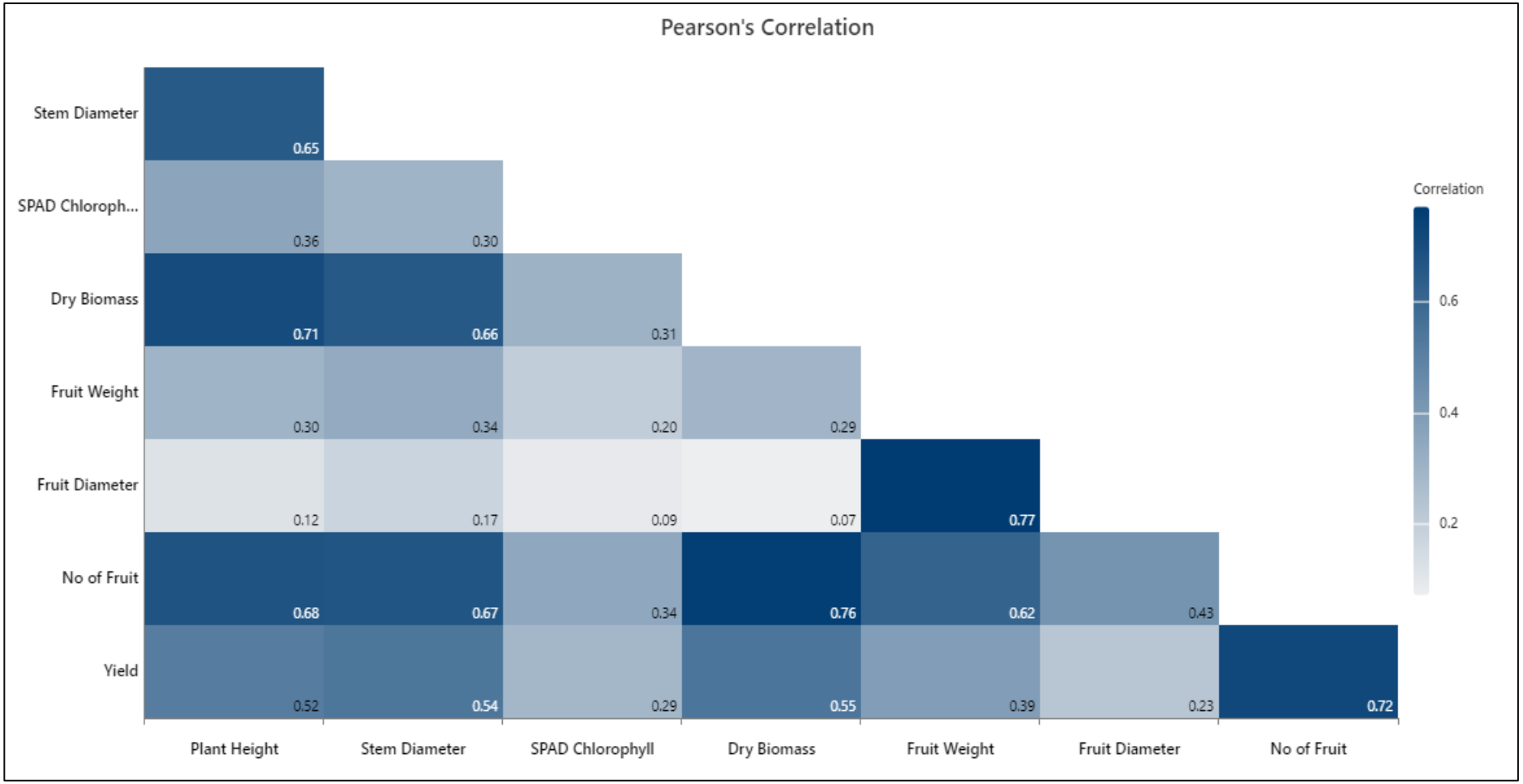


Figure 4.19 Correlation between Measured Parameters

Based on data presented in Figure 4.19, plant height demonstrated a strong correlation with dry biomass (r = 0.71), number of fruits (r = 0.68), and stem diameter (r = 0.65). These correlations suggest that taller plants generally have higher biomass accumulation, produce more fruits, and thicker stems. Meanwhile, moderate correlation with yield (r = 0.52) showed plant height subsequently yield better. However, its correlation with chlorophyll content (r = 0.36), and fruit weight (r = 0.30), were relatively weak, and fruit diameter (r = 0.12) was very weak, indicating that plant height alone may not significantly determine individual fruit size or chlorophyll content. As for the stem diameter, it exhibited a notably strong relationship with number of fruits (r = 0.67) and dry biomass (r = 0.66). These relationships imply that robust stem development supports overall biomass accumulation and potentially enhances the plant's capacity to bear more fruits. Moderate relationship was recorded for yield (r = 0.54), which indicates the stem diameter directly improving yield. Weak correlations were observed with fruit weight (r = 0.34), and chlorophyll content (r = 0.30), while very weak with fruit diameter (r = 0.17), highlighting a partial influence of stem diameter on fruit attributes. Furthermore, chlorophyll content showed weak correlations relationship with number of fruits (r = 0.34), dry biomass (r = 0.31), yield (r = 0.29), and fruit weight (r = 0.20), and very weak relationship with fruit diameter (r = 0.09). These findings indicate that chlorophyll content does not contribute to plant productivity.

Dry biomass demonstrated a strong positive correlation with the number of fruits (r = 0.76), a moderate correlation with yield (r = 0.55), a weak correlation with fruit weight (r = 0.29), and a very weak correlation with fruit diameter (r = 0.07). These results indicate that biomass accumulation significantly contributes to increased number of fruits, and moderately influences the yield, but has minimal direct influence on overall fruit weight and fruit diameter. In addition, fruit weight showed an exceptionally strong positive correlation with fruit diameter (r = 0.77) and number of fruits (r = 0.62), indicating that heavier fruits tend to be larger in size. The correlation with yield was also weak (r = 0.39), suggesting that while heavier fruits do enhance overall yield, the total yield also depends significantly on fruit number rather than just individual fruit weight. Fruit diameter had a moderate correlation with number of fruit (r = 0.43), and weak correlation with yield (r = 0.23). This pattern indicates fruit size is not associated with number of fruit and yield. The number of fruits produced exhibited a strong

positive correlation with yield (r = 0.72), clearly demonstrating that increased fruit number significantly enhances yield.

Similar findings were reported by Soares et al. (2017), who observed high correlations between yield per plant and both fruit number and plant height, highlight the importance of vegetative vigor in yield formation. These results reinforce the potential of selecting taller plants with higher plant biomass aimed at enhancing number of fruit and yield *C. chinense*. The study by Luitel et al. (2018), which performed a multivariate analysis on 23 genotypes, reported strong correlations between fruit diameter and fruit weight, confirming that larger fruits also tend to be heavier. This finding aligns closely with results obtained in the present study, where application of PLB and TBF enhanced fruit size parameters, suggesting that both may influence growth performance in terms of plant height and stem diameter, thereby improving fruit weight and fruit diameter in *C. chinense*. As well a study by Ali et al. (2019) found strong correlations between total fruit number and total fruit weight per plant, with average fruit weight also showing a strong correlation with fruit width and wall thickness in *C. chinense*. Similarly, in the present study, the application of PLB and TBF enhanced fruit weight and diameter, indicating that both amendments positively influence both the quality components of yield in *C. chinense*.

4.4 Conclusion

This study implies that application of PLB (75%) and TBF (25%) has increased the agronomic performance of *C. chinense* plants. Although T0 consistently recorded the highest mean values across all measured parameter, the combined application of PLB an TBF in T4 produced the best results among the organic treatments. Treatment T4 demonstrated significant performance in plant height (62.93 cm), stem diameter (1.03 cm), chlorophyll content (53.10), yield (403.69 g), fruits number (269), weight (8.87 g), and diameter (2.95 cm), total plant biomass (156.13 g) as well as nutrient content, indicating the synergistic benefits of the PLB and TBF in fertigated cocopeat media. The results highlight its potential as a sustainable alternative that enhances crop productivity while reducing reliance on chemical fertilizers. Therefore, the use of PLB and TBF at 75% and 25% respectively is recommended as a promising practice to support sustainable *C. chinense* production and long-term media health.

CHAPTER 5
NITROGEN RETENTION DYNAMICS IN FERTIGATED COCOPEAT MEDIA AMENDED WITH PINEAPPLE LEAF BIOCHAR AND *TRICHODERMA* BIOFERTILIZER

5.1 Introduction

Nitrogen retention in cocopeat media is governed by a series of interconnected physicochemical processes, of which adsorption and desorption are the primary mechanisms controlling nutrient availability and loss under fertigation. In cocopeat-based media, frequent irrigation and low buffering capacity promote rapid nutrient movement, making the retention of N within the growth media essential for maintaining nutrient use efficiency and sustaining plant growth. In this study, N retention is therefore evaluated through adsorption and desorption processes occurring in the cocopeat media, rather than plant tissue accumulation, which is commonly assessed indirectly through plant growth or tissue analysis (White & Ding, 2023).

Adsorption is a surface phenomenon in which nutrient ions from solution adhere to solid surfaces through electrostatic attraction, hydrogen bonding, and van der Waals forces, while desorption is the reverse process in which previously adsorbed nutrients are released back into the soil solution and become available for plant uptake or microbial transformation (Gupta & Germida, 2015; Sparks et al., 2023). These processes determine the capacity of the growth media to temporarily store nutrients and regulate their release in response to plant demand. Understanding adsorption–desorption behavior is therefore critical for minimizing N leaching and improving nutrient retention in fertigated cocopeat media.

Organic amendments such as PLB and TBF have been shown to modify adsorption sites and nutrient cycling in growing media. Biochar provides a porous structure and a large surface area that enhances nutrient sorption and retention, while *Trichoderma* spp. promote nutrient transformation, solubilization, and uptake through microbial activity and rhizosphere interactions (Mesbah et al., 2021; Tangga et al., 2022; Zhu et al., 2022; Karmaita et al., 2023). When applied together, PLB and TBF may alter both the strength and reversibility of nutrient adsorption, thereby improving

the synchronization between N retention in the media and N release for plant uptake (Mukhina et al., 2020; Kubheka & Ziena, 2022).

Despite extensive research on biochar and microbial biofertilizers, few studies have directly examined nitrogen adsorption and desorption behavior in cocopeat media, particularly before and after planting. Most existing studies have focused on soil or plant responses without quantifying the retention mechanisms operating in cocopeat media. Therefore, this study was conducted to quantitatively evaluate N adsorption and desorption in cocopeat media amended with PLB and TBF, using batch equilibrium experiments and adsorption isotherm analysis as described by Palanivell et al. (2020). By assessing N retention dynamics before and after planting *C. chinense*, this study provides mechanistic insight into how PLB and TBF influence N retention, release, and availability throughout the crop growth cycle.

5.2 Materials and Methods

5.2.1 Sample Collection and Preparation

Cocopeat samples were collected from two sampling periods: before planting (initial media) and after planting (20 weeks after treatment). The treatment compositions for each sampling period are summarized in Table 5.1.

Table 5.1
Treatment Composition Before and After Planting (20 Weeks After Treatment).

Treatment	Before planting	After planting
T0	Cocopeat only	Cocopeat + Chemical fertilizer
T1	Cocopeat only	Cocopeat + Organic fertilizer
T2	Cocopeat + OF + 100% PLB	Cocopeat + OF + 100% PLB
T3	Cocopeat + OF + 100% TBF	Cocopeat + OF + 100% TBF
T4	Cocopeat + OF + 75% PLB + 25% TBF	Cocopeat + OF + 75% PLB + 25% TBF
T5	Cocopeat + OF + 50% PLB + 50% TBF	Cocopeat + OF + 50% PLB + 50% TBF
T6	Cocopeat + OF + 25% PLB + 75% TBF	Cocopeat + OF + 25% PLB + 75% TBF

*Note: OF = Organic fertilizer; PLB = Pineapple leaves biochar; TB = *Trichoderma* biofertilizer

These samples were prepared for subsequent pH and EC determination, as well as adsorption–desorption analyses. Upon collection, the samples were air-dried at room temperature until constant weight was achieved. The dried samples were gently crushed using a mortar and pestle to break up aggregates and then sieved through a 2 mm mesh sieve to obtain a uniform particle size. The prepared samples were thoroughly homogenized and stored in clean, airtight containers prior to laboratory analyses.

5.2.2 Determination of pH and EC

The pH and EC values of the cocopeat sample were measured according to Hassan et al. (2021). The ratio was 1 g of cocopeat sample to 20 mL of deionized water (1:20). The sample was shaken for 90 minutes on a Digital Orbital Shaker to ensure sample and solution equilibration, thus, obtaining accurate pH readings. An Oakton pH 700 Benchtop Meter and a CON 700 EC meter were used to measure the pH and EC values respectively.

5.2.3 Nitrogen Adsorption and Desorption Determination

The N adsorption and desorption analysis was conducted based on Palanivell et al. (2020). A 2 g sample from each treatment was weighed and placed into a 250 mL centrifuge bottle, with three replicates for each treatment. Nitrogen solutions 0, 100, 200, 300, and 400 mg N L^{-1} were prepared by dissolving ammonium chloride (NH_4Cl) in a 0.2 M NaCl solution. Subsequently, 20 mL of these uniform N solutions were added to the centrifuge bottles, resulting in added N amounts of 0, 1000, 2000, 3000, and 4000 µg per sample. The use of uniform solutions ensured consistent ionic strength within the mixture and supplied competitive ions for exchange sites during this study.

Two drops of toluene were included in each sample to inhibit microbial activity. The samples were agitated for 24 hours at 180 rpm on an orbital shaker. Following agitation, they were centrifuged at 10,000 rpm for 15 minutes to obtain equilibrium solutions containing N. The N content in these solutions was determined using the steam distillation method. The quantity of N adsorbed per gram of soil was computed by subtracting the initial added N amount from the equilibrium solution's N content, measured in µg g^{-1} soil.

The sediments in the centrifuge bottles were washed with ethanol and centrifuged at 10,000 rpm for 10 minutes. The ethanol was then discarded, and 20 mL of 2 M KCl was added. This mixture was shaken for 24 hours at 180 rpm using an orbital shaker. Afterward, the samples were centrifuged at 10,000 rpm for 15 minutes, and the supernatants were collected to determine their N contents via the steam distillation method. Figure 5.1 showed the procedures in preaparing samples for adsorption and desorption determination analysis.



(a) Weighing of samples for analysis



(b) Preparation of working solutions



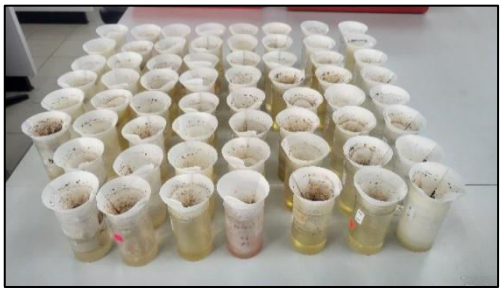
(c) Centrifuged of samples



(d) Shaking of samples on an orbital shaker



(e) Collection of samples for adsorption analysis



(f) Collection of samples for desorption analysis



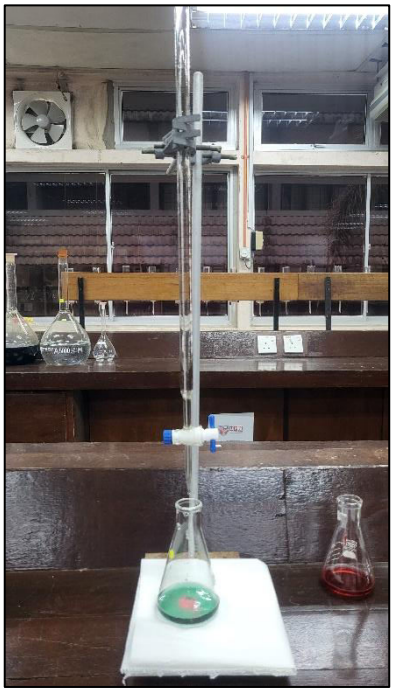
(g) N determination using team distillation



(h) Preparation of samples for titration



(i) Preparation of working solution



(j) Titration of samples

Figure 5.1 Procedures in Preparing Samples for Adsorption sand Desorption Determination Analysis

5.2.4 Statistical Analysis

The pH and EC data were analyzed statistically using analysis of variance (ANOVA) to determine differences among treatments and added N concentrations. Mean comparisons were performed using Tukey's test at $P \leq 0.05$. All statistical analyses were conducted using Minitab 21 (Version 2.1).

In contrast, adsorption–desorption data were analyzed descriptively based on observed trends, as no inferential statistical analysis was performed for these measurements. Linear regression analysis was used to describe the relationship between

added N concentration and equilibrium solution N, and the coefficient of determination (R^2) was obtained for each regression equation.

5.3 Results and Discussion

5.3.1 Effect of Pineapple Leaf Biochar and *Trichoderma* Biofertilizer on pH and EC Value of Cocopeat Media

Table 5.2 illustrates the results of the pH and EC values of cocopeat before and after planting. The analysis of variance (ANOVA) revealed significant differences ($p<0.05$) among the treatments for both parameters. The initial mean pH value of the soiless media recorded was 5.26. After adding PLB and TBF, the pH values were generally increased, indicating a shift towards a more neutral environment for all treatments. Treatment T3 recorded the highest pH mean value (6.75) with an increase of 1.49, suggesting that application of TBF only can substantially increase the pH of cocopeat. Treatment T0 and T1 had the lowest pH value (5.26), which is slightly acidic.

Table 5.2
Effects of PLB and TBF on pH and EC Value of Cocopeat

Treatment	pH before planting	pH after planting	Electrical conductivity before planting (dS m^{-1})	Electrical conductivity after planting (dS m^{-1})
T0	5.26 ± 0.01^{d}	5.87 ± 0.04^{d}	7.99 ± 0.28^{c}	9.92 ± 0.30^{a}
T1	5.26 ± 0.01^{d}	5.99 ± 0.09^{cd}	7.99 ± 0.28^{c}	8.06 ± 0.06^{bc}
T2	6.47 ± 0.01^{c}	6.22 ± 0.06^{bc}	8.38 ± 0.40^{bc}	7.52 ± 0.47^{c}
T3	6.75 ± 0.04^{a}	6.55 ± 0.03^{a}	12.25 ± 0.42^{a}	8.05 ± 0.31^{bc}
T4	6.57 ± 0.01^{bc}	6.47 ± 0.06^{ab}	8.54 ± 0.61^{bc}	7.53 ± 0.34^{c}
T5	6.69 ± 0.01^{ab}	6.61 ± 0.01^{a}	10.03 ± 0.28^{b}	9.13 ± 0.39^{ab}
T6	6.59 ± 0.05^{bc}	6.16 ± 0.10^{bcd}	9.91 ± 0.43^{bc}	7.63 ± 0.22^{bc}

*Note: Mean ± standard error of mean was analyzed by ANOVA. The same letter within each column indicates no significant differences at $p>0.05$ according to Tukey's Test ($\alpha = 0.05$). T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

According to data presented in Table 5.2, the changes in pH values before and after planting varied across the different treatments. Treatment T0 and T1 had showed an increase in pH value after planting with values of 0.61 and 0.73 respectively. However, the other treatments (T2-T6) that applied with organic amendment show a decrease in pH value, with T5 showing a smaller change with a value of 0.08 compared to other treatments. This suggests that the effectiveness of the treatment in altering pH may depend on the specific process or substances involved in each treatment. Additionally, the variability in the pH values before and after treatment, as indicated by standard error, suggests that the treatment effects were not consistent across all samples. This could be due to factors such as sample heterogeneity or variations in the treatment process. The optimal soil pH is crucial for nutrient availability and uptake by plants. Most plants prefer a slightly acidic to neutral pH range (6.0 to 7.0) for optimal growth. The higher pH observed in treatment T5 suggests improved conditions for nutrient uptake, potentially enhancing plant growth and health. These findings are consistent with previous research indicating that combining biochar with biofertilizers improved acidic soil properties, increasing pH and base cations while decreasing exchangeable acidity (Sasmita et al., 2017).

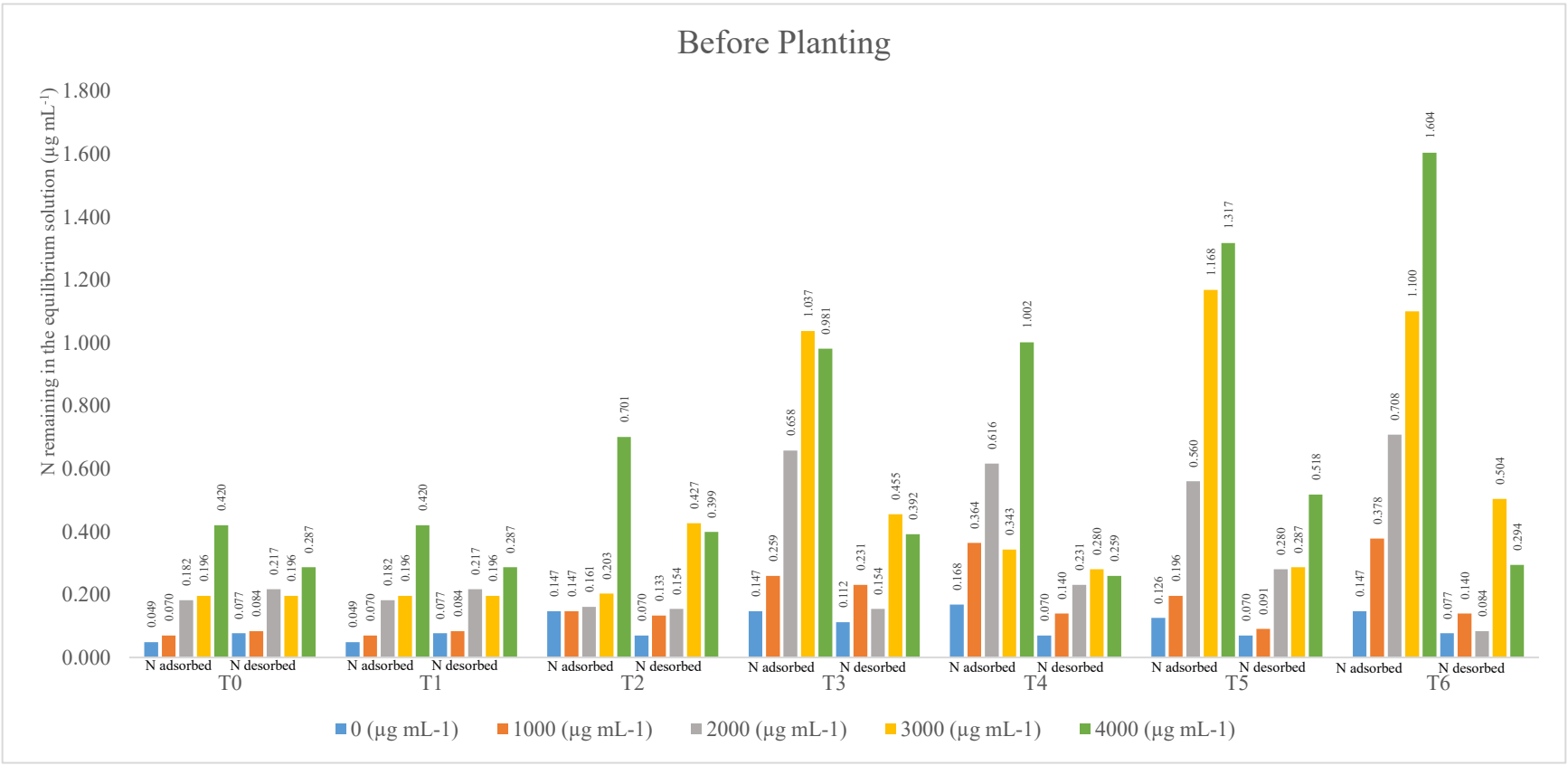
The EC value, which indicate the salt concentration and nutrient availability in the cocopeat, also varied significantly among the treatments. From the data presented in Table 5.2, application of PLB and TBF resulted in increased EC value of cocopeat. Specifically, T2 (8.38 dS m^{-1}), T3 (12.25 dS m^{-1}, T4 (8.54 dS m^{-1}), T5 (10.03 dS m^{-1}), and T6 (9.91 dS m^{-1}) recorded higher EC values, compared to T0 and T1, which did not recieve PLB or TBF and showed an EC value of 7.99 dS m^{-1}, indicating lower nutrient availability. The higher EC value, suggesting an increased concentration of soluble ions in the root zone, which can enhance nutrient availability and promote plant growth. As for the after planting, 20 weeks after treatmenr, the changes in EC value was varied across the different treatment. There was no consistent pattern observed in the changes in EC after planting across the different treatment. Based on data presented, the EC value is generally reduced for all the treatments except for T0 (9.92 dS m^{-1}) and T1 (8.06 dS m^{-1}). The increased in EC value could be due to the accumulation of unused fertilizers and high evapotranspiration in greenhouse conditions, which cause the water evaporates faster than salts removed thus leaving salts behind and increasing their concentration in cocopeat. This finding aligned with Ullah et al. (2021), stated that high evapotranspiration is a main reason of salt accumulation in soils and growing media,

which leads to increasing salinity and elevated EC. High EC values can enhance nutrient availability but can also lead to osmotic stress if excessively high, potentially hindering plant growth and reducing yield. This balance is crucial for maintaining optimal plant health and productivity. Haraz et al. (2020) concluded that biochar addition to peat moss growth medium increased pH by up to 1.5 units and reduced EC, thus enhancing nutrient retention and availability.

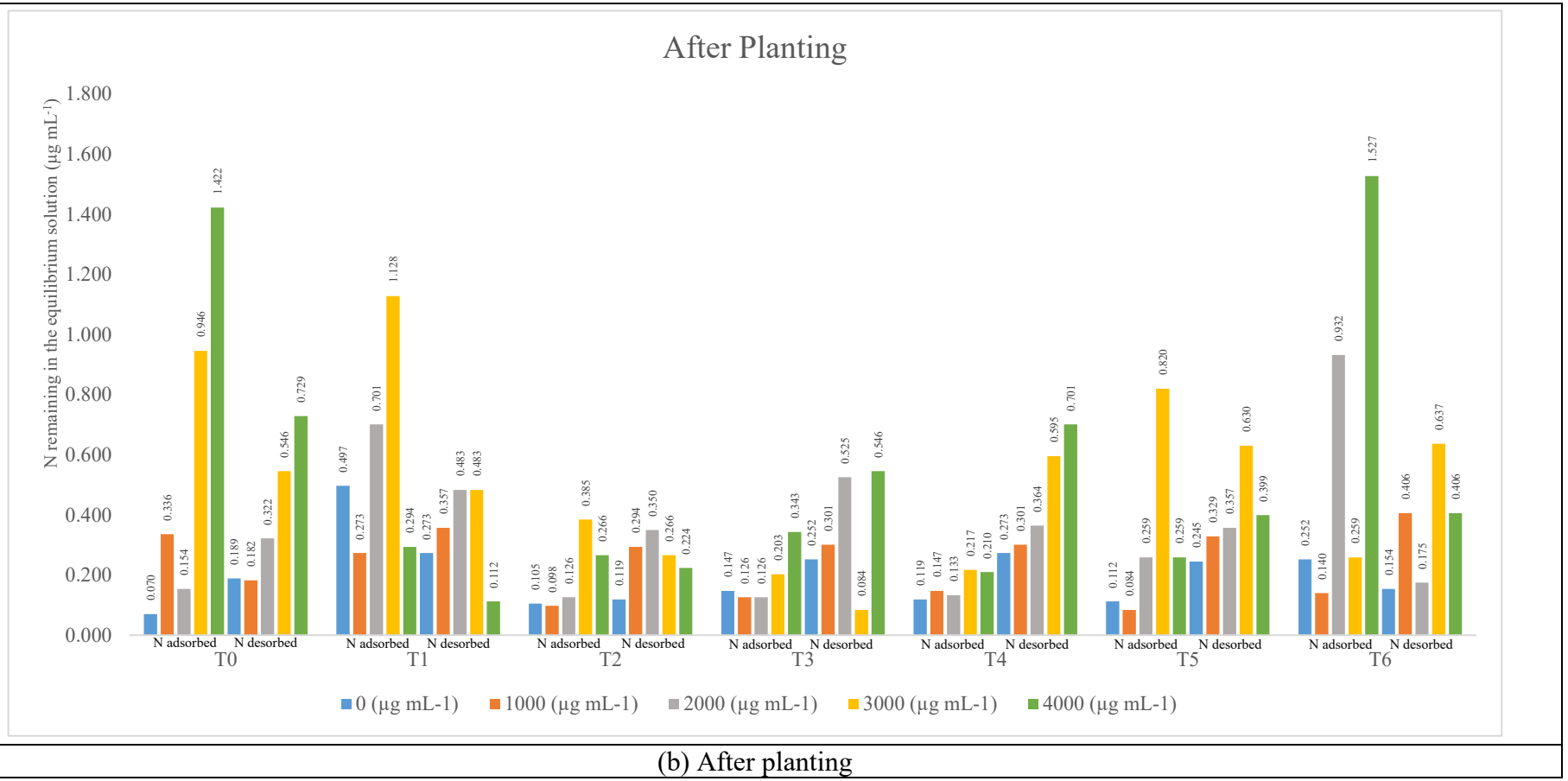
Based on the data presented in Table 5.2, the application of PLB and TBF generally resulted in a gradual decline in both pH and EC of the cocopeat over time, 20 weeks after treatment. The trend observed in this study, was could be attributed to several factors. Firstly, fresh PLB exhibits high alkalinity, but its alkalinity decreases as soluble basic compounds are leached and its surfaces undergo oxidation, forming acidic functional groups. The fresh PLB exhibits high alkalinity with pH of 10.28, due to the presence of soluble basic compound such as potassium carbonates and calcium oxides produced during pyrolysis. However, these compounds can be washed out of the PLB surface with repeated irrigation. At the same time, the exposure to oxygen and microbial activity introduces carboxyl and hydroxyl groups on PLB surfaces, which gradually contribute to acidification of the cocopeat, thus lowering its pH. Secondly, TBF contributes to rhizosphere acidification through the secretion of organic acids that solubilize nutrients, the stimulation of nitrification processes, and the enhancement of root proton (H^+) release. This acidification is generally beneficial as it increase the solubility and availability of nurients such as P, Fe, and Mn, but if excessive, it can reduce nutrient balance and harm plant root health. Lastly, the reduction in EC may be explained by the adsorption of soluble ions such as NH_4^+, K^+, and Ca^{2+} onto the high surface area and porous structure of PLB, leaching through irrigation, immobilization within microbial biomass complexes, and enhanced nutrient uptake by plants under bioactive conditions. Such shifts are generally beneficial when pH stabilizes in the slightly acidic range and EC remains at moderate levels, as these conditions optimize nutrient availability and promote root health. However, excessive declines in pH and EC may indicate undesirable acidification and nutrient depletion, necessitating corrective measures such as the reapplication of biochar or other liming materials.

5.3.2 Nitrogen Concentrations in the Solution

Figure 5.2**,** illustrates the effect of added N concentration on the amount of N remaining in the equilibrium solution for different treatments before and after planting of *C. chinense*.



(a) Before planting



(b) After planting

Figure 5.2 Effect of Added N Concentration on Equilibrium Solution N Concentration in Different Treatments for (a) Before Planting and (b) After Planting the *C. chinense* Plant. T0= Chemical Fertilizer (Control), T1= Organic Fertilizer, T2= Organic Fertilizer + 100% PLB, T3= Organic Fertilizer + 100% TBF, T4= Organic Fertilizer + 75% PLB + 25% TBF, T5= Organic Fertilizer + 50% PLB + 50% TBF, and T6= Organic Fertilizer + 25% PLB + 75% TBF.

As for before planting, the N in the equilibrium solution of T6 (1.604 μg mL^{-1}) and T5 (0.518 μg mL^{-1}) recorded the highest N adsorbed and desorbed respectively. Meanwhile, the N in the equilibrium solution of T0 (0.049 μg mL^{-1}) and T1 (0.049 μg mL^{-1}) recorded the lowest for N adsorbed while T2 (0.070 μg mL^{-1}), T4 (0.070 μg mL^{-1}), and T5 (0.070 μg mL^{-1}) for N desorbed. According to the column chart presented in Figure 5.2 (a), the N adsorbed was higher than the N desorbed in almost N concentrations and treatments. The N concentration of 4000 μg mL^{-1} gave the hysteresis effect as the amount of N adsorbed is consistently higher than N desorbed for all the treatments studied. This observation indicates that the cocopeat retains some of the N adsorbed and is not readily released during the desorption process, especially for organic treatment (T2-T6). This finding is supported by Li et al. (2023), biochar improves the retention of N, which has been shown to reduce N leaching and increase its availability to plants. Haraz et al. (2020)also found that biochar can improve the physical properties of planting media, particularly in nutrient retention.

Despite that, the finding also reveals that adding PLB and TBF in cocopeat can help increase the N equilibrium solution. It was proven when the N equilibrium solution for T2, T3, T4, T5, and T6 was higher than those for T0 and T1, which did not receive PLB or TBF. Another observation from this study is the different treatment combinations of PLB and TBF had different effects on N availability. Reducing the amount of PLB seems to increase N in the equilibrium solutions. A similar finding was observed by Palanivell et al. (2020), suggesting that the addition of biochar increased N adsorption. In contrast, increasing the amount of TBF increased the N in the equilibrium solutions and this is in line with a study by Yan et al. (2023), who demonstrated that partial substitution of chemical fertilizer with TBF improved N use efficiency and yield in wolfberry.

Meanwhile for after planting, the N in the equilibrium solution appears to fluctuate in all N concentrations and treatments. This could be due to the response of cocopeat to the treatment that has been applied throughout the study period (20 weeks after treatment). The highest N remaining in the equilibrium solution for adsorbed and desorbed was recorded by T6 (1.527 μg mL^{-1}) and T0 (0.729 μg mL^{-1}), and in contrast, the lowest was recorded by T0 (0.070 μg mL^{-1}) and T2 (0.119 μg mL^{-1}) respectively. Based on the trends shown in Figure 5.2 (b), T4 consistently exhibited a higher equilibrium N concentration during desorption compared to adsorption across all added N levels, indicating a greater tendency for N release back into the solution after planting.

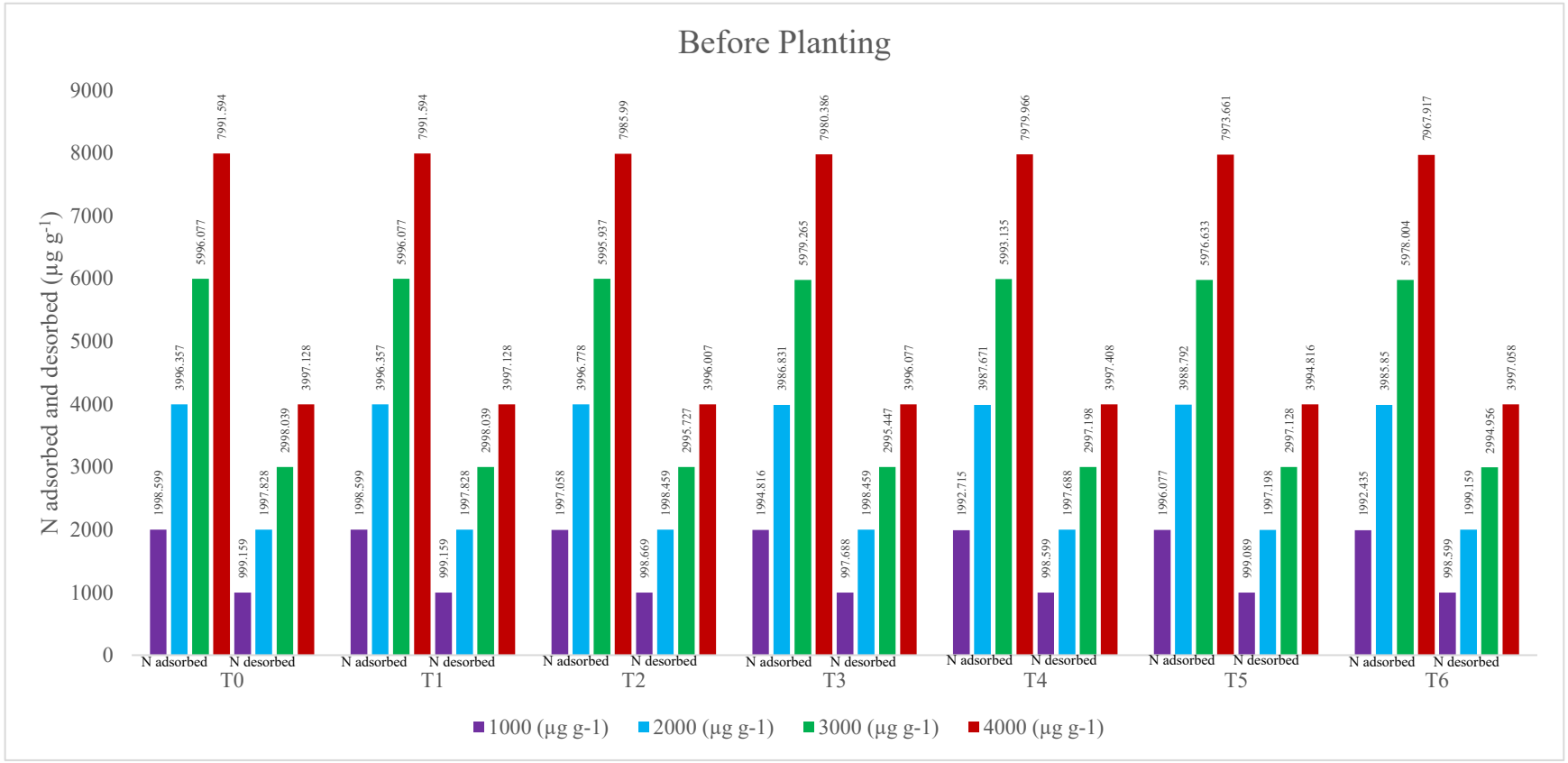
This observed pattern suggests that the combined application of PLB and TBF may have enhanced the N buffering behavior of the cocopeat media during the planting period.

The findings of this study indicate that the adsorption and desorption behavior of N in cocopeat was strongly influenced by the application of PLB and TBF, which governed both nutrient retention and release dynamics. Before planting, higher N adsorption relative to desorption across most treatments suggests that the porous structure, high surface area, and functional groups of PLB, together with microbial activity associated with TBF, enhanced N immobilization and reduced potential N losses. This combination of high adsorption and low desorption indicates that the cocopeat acted as a nutrient reservoir, temporarily retaining applied N and releasing it gradually during crop growth, thereby improving N use efficiency in the fertigated system.

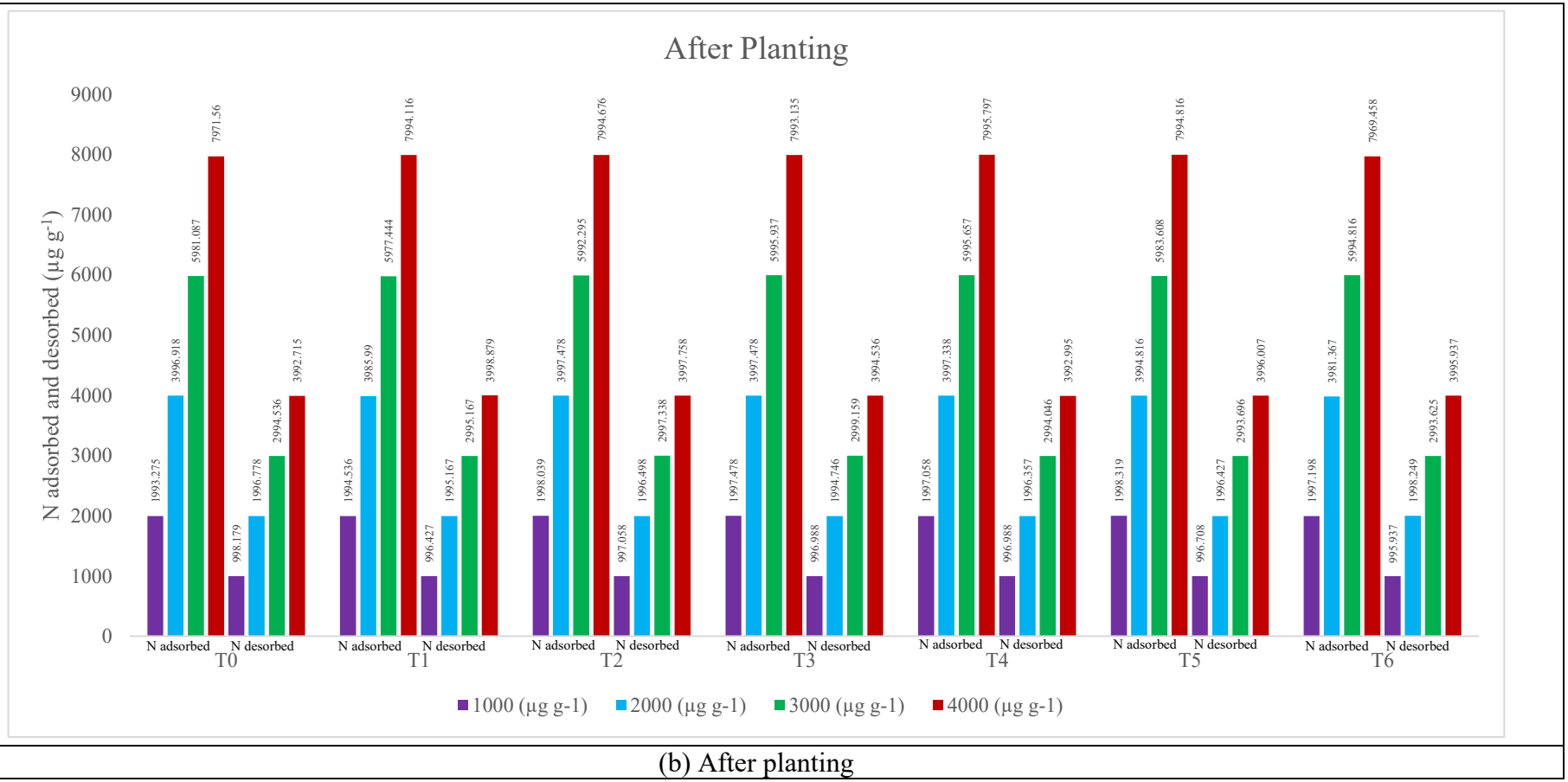
Meanwhile for after planting, plant uptake and microbial interactions reshaped the equilibrium, with fluctuations in N concentration across treatments, which notably, T4 demonstrated higher desorption than adsorption, reflecting that nutrients stored in the media were released back into solution to support crop demand, consistent with its superior growth and yield performance. These mechanisms collectively highlight that PLB and TBF improve N use efficiency by balancing strong retention capacity with timely release, thereby sustaining nutrient availability throughout the crop cycle. This result supports the reason why T4 recorded the highest growth, yield, and nutrient uptake among the organic treatments in Chapter 4.

5.3.3 Nitrogen Adsorption and Desorption in the Solution

Figure 5.3 shows the effects of different treatments on the amount of N adsorbed and desorbed in cocopeat before and after planting the *C. chinense* plant. Across both sampling periods, the combined application of PLB and TBF showed a similar adsorption pattern before and after planting, as observed from the graphical trends. In all treatments, the amount of N adsorbed increased with increasing added N concentration, indicating a concentration-dependent adsorption behavior of the cocopeat media. The desorption patterns generally followed the adsorption trends, suggesting that the retained N remained responsive to changes in solution N concentration after planting.



(a) Before planting



(b) After planting

Figure 5.3 Effects of Different Treatments on the Amount of N Adsorbed and Desorbed on Cocopeat (a) Before Planting and (b) After Planting the *C. chinense* plant. T0= Chemical Fertilizer (Control), T1= Organic Fertilizer, T2= Organic Fertilizer + 100% PLB, T3= Organic Fertilizer + 100% TBF, T4= Organic Fertilizer + 75% PLB + 25% TBF, T5= Organic Fertilizer + 50% PLB + 50% TBF, and T6= Organic Fertilizer + 25% PLB + 75% TBF.

Across all treatments, the adsorption capacity increased proportionally with added N concentration, confirming that the cocopeat media had sufficient binding sites to capture additional N as supply increased. Based on the column chart in Figure 5.3, the highest N adsorbed before planting was observed in T0 and T1 (7991.594 μg g^{-1}), while after planting the highest value was observed in T4 (7995.797 μg g^{-1}). The highest N desorbed before planting was observed in T4 (3997.408 μg g^{-1}), whereas after planting it was observed in T1 (3998.879 μg g^{-1}). All maximum adsorption values were observed at the highest added N concentration (4000 μg g^{-1}). Although these values represent the highest observed adsorption, the differences among treatments were minimal (<1%) across all added N concentrations. General trend indicated that N adsorption capacity increased with increasing N concentration, suggesting greater N availability in the cocopeat and a corresponding tendency for more N to be released back into the solution during the desorption process following *C. chinense* cultivation.

The results in Figure 5.3 reveled that T4 exhibited the highest N adsorption after planting and the highest N desorption before planting, which demonstrated its superior ability to both retain and release N in the cocopeat. This indicates that the PLB and TBF created a synergistic effect, where PLB provide abundant sorption sites for N retention, reducing leaching losses, while TBF enhanced biological cycling and facilitated the timely desorption of N into the equilibrium solution. Such a balance between adsorption and desorption is critical for sustaining nutrient availability, as it prevents rapid depletion while ensuring a steady supply of N to meet the continuous demand of *C. chinense* during its growth. This mechanism explains the superior agronomic performance of T4 observed in Chapter 4, highlighting the role of PLB and TBF in improving N use efficiency and supporting plant productivity.

The comparison was focused on T0 and T4 as these two treatments recorded the highest result in agronomic performance in Chapter 4. Compared to T0, the adsorption capacity of T4 after planting was increased by 0.19%, 0.01%, 0.24%, and 0.30% when the PLB and TBF were added to the cocopeat. This finding indicates that the adsorption capacity of N is influenced by the combination of PLB and TBF which bring synergistic effects to the growth of the *C. chinense* plant. The characteristics of PLB that high surface area, pore volume, and negative charged functional groups, provides abundant sites for electrostatic attraction and physical entrapment of NH_4^+ and NO_3^- ions. While, TBF enhances biological activity in the rhizosphere, promoting N mineralization and cycling, and releasing organic acids or enzymes that can dislodge N from weak sorption

sites, thereby improving bioavailability. This synergy ensures that N is not only well-retained but also mobilized in a timely manner when plant demand is high.

PLB has a porous structure with a high surface area that can provide more area for N adsorption thus enhancing its capacity. This is supported by Zhu et al. (2022), who found that biochar which has rich pores, large specific surface area, abundant functional groups, and exchangeable cations contributes to the absorption capacity of the soil. A study by Amanullah & Khan (2023) also found that PLB and *Trichoderma asperellum* L. can effectively adsorb and retain nutrients in the growing medium when the application can reduce the uptake of heavy metal in plants by up to 83%. The high CEC of biochar makes it a good adsorbent of nutrients (He et al., 2023b). Even though this study used cocopeat as a media, the response was similar to soil media.

Regardless of the characteristics of PLB, the role of TBF also contributes to the adsorption capacity of the cocopeat. Symbiotic relationships formed by *Trichoderma* fungi with *C. chinense* plant roots can enhance the ability of nutrient uptake of the plant. In addition, *Trichoderma* also can directly uptake N from the cocopeat and transfer it to the *C. chinense* plant, effectively increasing the N uptake capacity. Fiorentino et al. (2018) found that *Trichoderma*-based biostimulants enhance N use efficiency in leafy vegetables, especially in low N availability conditions.

A study by Mei et al. (2022) observed that Chinese wolfberry showed that *Trichoderma* facilitated the N uptake, assimilation, and accumulation under saline stress, ultimately promoting plant growth and improving N use efficiency. Yan et al. (2023), also found that *Trichoderma* helps to strengthen plant roots for N absorption by increasing root NH_4^+ and NO_3^- influxes. The findings from this study suggest that a combination of PLB and TBF can be a promising approach to improve the N adsorption capacity of the *C. chinense* plant.

5.3.4 Nitrogen Adsorption Isotherms

The experimental data on Langmuir's N adsorption of different treatments before and after planting showed in Table 5.3. The regression equation showed positive slope or intercepts for both before and after planting. The N adsorption data of the cocopeat before planting, T0 (R^2=0.5461), T1 (R^2=0.5461), T2 (R^2=0.4210), T3 (R^2=0.4783), T4 (R^2=0.2460), T5 (R^2=0.7113) and T6 (R^2=0.4382) are described by the Langmuir equation, with coefficients of determination (R^2) < 0.8. The highest

coefficient determination (R^2) value was recorded by T5 for both before and after planting with value of 0.7113 and 0.8467 respectively. This results indicates that the adsorption behavior of T5 follows the Langmuir assumptions more closely compared to the other treatments. The highest R^2 value was observed for the T5, suggesting a stronger conformity to the Langmuir model, which implies that N adsorption occurred more uniformly, with adsorption sites being relatively consistent and predictable.

In cocopeat studies, this is important because it shows that the T5 provides more consistent and reliable adsorption sites for N, which can improve nutrient retention and reduce leaching losses as well as ensuring a more sustained supply of N to the *C. chinense* plant. The higher R^2 value reflects a greater dominance of monolayer adsorption, indicating that N was more reliable retained on adsorption site with less interference from heterogeneous and biologial processes (Ayawei et al., 2017; Kalam et al., 2021). However, T4 resulted the lowest R^2 value for both before and after planting, with value 0.2460 and 0.0179 respectively. This could be attributed to the heterogeneous surface characteristics of PLB that creates a variety of adsorption sites with different affinities, deviating from Langmuir's assumption of uniform sites. Similar findings by Srikhaow et al. (2023) and Song et al. (2024) indicates that biochar exhibits heterogeneous, multilayer adsorption driven by its diverse pore structures and abundant, temperature-dependent functional groups, enabling multi-mechanism adsorption rather than a single uniform site energy. Beside that, the biological interactions from TBF also could be reasons as it is a living microorganism that colonizes PLB pores, secretes organic acids, and produces enzymes, which can alter the pH, redox potential, and ion exchange dynamics of the cocopeat, making the adsorption and desorption process become more dynamic and less predictable. This aligned with the study findings by Yang et al. (2024), who found that the high surface area and porous structure of biochar provide niches that support microbial colonization and activity in and on the pores.

In addition, before planting, the highest N adsorption bonding energy constant (K_L) was recorded by cocopeat only, which are T0 and T1 with a value 0.006849 μg g^{-1} for both treatments, while T5 (0.000141μg g^{-1}) recorded the lowest. The cocopeat without PLB or TBF present cleaner, more uniform adsorption sites, which can adsorb NH_4^+ relatively strong at the start. With no added TBF, no microbial interference also contribute to a comparatively high K_L value. The lowest K_L value recorded by T5 could be due to the highly heterogeneous surface of fresh PLB, which contained multi-scale

pores and mixed functional groups, and the lack of fully established microbial activity from TBF, leading to weak and inconsistent adsorption. However, after planting, T5 (0.029851μg g^{-1}) recorded the highest K_L value, reflecting the effect of rhizosphere conditioning. During *C. chinense* growth, root exudates, microbial metabolites, and oxidative aging of PLB surfaces introduced oxygenated functional groups and increased negative surface charges, while *Trichoderma* colonization further functionalized the PLB and cocopeat through organic acids, enzymes, and extracellular polysaccharides (Bolan et al., 2023; Cui et al., 2024; Majewska & Hanaka, 2025). This processes enhanced site affinity and masked low-energy sites, resulting in fewer but much stronger binding sites for NH_4^+. At the same time, competition from other ions released by PLB was reduced as it taken up by plants and microbes. This transformation explains the increase in K_L value for T5 before and after planting, highlighting the synergistic role of PLB and TBF in improving N retention efficiency.

Table 5.3
Variable from Langmuir Isotherm for N Adsorption of Different Treatments on Cocopeat 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 = 0.0001x + 0.0146	0.5461	0.006849	10000	68.4900
T2	y = 0.00009x + 0.0218	0.4210	0.004128	11111	45.8662
T3	y = 0.0001x + 0.0452	0.4783	0.002212	10000	22.1200
T4	y = 0.0001x + 0.0470	0.2460	0.002128	10000	21.2800
T5	y = 0.0001x + 0.0412	0.7113	0.000141	10000	1.4100
T6	y = 0.0001x + 0.0746	0.4382	0.001340	10000	13.4000
After planting					
T0	y = 0.0001x + 0.0445	0.5855	0.002247	10000	22.4700
T1	y = 0.0001x + 0.0230	0.3712	0.004348	10000	43.4800
T2	y = 0.0001x + 0.0126	0.3830	0.007937	10000	79.3700
T3	y = 0.00003x + 0.0280	0.0180	0.001071	33333	35.6996
T4	y = 0.00008x + 0.0210	0.0179	0.003810	12500	47.6250
T5	y = 0.0002x + 0.0067	0.8467	0.029851	5000	149.2550
T6	y = 0.0001x + 0.0215	0.6783	0.004651	10000	46.5100

*Note: T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

Table 5.4 presents the experimental data on Freundlich's N adsorption of different treatments before and after planting. The regression equation before planting showed a negative slope or intercepts for all treatment. Meanwhile, for after planting, the regression equation showed negative slopes or intercepts in all treatments except for T1. Based on data presented, the N adsorption data of the cocopeat before planting, T0 (R^2=0.5872), T1 (R^2=0.5872), T2 (R^2=0.1842), T3 (R^2=0.7120), T4 (R^2=0.6496), T5 (R^2=0.6143) and T6 (R^2=0.7946) are described by the Freundlich equation, with coefficients of determination (R^2) < 0.8. The highest R^2 value was observed for the T6, suggesting the adsorption behavior of this treatment combination is the best described by the Freundlich model among all treatments. Meanwhile, for the N adsorption data of the cocopeat after planting, T0 (R^2=0.5990), T1 (R^2=0.0024), T2 (R^2=0.2814), T3 (R^2=0.1152), T4 (R^2=0.0.4758), T5 (R^2=0.2630) and T6 (R^2=0.1404) are described by the Freundlich equation, with coefficients of determination (R^2) < 0.6. The highest R^2 value was observed for the T0, suggesting the adsorption behavior of cocopeat alone is the best described by the Freundlich model among all treatments.

High K_F values of T4 compared with other treatments for both before and after planting showed that treatment combinations have higher N adsorption capacity. Moreover, $1/n > 1$ for all the treatments suggests that the N adsorption is an unfavorable adsorption reaction (He et al., 2023). Experimental data that deviates from Freundlich isotherm frequently indicates complex adsorption dynamics influenced by various variables. The data suggests that the adsorption process may involve complexities such as surface heterogeneity, multilayer adsorption, or interaction among multiple components (Acharya et al., 2023). The surface heterogeneity resulting from the biochar complex pore structure and microbial activity of TBF might create various adsorption sites and biological interactions that influence N adsorption (Visconti et al., 2020; Skic et al., 2024). In multicomponent systems, the interactions among nutrients and organic matter can result in complex adsorption behaviors that traditional models fail to account for. Moreover, dynamic circumstances such as microbial activity or slow penetration into biochar pores, may inhibit equilibrium, which is the fundamental basis of these two models, Langmuir and Freundlich (Nworie et al., 2019).

Table 5.4
Variable from Freundlich Isotherm for N Adsorption of Different Treatments on Cocopeat Before and After Planting

Treatment	Regression Equation	R^2	K_F (µg g^{-1})	$\frac{1}{n}$
Before planting				
T0	y = 3.37x - 4.3035	0.5872	2.0114E+04	3.37
T1	y = 3.37x - 4.3035	0.5872	2.0114E+04	3.37
T2	y = 2.4465x - 2.8062	0.1842	6.4003E+02	2.4465
T3	y = 3.7033x - 7.0141	0.7120	1.0330E+07	3.7033
T4	y = 4.5503x - 9.0178	0.6496	1.0418E+09	4.5503
T5	y = 2.8266x - 4.6194	0.6143	4.1629E+04	2.8266
T6	y = 3.5861x - 7.012	0.7946	1.0280E+07	3.5861
After planting				
T0	y = 2.3529x - 3.055	0.5990	1.1350E+03	2.3529
T1	y = 0.3092x + 2.0811	0.0024	1.2053E+02	0.3092
T2	y = 3.2909x - 4.4056	0.2814	2.5445E+04	3.2909
T3	y = 3.0296x - 3.8772	0.1152	7.5370E+03	3.0296
T4	y = 9.6142x - 18.286	0.4758	1.9320E+18	9.6142
T5	y = 2.1855x - 2.2041	0.2630	1.5999E+02	2.1855
T6	y = 1.4199x - 0.8085	0.1404	6.4343	1.4199

*Note: T0= Chemical fertilizer (Control), T1= Organic fertilizer, T2= Organic fertilizer + 100% PLB, T3= Organic fertilizer + 100% TBF, T4= Organic fertilizer + 75% PLB + 25% TBF, T5= Organic fertilizer + 50% PLB + 50% TBF, and T6= Organic fertilizer + 25% PLB + 75% TBF.

The physicochemical characteristics of media as discussed in Chapter 4, section 4.3.1 also can contribute to the high CEC of cocopeat, which influence the N adsorption capacity. It is proven when the findings revealed T0 and T1 recorded the highest N adsorption bonding energy constant (K_L) as compared to the other treatments that applied with PLB and TBF. The data of N adsorption almost fitted in the Langmuir isotherm model because the coefficient determination (R^2) value of T5 (after planting) was close to 0.9 (90%). Examining the presence of PLB and TBF is crucial, as it can introduce additional variables affecting N adsorption dynamics. The high pH and EC recorded by PLB modified the ionic environment of the media, which affecting the equilibrium and competition between NH_4^+ and NO_3^- ions. The large BET surface area, total pore volume and diverse macro and micropores enhanced both physical entrapment and chemical adsorption of N. Furthermore, the aromatic functional groups contributed to stabilization through electrostatic attraction and interaction of cations with aromatic rings, where nutrient cations bind to the electron-rich aromatic surfaces of biochar. Meanwhile, the introduction of TBF further enriched these effects by colonizing PLB pores and releasing organic acids, enzymes, and polysaccharides that altered surface charge, pH, and redox conditions, thereby generating additional active sites. Collectively, these synergistic processes made N adsorption and desorption more dynamic, enhancing nutrient availability for plant uptake.

5.4 Conclusion

This study suggests that the application of PLB and TBF significantly improved N retention in the fertigated cocopeat media grown with *C. chinense*. Treatment T4 recorded the highest K_F values before and after planting, which indicates superior N adsorption capacity by the cocopeat. The enhanced N retention was closely related to the favorable surface morphology, higher surface area, and abundant functional groups of PLB, which provided more active binding sites for NH_4^+ and NO_3^- , while TBF contributed through microbial colonization, organic acid secretion, and rhizosphere interactions. Application both amendments created a synergistic effect that increased the stability and availability of N in the root zone, thus support better nutrient management. These findings confirms that application of PLB and TBF in fertigated cocopeat is an effective strategy to enhance N retention, thereby contributing to sustainable *C. chinense* production.

CHAPTER 6
CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusion

This study contributed to elucidating the effects of PLB and TBF on the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media, with key findings on the optimization of PLB production, the agronomic performance of plants treated with PLB and TBF, and the mechanisms governing N-retention in the media.

The first objective was to optimize the production of biochar from pineapple leaf waste. As demonstrated by the data presented in Chapter 3, biochar production from MD2 pineapple leaf waste that optimized at 500 °C, yielding a material with high pH and EC, appreciable BET surface area and pore volume, well-developed macro and microporosity, and enhanced aromaticity and stability-properties consistent with a reactive, durable sorbent for nutrient management. The characteristic of PLB is important as it influence the adsorption capacity of the nutrient as well as the overall growth and development of the *C. chinense* plant. Thus, 500°C was suggested as the optimum temperature for producing PLB that was further tested on the *C. chinense* plant.

The second objective was to evaluate the effects of PLB and TBF on the growth, yield, and nutrient content of *C. chinense* grown in fertigated cocopeat media. Supported by agronomic evaluation in Chapter 4, T0 (chemical fertilizer) delivered the highest overall performance across measured parameters. Meanwhile, for the organic treatments, the T4 (75% PLB: 25% TBF) produced superior results, with high values in plant height, stem diameter, chlorophyll content, yield, fruit number, fruit size and weight, total plant biomass, and nutrient content. This is evidence of a clear synergy between PLB and TBF under fertigated cocopeat media, where the PLB retains nutrients while providing a habitat for *Trichoderma*, and *Trichoderma* in turn releases and mobilizes these nutrients, thus resulting in better plant growth, and yield than either amendment alone. This finding suggests that combining the optimal ratios of PLB and

TBF could serve as an alternative fertilizer that can reduce reliance on chemical fertilizer in cultivating *C. chinense*.

The third objective was to investigate the effects of PLB and TBF on N retention of *C. chinense* grown in fertigated cocopeat media. Based on results in Chapter 5, the application of PLB and TBF enhanced N retention of the cocopeat with T4 showed the highest K_F values for both before and after planting, indicating superior adsorption capacity. Mechanistically, PLB's surface area, pore architecture, and functional groups increased binding sites for NH_4^+ and NO_3^-, while TBF colonization and secretion of organic acids and enzymes improved nutrient cycling and rhizosphere activity. Both applications helped stabilize N in the root zone and supporting more efficient nutrient use.

Overall, while Control maximized immediate growth and yield, 75% PLB: 25% TBF demonstrated the best-performing organic strategy, by balancing productivity with improved nutrient retention and reduced dependence on chemical fertilizers. The application of PLB and TBF therefore represents a viable, more sustainable cultivation option for *C. chinense* in fertigated cocopeat media.

6.2 Recommendation

As a recommendation for future research, to strengthen the applicability of the nature of this kind of study and to evaluate the sustainable effects of PLB and TBF application on media health, nutrient dynamics, and crop productivity under real agricultural conditions and diverse environmental stressors, a long-term field trials spanning multiple cropping cycles are recommended. In addition, the inclusion of economic viability assessments would provide valuable insights into the cost-effectiveness and feasibility of adopting PLB and TBF at the commercial level. Furthermore, their efficacy could be evaluated across a wider range of agricultural crops to determine the broader potential of these amendments as a sustainable cultivation strategy.

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AUTHOR'S PROFILE



Suraiya binti Mahdian obtained her Diploma in Planting Industry Management from Universiti Teknologi MARA (UiTM), Sarawak Branch, Samarahan Campus in 2010, followed by a Bachelor of Science (Hons.) in Plantation Technology and Management from UiTM Shah Alam in 2012, and a Master in Land Resource Management from Universiti Putra Malaysia in 2014. She began her academic career as a Part-Time Full-Time (PTFT) Lecturer at UiTM Sarawak in 2014 before being appointed as a permanent lecturer in March 2017. Her teaching and research focus primarily on sustainable agriculture, with emphasis on the use of biochar and microbial inoculants for soil and crop improvement. She has actively shared her work through oral and poster presentations at national and international conferences and has published indexed journal articles in her field. Her research outputs have also been recognized through intellectual property registration and innovation awards, including copyrights and medals at innovation competitions. Details of these achievements are summarized in Table 1. Her continuous contributions in research, publications, and innovation highlight her commitment to advancing sustainable agricultural practices through the valorization of agricultural residues and the integration of biofertilizer technologies.

LIST OF PUBLICATIONS

Mahdian, S., Mohidin, H., Khalid, K., Abdullah, R., Rosli, N., & Jos, S. (2025). Growth, yield, and nutrient content of habanero chili (*Capsicum chinense*) in response to different pineapple leaf biochar and *Trichoderma* biofertilizer ratios. AGRIVITA Journal of Agricultural Science, 47(1), 1–10.

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INTELLECTUAL PROPERTIES

Mahdian, S., Mohidin, H., Khalid, K., & Abdullah, R. (2023). Effect of pineapple leaf biochar and *Trichoderma* biofertilizer on the growth, yield, and nutrient uptake of habanero chili (*Capsicum chinense*).

Mahdian, S., Ali, A. S., Basri, S. R., Sahmat, S. S., & Merali, M. M. (2025). BioGro Pearl (BGP).

INNOVATION AWARDS

1. Pinechar Trichomix – Gold Medal, International Borneo Innovation Exhibition and Competition (IBIEC), 2024.
2. BioGrow Pearl – Gold Medal & Best of the Best Award, Youth Innovation Competition (YIC) 2.0, 2024.
3. BioGro Pearl – Gold Medal, Invention, Innovation and Design Exhibition (iidex), 2025.

BEST PAPER PRESENTATION AWARD

Mahdian, S., Mohidin, H., Khalid, K., Abdullah, R., & Rosli, N. (2022). Habanero chili (*Capsicum chinense*) growth performance and yield attributes in response to pineapple leaf biochar and *Trichoderma* biofertilizer-amended media. Paper presented at the International Congress on Impact of Climate Change on Agriculture, Ecosystems and Human Health (ICCC).

ORAL PRESENTATIONS

Mahdian, S., Mohidin, H., Khalid, K., & Abdullah, R. (2022). The feasibility study of habanero chili (*Capsicum chinense*) using pineapple leaf biochar and *Trichoderma* biofertilizer. Paper presented at the 15th International Conference of the East and Southeast Asia Federation of Soil Science Societies (ESAFS).

Mahdian, S., Mohidin, H., Khalid, K., Abdullah, R., & Rosli, N. (2022). Habanero chili (*Capsicum chinense*) growth performance and yield attributes in response to pineapple leaf biochar and *Trichoderma* biofertilizer-amended media. Paper presented at the International Congress on Impact of Climate Change on Agriculture, Ecosystems and Human Health (ICCC).

Mahdian, S., Mohidin, H., Khalid, K., Abdullah, R., Rosli, N., & Jos, S. (2023). Effect of pineapple leaf biochar and *Trichoderma* biofertilizer on habanero chili cultivated in soilless media. Paper presented at the 1st International Conference on Biotechnology, Smart Farming, and Entrepreneurship for Food Security (BioSFE).

Mahdian, S., Mohidin, H., Khalid, K., & Abdullah, R. (2024). Enhancing growth performance and yield attributes of *Capsicum chinense* through pineapple leaf biochar enriched with *Trichoderma* biofertilizer. Paper presented at the 2nd Biochar Malaysia Association International Conference (BMAIC).

POSTER PRESENTATIONS

Mahdian, S., Mohidin, H., Khalid, K., Abdullah, R., Rosli, N., & Jos, S. (2023). Agronomic performance of habanero chili (*Capsicum chinense*) with different ratios of pineapple leaf biochar and *Trichoderma* biofertilizer. Poster presented at the *Persidangan Keterjaminan Makanan Kebangsaan*.

Mahdian, S., Mohidin, H., Khalid, K., Abdullah, R., Rosli, N., & Jos, S. (2023). The nutritional and physical characteristics of pineapple leaf biochar (MD2) as an organic amendment. Poster presented at the 1st BioSFE Conference.

Mahdian, S., Mohidin, H., Khalid, K., & Abdullah, R. (2024). Comparative characterization of pineapple leaf biochar produced at different temperatures. Poster presented at the 2nd BMAIC.

LAMPIRAN

Bil.	Judul Bahan	Hardcopy	Softcopy
1.	The Growth, Yield, and Nutrient Content of Habanero Chili (*Capsicum chinense*) as Influenced by Pineapple Leaf Biochar and *Trichoderma* Biofertilizer in Fertigated Cocopeat Media		/