



Faculty of Resource Science and Technology

**Organic-Based Fertilizers Produced from Sago *Hampas* and Decanter
Cake and Their Uses in Maize (*Zea Mays* L.) Cultivation**

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Organic-Based fertilizers Produced from Sago *Hampas* and Decanter Cake
and Their Uses in Maize (*Zea Mays* L.) Cultivation

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DECLARATION

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



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ABSTRACT

Sustainable agriculture requires innovative strategies to enhance soil fertility while reducing the environmental impacts of agro-industrial waste. This study investigated the synergistic effects of Black Soldier Fly (BSF) frass and decanter cake (DC) biochar on maize (*Zea Mays* L.) growth and soil fertility in tropical acidic soil. BSF larvae were used to bioconvert sago *hampas* and DC into nutrient-rich frass, while DC was pyrolyzed to produce biochar. Laboratory incubation and pot experiments were conducted with eight treatments: control (F0B0C0), 100% chemical fertilizer (F0B0C1), 100% BSF frass alone (F1B0C0), 100% biochar alone (F0B1C0), 50% frass + biochar + chemical fertilizer (F2B2C2), 50% frass + chemical fertilizer (F2B0C2), 50% biochar + chemical fertilizer (F0B2C2), and 50% frass + biochar (F2B2C0). Soil chemical properties, nutrient availability, and maize biomass were assessed after 52 days. Results showed that the combined application of frass and biochar significantly improved soil pH, cation exchange capacity, and nutrient retention compared to untreated soil. The integrated treatment (F2B2C2) recorded the highest improvements, with a 41% increase in total nitrogen, 58% enhancement in phosphorus, 22% improvement in potassium, and a 37% increase in zinc relative to the control. These nutrient enhancements translated into the highest maize dry weight among treatments. The study concludes that BSF frass and DC biochar, particularly in combination with reduced chemical fertilizers, enhance nutrient-use efficiency, sustain soil fertility, and improve maize productivity. This integrated approach valorizes agro-industrial wastes, reduces dependence on synthetic inputs, and contributes to sustainable tropical agriculture.

Keywords: Black Soldier Fly frass, biochar, decanter cake, maize (*Zea Mays* L.), soil fertility, sustainable agriculture

Kajian Kesan Baja Berasaskan Organik Yang Dihasilkan Daripada Sagu Hampas dan Kek Decanter Terhadap Penanaman Jagung (Zea Mays L.)

ABSTRAK

Pertanian lestari memerlukan pendekatan inovatif untuk meningkatkan kesuburan tanah sambil mengurangkan kesan sisa agro-industri. Kajian ini menilai kesan Black Soldier Fly (BSF) frass dan biochar daripada decanter cake (DC) terhadap pertumbuhan jagung (Zea Mays L.) dalam tanah berasid tropika. Larva BSF digunakan untuk menukarkan hampas sagu dan DC kepada frass, manakala DC dipirolisis menghasilkan biochar. Eksperimen inkubasi makmal dan pasu dijalankan dengan lapan rawatan: kawalan (F0B0C0), 100% baja kimia (F0B0C1), 100% frass sahaja (F1B0C0), 100% biochar sahaja (F0B1C0), 50% frass + biochar + baja kimia (F2B2C2), 50% frass + baja kimia (F2B0C2), 50% biochar + baja kimia (F0B2C2), dan 50% frass+ biochar (F2B2C0). Parameter dikaji termasuk pH tanah, kapasiti pertukaran kation, nutrien tersedia, dan biojisim jagung selepas 52 hari. Hasil menunjukkan gabungan frass dan biochar meningkatkan ciri kimia tanah berbanding kawalan. Rawatan bersepadu (F2B2C2) memberi kesan tertinggi dengan peningkatan nitrogen 41%, fosforus 58%, kalium 22%, dan zink 37%. Peningkatan ini menyumbang kepada biojisim jagung tertinggi. Kajian membuktikan BSF frass dan DC biochar, khususnya dengan baja kimia berkurangan, mampu meningkatkan kecekapan nutrien, mengekalkan kesuburan tanah, serta menyokong produktiviti jagung secara mampan.

Kata kunci: *Frass Lalat Askar Hitam; biochar; kek decanter; jagung (Zea Mays L.); kesuburan tanah; pertanian lestari*

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
KCl	Potassium chloride
CEC	Cation exchange capacity
C/N	Carbon to nitrogen
AAS	Atomic Absorption Spectrum
FTIR	Fourier Transform Infrared Spectroscopy
CHNS	Carbon, hydrogen, nitrogen, and sulphur
EC	Electrical conductivity
NH_4^+	Ammonium ions
NO_3^-	Nitrate
SAS	Statistical analysis system
NH_4OAc	Ammonium acetate
HNO_3	Nitric acid
HCl	Hydrochloric acid

CHAPTER 1

INTRODUCTION

1.1 Study Background

Sustainable agriculture is pivotal to ensuring global food security while minimizing environmental degradation. It emphasizes the efficient use of resources, recycling of organic residues, and maintaining long-term soil productivity (Tilman *et al.*, 2002; Pretty, 2008). One of the major challenges in achieving these goals lies in managing agro-industrial wastes, which, if left untreated, contribute to nutrient runoff, water pollution, and greenhouse gas emissions (Kumar *et al.*, 2020). Adopting organic soil amendments derived from waste streams represents a dual solution, enhancing soil fertility while diverting waste from the environment (Agegnehu *et al.*, 2017; Beesigamukama *et al.*, 2020).

Agricultural waste, such as sago waste, represents a significant challenge for waste management in developing countries. The sago starch production was generated on a large scale, with an estimated 27.5 million tonnes annually worldwide (Bujang, 2010), where this by-product is often improperly disposed of. Global sago starch consumption is approximately 200,000–300,000 tonnes per year, yet substantial waste is discarded daily. Uncontrolled disposal, particularly into the waterways, can cause severe environmental consequences, including water pollution from high sugar content and bacterial proliferation. These concerns underscore the urgent need for sustainable waste management strategies to mitigate environmental degradation.

Besides, palm oil production presents a similar waste management issue. Malaysia and Indonesia, together accounting for approximately 90% of global palm oil output, also generate substantial quantities of associated by-products (Kaniapan *et al.*, 2021). In Malaysia alone, 17.73 million tonnes of palm oil and 2.13 million tonnes of palm kernel oil were produced in 2015 (Ferdous Alam *et al.*, 2015). Palm oil mills produce roughly 4–5 tonnes of decanter cake (DC) for every 100 tonnes of fresh fruit bunch processed. DC, a lignocellulosic residue obtained from dehydrating palm oil mill effluent (Dewayanto *et al.*, 2009), accumulates rapidly and, if left unmanaged, it may pose long-term environmental risks.

The Black Soldier Fly Larvae (BSFL; *Hermetia illucens* L.) have emerged as a promising bioconversion agent for managing organic agricultural waste. Capable of degrading high-lignocellulosic substrates such as sago *hampas* and decanter cake (Purnamasari & Khasanah, 2022), BSFL convert organic residues into valuable insect biomass while producing a nutrient-rich by-product known as frass. This frass, consisting of larval excreta, shed exoskeletons, and undigested feed material (Beesigamukama *et al.*, 2020), is increasingly recognized as a sustainable organic fertilizer. Its agronomic effectiveness largely depends on nutrient composition, mineralization rate, and storage stability (Beesigamukama *et al.*, 2020). Compared with synthetic fertilizers, which may contain harmful elements such as cadmium, uranium, and arsenic, BSFL frass offers a safer alternative for soil amendment (Lievens *et al.*, 2021) and has demonstrated potential to enhance soil fertility and crop yields (Klammsteiner *et al.*, 2020) and contains essential macro- and micronutrients, beneficial microbes, and organic matter that can function as an organic soil amendment to improve nutrient availability, soil structure, and microbial diversity (Beesigamukama *et al.*, 2020).

Complementary to BSFL frass, another sustainable soil amendment is biochar. Biochar has been shown to improve soil health, enhance fertility, and mitigate greenhouse gas emissions. Biochar produced from the pyrolysis of decanter cake under low-oxygen conditions has been shown to enhance cation exchange capacity, water-holding capacity, and long-term carbon storage, while improving soil physical and chemical properties (Lehmann *et al.*, 2011; Domingues *et al.*, 2020). The combined application of BSFL frass and biochar represents an innovative integrated soil amendment strategy that aligns with circular bioeconomy principles.

Biochar produced via pyrolysis can increase crop growth through nutrient enrichment (Agegnehu *et al.*, 2017) while preventing CO₂ emissions associated with open burning and decomposition of organic residues. Its application has been linked to improved mycorrhizal colonization (Gujre *et al.*, 2021), enhanced phosphorus solubility (S. Gao & DeLuca, 2018), stabilization of organic nutrient sources (Song *et al.*, 2021), and reduced nutrient leaching (Lehmann & Rondon, 2006). Owing to its high surface area, porosity, and cation exchange capacity (CEC), biochar can improve soil water retention, nutrient holding capacity, and base saturation (Domingues *et al.*, 2020). Its properties vary according to pyrolysis temperature (Bornermann *et al.*, 2007; Gundale & DeLuca, 2006). Moreover, biochar contributes to water quality improvement, increases agricultural productivity, and reduces reliance on chemical fertilizers (Gogoi *et al.*, 2019; Zhu *et al.*, 2020).

Within this context, maize (*Zea Mays L.*) holds a pivotal role as one of the world's most important cereal crops and a vital component of food security and livestock feed systems (Shiferaw *et al.*, 2011). In Malaysia, maize production has been steadily increasing,

reflecting growing demand in both human consumption and the animal feed industry (Nasir & Kamaruddin, 2023). From a sustainability perspective, maize is an ideal crop for integrated soil fertility management studies because of its high sensitivity to nutrient availability. Its growth, yield, and grain quality are directly influenced by the balance of macro- and micronutrients in the soil (Khan *et al.*, 2016; Timsina, 2018). Maize exhibits measurable physiological and morphological responses to nutrient deficiency, such as stunted growth, leaf chlorosis, and reduced kernel set and making it an effective bioindicator for assessing soil fertility and the effectiveness of soil amendments (Ramage & Williams, 2002; Hawkesford *et al.*, 2012).

This sensitivity allows maize to serve as a test crop in evaluating the impact of organic and inorganic amendments on plant performance and soil nutrient dynamics. Organic amendments such as Black Soldier Fly Larvae (BSFL) frass and biochar derived from decanter cake not only supply essential nutrients but also improve soil structure, water retention, and cation exchange capacity (Beesigamukama *et al.*, 2020; Domingues *et al.*, 2020). By integrating these organic inputs with conventional fertilizers, it is possible to achieve higher nutrient-use efficiency, maintain long-term soil health, and enhance maize productivity under challenging soil conditions such as the acidic Ultisols and Oxisols prevalent in Malaysia (Shamshuddin *et al.*, 2016). Therefore, this study investigates the application of BSFL for the bioconversion of sago waste and decanter cake, alongside using decanter cake-derived biochar, as a dual strategy to reduce agricultural waste and enhance soil fertility for maize cultivation.

1.2 Problem Statement

BSFL frass and biochar have been studied individually as soil amendments. However, a limited understanding of their synergistic effects remains when produced from specific tropical agro-industrial wastes such as sago *hampas* and decanter cake. Existing research predominantly focuses on single-waste substrates for BSFL bioconversion, such as food waste, manure, or biochar derived from common agricultural residues (rice husk, wood chips). However, sago *hampas* and decanter cake possess unique physical and chemical characteristics such as high fiber content, variable moisture levels, and distinct nutrient compositions, which may influence both the nutrient profile of frass and the physicochemical properties of biochar in ways not observed in other feedstocks.

Furthermore, the co-application of these two amendments of BSFL frass from a mixed-waste substrate (sago *hampas* + decanter cake) and biochar derived from decanter cake affects soil fertility, nutrient retention, and crop performance, especially under tropical conditions. While biochar is known for its long-term carbon stability and enhancement of soil structure, frass contributes readily available nutrients and microbial activity. Therefore, the interaction between these short-term and long-term benefits has not been systematically evaluated, particularly concerning nutrient-sensitive crops such as maize grown on nutrient-poor acidic soils common in Malaysia.

1.3 Objectives

This can be achieved through the following set of objectives:

- i. To produce the biochar from the decanter cake
- ii. To analyse the chemical and physical properties of BSFL frass derived from sago *hampas* and decanter cake,
- iii. To investigate the nutrient uptake of BSFL frass and decanter cake biochar on maize cultivation in a tropical acid soil.

1.4 Summary

Sustainable agriculture aims to secure food production while conserving resources and minimizing environmental harm. Agricultural waste, such as sago *hampas* from sago starch production and decanter cake (DC) from palm oil processing, poses significant environmental challenges due to improper disposal. Black Soldier Fly Larvae (BSFL) offer a biological solution by converting these wastes into nutrient-rich frass, an effective organic fertilizer. Complementing this, biochar derived from DC enhances soil fertility, water retention, and carbon storage. The combined use of BSFL frass and biochar aligns with circular bioeconomy principles, providing a sustainable alternative to synthetic fertilizers. Maize, a globally important cereal crop highly sensitive to nutrient availability, serves as an ideal test crop for evaluating these amendments. This study explores the integration of BSFL bioconversion of sago waste and DC with DC-derived biochar to address waste management issues, improve soil health, and boost maize productivity.

CHAPTER 2

LITERATURE REVIEW

2.1 Sustainable Agriculture and Organic Amendments

Sustainable agriculture is increasingly recognized as a cornerstone for achieving global food security while preserving environmental quality and resource integrity (Tilman *et al.*, 2002; Pretty, 2008). The approach emphasizes efficient nutrient management, organic residue recycling, and adopting soil health-oriented practices to maintain long-term productivity. One significant challenge in sustainable agriculture is the growing accumulation of agricultural and agro-industrial wastes. If not effectively managed, these residues contribute to environmental degradation, including water pollution, greenhouse gas emissions, and ecosystem nutrient imbalances (Kumar *et al.*, 2020).

Organic soil amendments, such as compost, biochar, and insect-derived fertilizers, have been widely studied for their potential to improve soil fertility and crop productivity while reducing reliance on synthetic fertilizers (Agegnehu *et al.*, 2017; Beesigamukama *et al.*, 2020). Compared to chemical fertilizers, which may introduce heavy metals and degrade soil structure over time (Lievens *et al.*, 2021), organic amendments offer a renewable, environmentally friendly alternative.

2.2 Sago *Hampas* and Decanter Cake as Agro-Industrial Wastes

The processing of agro-industrial crops like sago and palm oil generates vast amounts of waste, which pose environmental challenges. Global sago starch production generates approximately 27.5 million tonnes of lignocellulosic residues known as sago *hampas* primarily due to their high fiber and sugar content (Bujang, 2010). When disposed of improperly, this waste can lead to water contamination and microbial overgrowth. Likewise, the palm oil industry, dominated by Malaysia and Indonesia, produces large volumes of decanter cake (DC), a semi-solid by-product of effluent dehydration. DC output averages 4–5 tonnes per 100 tonnes of fresh fruit bunch input (Dewayanto *et al.*, 2009), creating significant disposal burdens.

Both sago *hampas* and DC present waste management complexities due to their characteristics: high moisture, fiber content, and variable nutrient profiles. However, these same traits make them promising candidates for valorization as soil amendments or bio-raw materials. Transforming this waste into beneficial products not only addresses environmental concerns but also aligns with circular economy goals. Although research in this area is still emerging, the potential value of converting such high-volume tropical residues into organic inputs offers an important route toward sustainable waste management and agricultural resource efficiency.

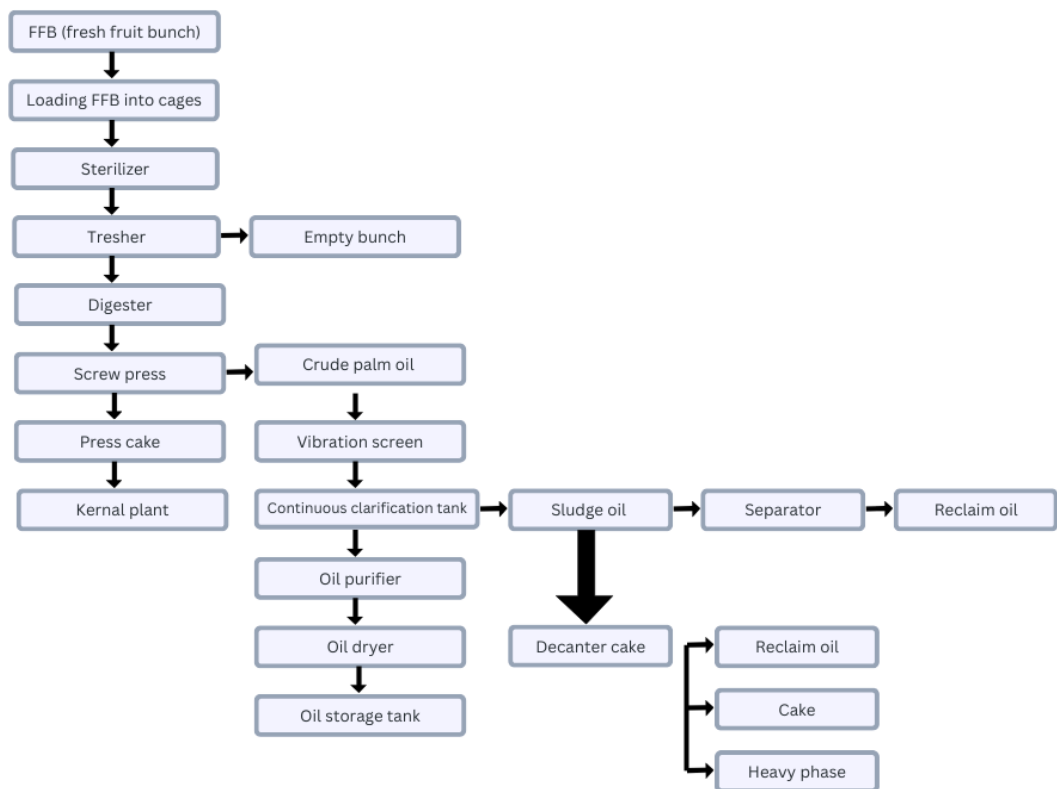


Figure 2.1: Palm oil processing. (Image by Deborah Renting Jimmy, 2025)

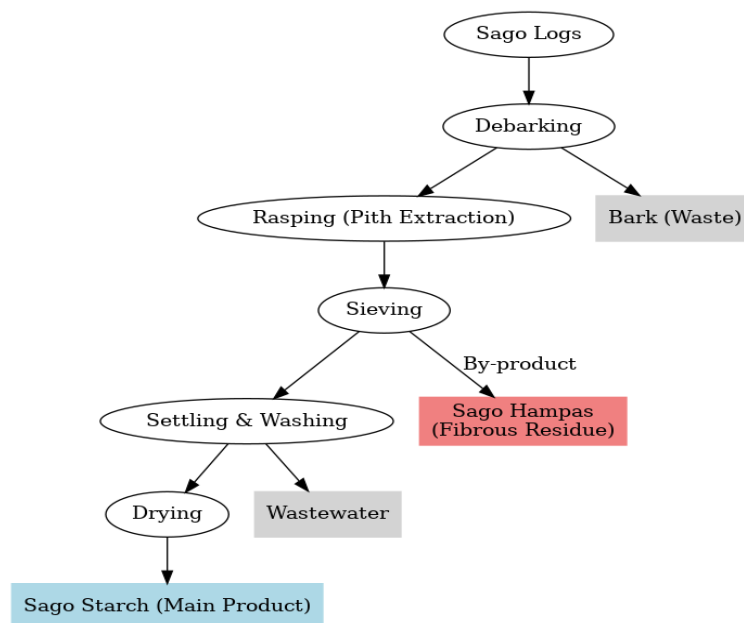


Figure 2.2: Sago *hampas* processing and potential utilization pathways.

(Image by Deborah Renting Jimmy, 2025)

Palm oil production generates several by-products, including empty fruit bunches, press cake, and sludge oil, with decanter cake emerging as a significant residue during the clarification process (Figure 2.2). The decanter cake is a nutrient-rich biomass containing nitrogen, phosphorus, potassium, calcium, and carbon, making it highly suitable for agricultural applications (Adam, Saiful, & Syd, 2016). Its nutrient profile indicates potential as a soil amendment and organic fertilizer, providing an alternative to chemical fertilizers while improving soil fertility. In agriculture, oil palm decanter cake has been widely studied for its contribution to crop growth. According to Embrandiri *et al.* (2013a), found that substituting conventional fertilizers with decanter cake in oil palm nurseries produced comparable growth responses in seedlings, confirming its potential as a sustainable alternative. However, challenges remain, particularly in managing its high moisture content, which affects storage and handling. Advances in co-composting, drying, and fermentation technologies are being explored to overcome these limitations and improve their applicability. Therefore, integrating decanter cake into agricultural systems offers multiple benefits that enhance soil fertility, reduce dependency on inorganic fertilizers, effectively valorise waste, and align with circular economy principles. Its adoption can significantly reduce palm oil mill residues while creating value-added products that support sustainable farming practices.

Besides, sago processing is primarily for starch extraction, generating substantial by-products, with sago *hampas* (residual fibrous pulp) being the most significant waste stream (Figure 2.2). This residue, typically discarded into waterways, presents both environmental and resource management challenges. However, sago *hampas* is rich in organic matter and nutrients, containing carbohydrates, lignocellulosic components, and essential minerals such

as potassium, calcium, and trace elements (Bujang, 2010; Noor *et al.*, 2018). Its composition makes it a promising feedstock for organic soil amendments and bioresource applications. In terms of agricultural application, sago *hampas*-based compost has been shown to enhance soil fertility by improving organic carbon content, nutrient availability, and microbial activity (Ling *et al.*, 2017). When integrated with other organic residues, such as livestock manure or agro-industrial by-products, it accelerates decomposition and nutrient mineralization, producing a stable, nutrient-rich compost suitable for acidic tropical soils. Therefore, valorizing sago *hampas* aligns with sustainable development goals by addressing waste management issues, reducing environmental pollution, and providing low-cost, eco-friendly soil amendments. Its integration into agricultural practices can reduce reliance on chemical fertilizers, improve soil health, and promote resource-efficient farming.

Therefore, Tables 2.1 and 2.2 summarize the diverse agricultural applications of decanter cake and sago *hampas*, respectively. These examples highlight their potential roles in sustainable farming systems as soil amendments, composting materials, biochar feedstocks, and sources of nutrients for crop production and livestock feeding.

Table 2.1: The examples of applications of decanter cake in agriculture

Decanter cake applications	Findings	References
Biochar	• Biochar is used in agriculture from different plant species.	Alefsi <i>et al.</i> , 2019
Soil amendment	• Used as a nutrient-rich organic fertilizer to improve soil fertility and structure.	Duaja <i>et al.</i> , 2024
Crop production	• Used as a mulching material and in biofertilizer formulations to enhance crop yield	Duaja <i>et al.</i> , 2021
Composting	• Incorporated into composting systems to enhance microbial activity and nutrient content.	Minh <i>et al.</i> , 2022
Biogas production	• Utilized in anaerobic digestion to produce biogas and nutrient-rich digestate.	Tepsour et al., 2019

Table 2.2: The examples of sago *hampas* application in agriculture

Sago <i>hampas</i> applications	Findings	References
Soil amendment	• Used to improve soil structure and fertility due to its organic matter content.	Amin <i>et al.</i> , 2019
Organic mulch	• Applied as mulch to suppress weeds, retain soil moisture, and regulate temperature.	Awg-Adeni <i>et al.</i> , 2010
Animal feed	• Processed into feed for livestock, providing fiber and nutrients.	Wardono <i>et al.</i> , 2021
Composting materials	• Incorporated into composting systems to enhance nutrient content and microbial activity.	Fetriyuna <i>et al.</i> , 2024
Biofertilizer	• Potential use as a biofertilizer due to its nutrient content and ability to support beneficial microorganisms.	Amin <i>et al.</i> , 2019

2.3 Black Soldier Fly Larvae (BSFL) Bioconversion and Frass

2.3.1 Black Soldier Fly Origin

The black soldier fly (BSF) (*Hermetia illucens*), a species within the order Diptera, family Stratiomyidae, and genus *Hermetia*, is a well-known fly species predominantly found in tropical and temperate regions. Native to the Americas, it is distributed across North and South America as well as the Australasian regions, from Samoa to Hawaii (Kaya *et al.*, 2021). The BSF are commonly found in moist organic waste, such as agricultural residues and domestic waste, where they serve as efficient bio-degradation agent (Yuwono *et al.*, 2021). Their ability to feed on a wide range of organic materials makes them highly effective in managing untreated organic waste. Importantly, BSF does not transmit diseases, further underscoring their environmental utility. During the larval stage, the black soldier fly larvae (BSFL) actively consume organic matter. Once they transition into the adult phase, they lose the ability to feed due to non-functional mandibles, surviving only for 5–9 days, primarily to reproduce (Figure 2.3).

2.3.2 Life Cycle of Black Soldier Fly Larvae

The Black Soldier Fly (BSF) bioconversion method involves using BSF larvae to efficiently reduce and convert organic waste into a protein- and lipid-rich biomass (Siddiqui *et al.*, 2022). This biomass can be used for various applications, including animal feed, biodiesel, and chitin production. The bioconversion process reduces the volume of waste and repurposes it into high-value products. Studies have demonstrated the ability of BSF larvae to convert different types of organic wastes, including agricultural residues (Rashidah *et al.*,

2024). One study explored the bioconversion of three organic wastes by BSF larvae, highlighting the significant potential for waste reduction and nutrient recycling (Z. Liu *et al.*, 2018). Another study investigated the performance of BSF larvae on fermented maize straw, showing that the bioconversion method could increase economic returns by producing valuable larvae biomass from maize straw residue. The utilization of *Hermetia illucens* larvae, commonly known as BSF larvae, as a bioconversion agent, has been shown to reduce various types of organic waste more efficiently compared to the conventional composting method (Fadhillah & Bagastyo, 2020).

The BSF bioconversion procedure typically involves feeding the larvae directly without moistening the substrate. Khairuldin *et al* (2023) also addressed optimizing conditions to enhance the efficiency of bioconversion. In summary, the BSF bioconversion method presents an innovative and sustainable approach to managing organic waste, turning it into valuable resources while contributing to waste reduction and environmental sustainability.

Therefore, BSF larvae effectively convert diverse organic wastes into useful byproducts, which helps reduce the environmental footprint of agricultural practices and the volume of waste that would otherwise require disposal. Besides, BSF can produce high-quality nutrients for animal feed, reducing the need for conventional feed sources and supporting sustainable livestock production. The frass produced by BSF larvae serves as an organic fertilizer that can be incorporated into agricultural fields to enhance soil fertility (Lopes *et al.*, 2022). A study investigated the bioconversion of different animal manures by BSF larvae, noting improvements in the composition and humification of the treated manure.

The research indicated that BSF bioconversion can enhance the value of manure as an organic fertilizer. According to Siddiqui *et al* (2022), BSF can be farmed on diverse organic wastes to produce nutrient-rich animal feed, fuel, and organic fertilizer. The study highlighted the opportunity for BSF to contribute to sustainable waste management and agricultural practices (Rehman *et al.*, 2023). Besides, a review focused on pretreatment methods to enhance the bioconversion of agri-food waste by BSF larvae, in which the study addressed the variability in BSFL bioconversion and processing due to different waste types and outlined pretreatment strategies to improve bioconversion efficiency (Peguero *et al.*, 2024). These studies collectively demonstrate the potential of BSF larvae to transform organic waste into valuable resources, significantly contributing to sustainable waste management and the development of circular economy models in agriculture.

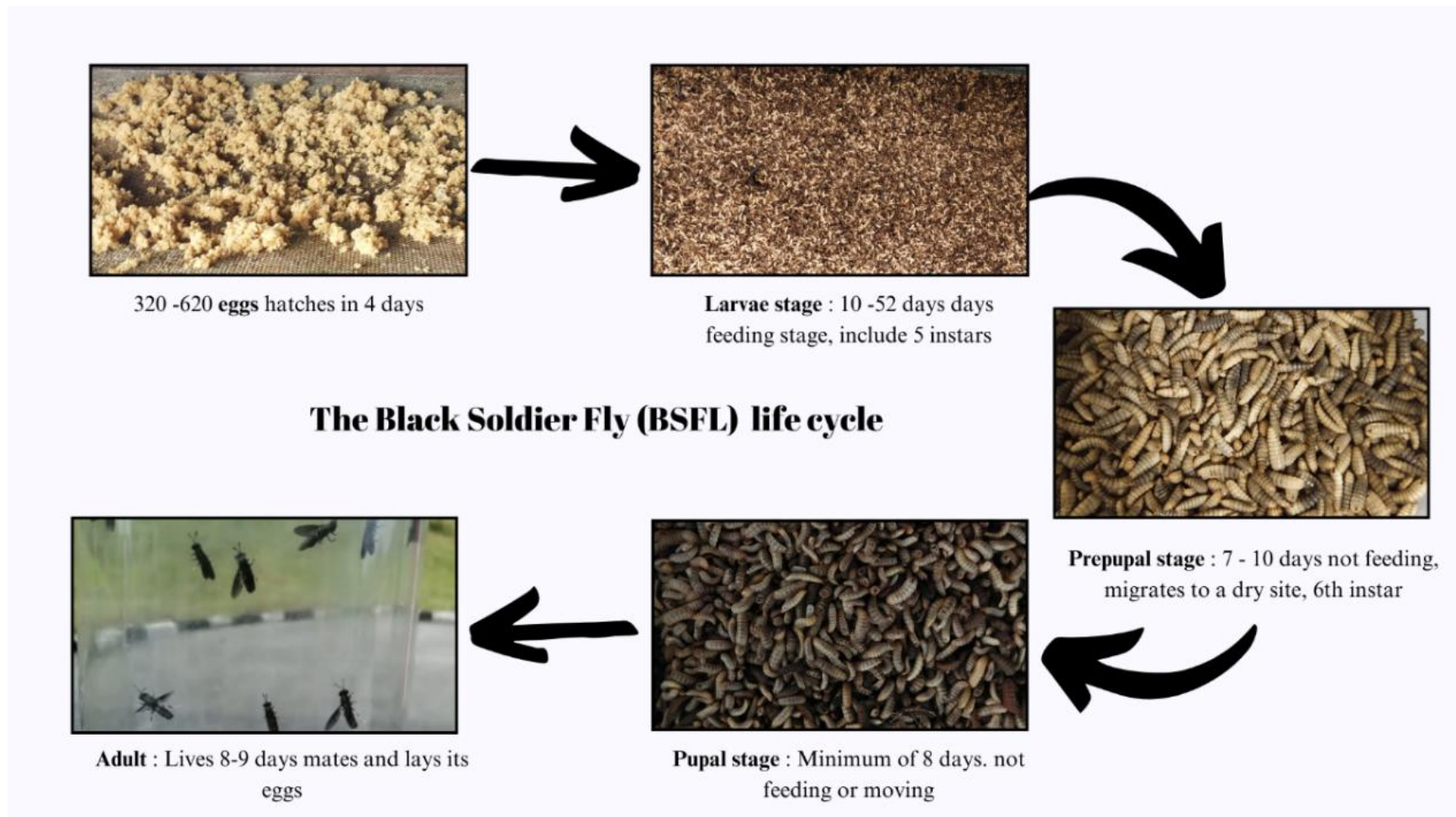


Figure 2.3: The life cycle of the Black Soldier Fly (BSFL) (Image by Deborah Renting Jimmy, 2025)

2.3.3 BSFL Bioconversion of Agricultural Waste into Fertilizer

Black Soldier Fly (BSF) larvae are increasingly used to convert agricultural waste into valuable products such as organic fertilizer. This process is recognized for its efficiency in bioconversion and nutrient recycling. BSF larvae can decompose organic matter rapidly, and the resulting by-product, known as frass, is a nutrient-rich material that can be used as an organic fertilizer (Lopes *et al.*, 2022). According to Beesigamukama *et al.* (2020) has outlined low-cost technologies for recycling agro-industrial waste into nutrient-rich organic fertilizer using BSF larvae. Composting has been cited as a common method to convert BSF larvae frass into mature and stable compost ready for agricultural use. For example, BSF larvae fed on cassava peel wastes can produce substantial compost. The technique of utilizing BSF larvae for enhanced decomposition of biodegradable wastes has been comprehensively reviewed. This method is particularly noted for its rapid composting capabilities in the context of household and agricultural organic waste management. Furthermore, the potential of BSF in organic waste bioconversion has been evaluated, emphasizing the conversion process, nutrient composition, and the use of BSF biomass as animal feed.

The frass fertilizer from BSF bioconversion is recognized for its nutrient richness and hygienic properties, making it a suitable organic fertilizer (Lopes *et al.*, 2022). Overall, BSF techniques are seen as a green technology that reduces organic waste while producing high-quality organic fertilizer that can enrich the soil and promote plant growth. Further research and optimization of these techniques can contribute significantly to sustainable waste management and agricultural practices.

BSFL bioconversion transforms agricultural waste into high-value organic fertilizers, offering a rapid, eco-friendly alternative to traditional composting. Its ability to enhance soil fertility, reduce pollution, and lower costs positions it as a key technology for sustainable agriculture. Future microbial optimization and scalable processing advancements will further unlock its potential in global waste management systems.

2.3.4 Nutrient composition and soil fertility benefits

Frass derived from BSF larvae is recognized for its nutrient richness and hygienic properties, making it suitable for direct agricultural use (Lopes *et al.*, 2022). It typically contains essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), which improve soil fertility and promote plant growth. The physical and chemical characteristics of frass contribute to its effectiveness as a soil conditioner. Its relatively high organic matter and favorable pH help improve soil structure, enhance microbial activity, and increase water-holding capacity. Such properties make BSF frass an efficient organic amendment, particularly in soils with low fertility. By enhancing soil fertility, improving microbial activity, and reducing reliance on chemical fertilizers, BSF frass contributes to sustainable agricultural practices. Future advancements in microbial optimization and large-scale processing technologies will further expand its role in global waste management and agricultural systems.

Table 2.3 presents various organic wastes commonly used as substrates for Black Soldier Fly (BSF) larvae to produce frass. The pH of these substrates generally ranges between 5.6 and 8.0, which is optimal for larval development. Kitchen waste and municipal

food waste exhibit low C/N ratios (8:1–9:1), promoting efficient decomposition and nutrient cycling. In terms of nutrient enrichment, household food waste contains the highest total nitrogen content (2.2%), whereas a mixture of food waste, chicken faeces, and sawdust (3:2:1 ratio) provides a balanced nutrient composition, with 1.7% N, 1.1% P, and 2.1% K, making it a superior option for producing nutrient-rich frass. Moisture content also varies significantly, with municipal food waste (63–65%) and mixed waste substrates (72%) offering ideal conditions for BSF larvae feeding. Additionally, agro-industrial residues such as decanter cake combined with palm kernel expeller show a favourable C/N ratio of 16:1, indicating potential for large-scale frass production when integrated with BSF bioconversion.

Table 2.3: The examples of wastes used as a source to produce BSF frass

Frass source	pH	C/N ratio	Moisture	Temperature °C	Total N (%)	Total P (%)	Total K (%)	References
Kitchen waste	7	8:01	50	-	-	-	-	Ritika <i>et al.</i> , 2015
Fruit and vegetables	5.6	27.1	10	-	1.8	-	-	Klammsteiner <i>et al.</i> , 2020
Household food waste	7.4	17.1	56	-	2.2	0.1	0.1	Kawasaki <i>et al.</i> , 2020
Municipal food waste	7.3-7.4	8:1 - 9:1	63-65	26.3 - 26.5	-	-	-	Sarpong <i>et al.</i> , 2019
Food waste, chicken faeces, and sawdust (3:2:1 ratio)	6.1-8.0		72	27	1.7	1.1	2.1	Attiogbe <i>et al.</i> , 2019
Decanter cake and palm kernel expeller (PKE)	7.41	16:01	-	-	-	-	-	Visvini <i>et al.</i> , 2022

2.3.5 Agronomic Potential and Applications of BSF Frass

Beyond its role as a nutrient source, BSF frass functions as both a fertilizer and a soil conditioner due to its unique biochemical properties. The organic matter in frass contributes to soil carbon pools, improving cation exchange capacity (CEC) and enhancing nutrient retention. Studies indicate that frass application can increase microbial biomass carbon and enzymatic activity, creating a favorable rhizosphere environment for crop growth (Beesigamukama et al., 2020). The presence of beneficial microorganisms within frass also promotes plant health by suppressing soil-borne pathogens, reducing the need for chemical pesticides (Peguero et al., 2024).

Experimental trials have shown that crops treated with BSF frass exhibit improved germination rates, higher biomass accumulation, and greater nutrient uptake efficiency compared to conventional compost treatments (Lopes et al., 2022). Furthermore, the slow-release nature of nitrogen in frass ensures a steady nutrient supply throughout the growing season, reducing leaching losses often associated with synthetic fertilizers.

BSF frass has also demonstrated potential in integrated soil fertility management (ISFM) systems, particularly with biochar or other organic amendments. When co-applied with decanter cake biochar, frass improves soil aeration, water retention, and nutrient mineralization, offering synergistic benefits for crop productivity (Rashidah et al., 2024). This positions BSF frass as a cornerstone input in sustainable and circular agricultural systems, where waste is repurposed into valuable resources.

2.4 Biochar from Decanter Cake

Biochar is a carbon-rich material produced via pyrolysis under low-oxygen conditions and has been shown to enhance soil structure, water-holding capacity, and cation exchange capacity (CEC) while sequestering carbon (Lehmann *et al.*, 2011; Domingues *et al.*, 2020). Decanter cake (DC), a nutrient-rich lignocellulosic by-product of palm oil processing, presents a promising but underutilized feedstock for biochar production. Its inherent organic matter, high moisture content, and mineral profile could yield biochar with unique properties suited for tropical soils.

2.4.1 Characterization of Biochar

The characterization of biochar is essential to determine its suitability for soil application. Properties such as pH, ash content, elemental composition, functional groups, and surface area influence its interactions with soil and plants (Xiao *et al.*, 2018). According to Tsois & Barouchas (2023), biochar is increasingly recognized for its potential to enhance soil properties, particularly pH, CEC, and water retention. Biochar has effectively raised soil pH, especially in acidic soils (Tusar *et al.*, 2023). The alkaline nature of many biochars helps neutralize soil acidity, creating a more favorable environment for plant growth. For instance, one study noted that biochar application increased soil pH from 5 to 7.15, demonstrating its capacity to ameliorate acidic conditions (Alkharabsheh *et al.*, 2021).

2.4.2 Factors Affecting Biochar Properties

The properties of biochar are largely influenced by feedstock type, pyrolysis temperature, heating rate, and residence time. These parameters determine the physicochemical characteristics of the final product (Azzi *et al.*, 2022). Higher pyrolysis

temperatures typically increase surface area and aromaticity but reduce yield and volatile matter (Zhao *et al.*, 2017). Feedstocks with higher lignin and mineral content often produce biochars with greater stability and ash content, making them more effective for long-term soil amendment (Leng *et al.*, 2021). In addition, application rates and soil types further modulate biochar's effectiveness, highlighting the importance of tailoring biochar production and use to specific agroecosystems.

2.4.3 Biochar–Soil Interactions and Nutrient Dynamics

Biochar significantly enhances soil microbial interactions and nutrient cycling, which are crucial for soil health and agricultural productivity. It affects microbial biomass, diversity, and activity, varying outcomes according to biochar properties and soil conditions. The high surface area and porous structure of biochar enhance nutrient retention, enabling it to sequester nitrogen in forms such as nitrate and improve phosphorus availability through its inherent nutrient content (Alkharabsheh *et al.*, 2021). Biochar applications can also increase the levels of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) in soils. For example, Gao *et al.* (2018) observed that applying biochar significantly increased available nitrogen and phosphorus levels post-harvest.

2.4.4 Applications of Biochar in Agriculture

Table 2.4 summarizes examples of biochar applications in agriculture using different lignocellulosic feedstocks. Hardwood-derived biochar has been applied to improve seed germination and growth of *Tagetes patula* (Olesja *et al.*, 2021). Rice husk biochar has been used to enhance soil fertility in agricultural systems (Daljit *et al.*, 2022). Similarly, switchgrass biochar produced via an auger reactor has been applied in sustainable soil

management (Patrick *et al.*, 2018), while sugarcane bagasse biochar generated through thermochemical conversion has been tested for agricultural use (Kungsley *et al.*, 2022). These examples highlight the versatility of biomass sources for biochar production and their potential to improve soil health and crop productivity.

Table 2.4: The examples of biochar application in agriculture

Biochar source	Agriculture application	References
Hardwood	• Seed germination and growth of <i>Tagetes patula</i>	Olesja <i>et al.</i> , 2021
Rice husk	• Agriculture application	Daljit <i>et al.</i> , 2022
Switchgrass	• Switchgrass in an auger reactor for biochar production	Patrick <i>et al.</i> , 2018
Sugarcane bagasse	• Thermochemical conversion of sugarcane bagasse	Kungsley <i>et al.</i> , 2022

2.5 Maize as a Test Crop for Soil Amendment Studies

Maize (*Zea Mays* L.) is one of the world's most important cereal crops, widely cultivated for human consumption and livestock feed (Shiferaw *et al.*, 2011). In Malaysia, maize production has steadily risen to meet the growing food and animal feed industry demand (Nasir & Kamaruddin, 2023). Maize is particularly suitable for soil amendment studies because of its high sensitivity to nutrient availability; deficiencies in nitrogen, phosphorus, or potassium quickly manifest in physiological symptoms such as leaf chlorosis, stunted growth, and reduced grain set (Khan *et al.*, 2016; Hawkesford *et al.*, 2012).

Nutrient deficiencies, particularly of nitrogen, phosphorus, and potassium, rapidly manifest in maize through visible physiological symptoms such as leaf chlorosis, reduced leaf expansion, stunted vegetative growth, and poor grain formation (Khan *et al.*, 2016; Hawkesford *et al.*, 2012). This responsiveness allows researchers to observe and quantify the effects of different soil amendments, making maize an excellent bioindicator of soil health and nutrient availability.

2.5.1 Macro Composition of Different Frass Types

The nutrient composition of frass varies depending on the organic substrate consumed by BSF larvae, which directly influences its effectiveness as a soil amendment. Key macronutrients include nitrogen (N), phosphorus (P), and potassium (K), which are essential for plant growth. For Nitrogen (N), frass derived from food waste typically contains high nitrogen levels, often exceeding 2.0%, supporting vegetative growth and chlorophyll development (Lopes *et al.*, 2022). Mixtures of food waste with livestock manure and sawdust

yield more balanced N contents, contributing to sustained nutrient release (Beesigamukama *et al.*, 2020). While for Phosphorus (P), frass from agro-industrial residues such as cassava peels and oil palm by-products provide moderate phosphorus levels, which are essential for root development and energy transfer in plants. Lastly, for Potassium (K): Substrates with higher lignocellulosic content, such as decanter cake combined with palm kernel expeller, produce frass enriched with potassium, which enhances stress resistance, grain filling, and water-use efficiency (Beesigamukama *et al.*, 2020). In addition to macronutrients, frass contributes organic matter that improves soil structure, microbial activity, and moisture retention, further supporting plant growth in degraded soils.

Previous studies consistently report that maize responds positively to organic amendments such as compost, animal manure, and biochar, with improvements in soil structure, nutrient retention, and water-holding capacity. In many cases, these organic inputs sustain and even enhance crop yields compared to conventional synthetic fertilizers (Agegnehu *et al.*, 2017; Beesigamukama *et al.*, 2020). The synergistic effects of organic amendments are particularly beneficial in tropical soils, which are often prone to nutrient depletion and reduced organic matter content.

Given these characteristics, maize represents a reliable test crop for evaluating novel soil management strategies. Its sensitivity and economic significance make it an ideal candidate for assessing the combined application of Black Soldier Fly Larvae (BSFL) frass and decanter cake (DC) biochar, offering insights into their potential to improve soil fertility, enhance crop performance, and promote sustainable agricultural practices.

Table 2.5 summarizes previous studies on the application of BSF frass and oil palm residue-derived biochar in maize production. Evidence suggests that BSF frass consistently enhances early growth, nutrient uptake, yield, and plant resilience, while offering cost-effective benefits. Similarly, decanter cake biochar and related oil palm residues have shown improvements in soil physicochemical properties, particularly CEC and fertility, thereby supporting sustainable maize cultivation. The combined application of frass and biochar holds significant potential as a soil amendment strategy, leveraging the nutrient richness of frass with the structural and long-term soil conditioning properties of biochar. This synergy could address nutrient depletion and organic matter loss in tropical soils while ensuring sustainable maize production.

Table 2.5: Previous studies on BSF frass and oil palm residue biochar in maize

Amendment	Study Details	Crop	Key Findings	Citation
BSF Frass	Growth response of maize seedlings to frass from food-waste substrate (up to 2% w/w)	Maize	Enhanced early growth and nutrient uptake compared to the control	Nyakeri <i>et al.</i> , 2019
BSF Frass (Review)	Summary of multiple maize trials with BSF frass	Maize	Frass supplies nutrients and beneficial microbes, often comparable to mineral NPK	Chiam <i>et al.</i> , 2021
BSF Frass	Frass effect on plant defence and growth	Maize	Increased yield and plant resistance, with positive economic returns	Mwaniki <i>et al.</i> , 2023
Decanter Cake (DC)	Physicochemical characterization of DC vs EFB & corn-cob biochars; tested on sweet corn	Sweet Corn (<i>Zea Mays</i>)	DC showed the highest CEC (19.17 cmol kg ⁻¹); improved soil properties	Zainuddin <i>et al.</i> , 2020
Oil Palm Biochar (Review)	Evaluation of palm residues (EFB, sludge, DC potential)	Maize & tropical crops	Supports the viability of oil-palm residues for biochar in soil fertility	Abnisa & Daud, 2021

2.6 Combined Application of BSF Frass, Biochar, and Chemical Fertilizers (NPK)

BSFL frass and biochar have been widely recognized for their potential to improve soil fertility and crop productivity. Recent studies have explored their combined use with conventional chemical fertilizers such as NPK to maximize nutrient availability and crop yields (Agegnehu *et al.*, 2016; Beesigamukama *et al.*, 2020). Organic amendments can supply slow-release nutrients, improve soil structure, and enhance microbial activity. In contrast, NPK fertilizers provide readily available macronutrients, particularly during early crop growth stages when nutrient demand is high (Ch'ng *et al.*, 2014).

The synergistic integration of frass, biochar, and NPK has been reported to improve nutrient use efficiency by reducing leaching losses and prolonging nutrient availability throughout the growing season (Major *et al.*, 2010; Liu *et al.*, 2022). Biochar's porous structure and high cation exchange capacity (CEC) allow it to adsorb ammonium, potassium, and phosphate ions from NPK fertilizers, gradually releasing them into the soil solution and reducing volatilization and runoff (Lehmann & Joseph, 2015). Meanwhile, BSFL frass introduces beneficial microorganisms and organic matter, which can further mineralize nutrients and stimulate root development.

In maize cultivation, such combinations have been shown to enhance grain yield, biomass production, and nutrient uptake compared to the sole application of chemical fertilizers or organic amendments (Beesigamukama *et al.*, 2020; Munda *et al.*, 2021). However, existing studies have primarily tested biochar and frass from single feedstocks, and there is a lack of research on mixtures derived from tropical agro-industrial residues

such as sago *hampas* and decanter cake. This represents a significant knowledge gap in optimizing amendment blends for tropical maize-based systems.

Table 2.6 compares the characteristics of conventional NPK fertilizers with organic alternatives such as BSF frass, decanter cake biochar, and their combination in maize cultivation. While NPK provides rapid nutrient availability and high yield potential, it is limited by nutrient losses, soil acidification, and higher costs. In contrast, BSF frass and biochar contribute to soil health through improved microbial activity, carbon sequestration, and nutrient retention, though they generally supply lower immediate nutrient levels. Integrating frass and biochar offers synergistic benefits by combining quick nutrient release with long-term soil fertility enhancement, supporting sustainable maize production.

Table 2.6: Characteristics of good fertilizers for maize: Conventional NPK vs Organic Sources

Fertilizer Type	Typical Composition	Role in Maize Nutrition	Key Advantages	Limitations	Citation
Conventional NPK	Common ratios: 15:15:15, 16:16:16; Urea (46-0-0) for topdressing	Supplies readily available N, P, K for early and sustained growth	Fast nutrient release, high yield potential	High leaching losses (N), soil acidification, and cost	Ciampitti & Vyn, 2014
BSF Frass	Variable; typically, 3–4% N, 1–2% P, 1–2% K; plus, Ca, Mg, Zn, beneficial microbes	Provides readily available nutrients + organic matter, enhances microbial activity	Improves soil biology, slows down mineralization, and reduces leaching	Nutrient content lower than NPK; may need supplementation	Mutungi <i>et al.</i> , 2020; Chiam <i>et al.</i> , 2021
Decanter Cake Biochar	High in C; contains K, Ca, Mg; low N	Improves soil structure, CEC, water retention, and enhances long-term fertility	Carbon sequestration, pH buffering reduces nutrient loss	Low immediately available N and P; often used with other inputs	Chan <i>et al.</i> , 2022; Zainuddin <i>et al.</i> , 2020
Combined (Frass + Biochar)	Mix organic nutrients + stable carbon	Synergistic effect: frass gives quick nutrients, biochar improves retention	Enhanced nutrient use efficiency, better soil pH balance	Still less N than chemical fertilizers alone; the cost of production	Mwaniki <i>et al.</i> , 2023; Abnisa & Daud, 2021

2.7 Summary

Sustainable agriculture seeks to maintain productivity while reducing environmental costs by improving nutrient-use efficiency, recycling organic residues, and enhancing soil health. In Southeast Asia, two major agro-industrial residues, such as sago *hampas* and palm oil decanter cake (DC), accumulate in large volumes and pose pollution risks but also offer promise as feedstocks for value-added soil amendments. The BSFL converts these organic wastes into a nutrient-rich amendment containing macronutrients and micronutrients, organic matter, and beneficial microbes. BSF frass improves soil structure, biological activity, and plant performance. However, most studies use food waste or manure substrates rather than mixed tropical residues like sago *hampas* and DC. Besides, biochar improves soil physical and chemical properties (water retention, CEC, pH buffering) and stabilizes nutrients while sequestering carbon. Its agronomic performance depends on feedstock and pyrolysis conditions. Although biochar from rice husk or wood is well-studied, DC-derived biochar remains underexplored, particularly in tropical acidic soils common in Malaysia. Moreover, maize (*Zea Mays* L.) is an ideal test crop due to its high nutrient demand and sensitivity to N, P, and K availability, making it a strong bioindicator of amendment efficacy. Prior work shows organic amendments can match or exceed yields from synthetic fertilizers under certain conditions. Therefore, the combined application (frass + biochar + NPK) is emerging as a promising integrated strategy where biochar adsorbs and slowly releases nutrients, curbing leaching and volatilization; frass supplies slow-release nutrients and inoculates beneficial microbes, and NPK meets early rapid demand.

CHAPTER 3

CHARACTERIZATION OF DECANter CAKE BIOCHAR FOR AGRICULTURE APPLICATION

3.1 Introduction

The palm oil industry is one of Malaysia's largest agro-industrial sectors, but it also generates vast quantities of biomass residues, including decanter cake (DC), a by-product of palm oil mill effluent clarification. The improper disposal of DC through landfilling or open dumping poses environmental risks, including soil and water contamination due to its high organic content, residual oils, and nutrient load. Accumulation of this waste not only threatens environmental quality but also challenges the sustainability image of the palm oil sector (Embrandiri *et al.*, 2013b; Adam *et al.*, 2016).

Given its lignocellulosic composition and substantial levels of nitrogen, phosphorus, potassium, and magnesium, DC has been investigated for various value-added uses, including methane production, bio-oil generation via pyrolysis, and direct application as an organic fertilizer (Kittikun *et al.*, 2021a; Duaja *et al.*, 2019). While direct application can improve crop growth, studies report variable results and risks of phytotoxicity at high rates due to excessive organic load (Embrandiri *et al.*, 2013b). This variability underscores the need for stabilization or conversion before use in agriculture.

Biochar production via pyrolysis offers a promising approach to converting DC into a stable, carbon-rich soil amendment. Biochar's physicochemical properties, including high

surface area, porosity, alkaline pH, and nutrient retention capacity, can improve soil fertility, enhance water holding capacity, increase cation exchange capacity (CEC), and mitigate soil acidity (Tomczyk *et al.*, 2020; Singh Yadav *et al.*, 2023). Studies have demonstrated biochar's potential to boost crop yields (Novak *et al.*, 2012), improve phosphorus availability (Gao & DeLuca, 2018), and support beneficial soil microbiota (Oni *et al.*, 2019).

Although biochar from common agricultural residues such as rice husk or wood chips is well-documented, research on biochar derived from DC remains limited. Its distinct composition, that rich in residual oils, fibers, and minerals, may influence pyrolysis behaviour, yield, and final biochar quality in ways that differ from conventional feedstocks (Sakhiya *et al.*, 2020; Abioye *et al.*, 2023). Furthermore, the agricultural value of DC biochar depends on its chemical characteristics (pH, nutrient profile, ash content, fixed carbon) and its potential to improve soil conditions in tropical acid soils, which are often nutrient-poor and highly weathered.

Therefore, the first objective of this study (in Chapter 3) is to produce and characterize biochar derived from decanter cake for potential agricultural applications. By evaluating its physical and chemical properties, this research seeks to establish baseline data for optimizing DC biochar production and informing its integration into sustainable soil fertility management systems.

3.2 Materials and Methods

Figure 3.1 illustrates the methodology for this study through a flowchart. It outlines the sequential processes involved in preparing and characterizing biochar from oil palm decanter cake, starting from feedstock collection and concluding with analytical evaluations.



Figure 3.1: Sequential processes involved in the preparation and characterization of biochar from oil palm decanter cake.

3.2.1 Biochar Preparations

Figures 3.2 and 3.3 show the preparation of biochar using a modified drum kiln and the product of biochar from decanter cake. Biomass feedstock was subjected to pyrolysis under limited oxygen conditions to facilitate thermal decomposition and carbonization.



Figure 3.2. Preparation of biochar using a modified drum kiln. The feedstock is heated under limited oxygen conditions to produce carbon-rich biochar. (Image by Deborah Renting Jimmy, 2025)



Figure 3.3. Biochar was produced from decanter cake via pyrolysis using a traditional drum kiln (Image by Deborah Renting Jimmy, 2025)

Biochar was produced from oil palm decanter cake using a traditional 200 L drum kiln under limited oxygen conditions (Figure 3.2). The feedstock was air-dried to a 10–15% moisture content before pyrolysis. Approximately 10 kg of decanter cake was loaded into the kiln's inner chamber, which was then sealed except for a chimney vent to allow volatile gases and tars to escape. A firewood base beneath the kiln served as the primary heat source. Once ignited, the heat was transferred to the biomass chamber, with internal temperatures maintained between 300–600 °C for approximately 6.5 hours (392 minutes). This

temperature range ensured effective carbonization while minimizing ash formation. Temperature and residence time were monitored to optimize yield and quality.

Upon completion, the kiln was allowed to cool for 12–18 hours to prevent spontaneous combustion of the biochar. In some cases, quenching with water was applied to reduce ignition risk further. The cooled biochar was manually crushed and sieved through a 2 mm mesh to ensure uniform particle size for subsequent physicochemical characterization. The resulting biochar exhibited a porous structure, high surface area, alkaline pH, and appreciable nutrient content (NPK), making it suitable for soil amendment applications by improving soil aeration, water retention, cation exchange capacity, and nutrient availability.

3.2.2 Characterization of Decanter Cake Biochar

The decanter cake was collected from Felcra Jaya Samarahan in Kota Samarahan, Sarawak, Malaysia. The pH of the decanter cake biochar was determined in a ratio of 1:10 (soil: distilled water) suspension and 1M KCl solution using a glass electrode (Peech, 2016). However, the pH of the sago wastewater was determined directly from filtered samples using a glass electrode. The soil total carbon, N and organic matter were determined using Leco CHNS Analyzer (LECO Truspec Micro Elemental Analyzer CHNS, New York). Total P was extracted using the double acid method (Tan, 2005) followed by the blue method (Murphy & Riley, 1962). However, only total K was extracted using Aqua Regia method (Bernasl, 1968). Determination of K content in the extracts was conducted using Atomic Absorption Spectrophotometry (novAA 800, Analytik Jena, Technology Quality Innovation, Germany). Exchangeable cations were extracted using the leaching method (Cottenie, 1980),

and their concentrations were determined using Atomic Absorption Spectrometry (AAS). Soil CEC was determined by the leaching method followed by steam distillation (Bremner, 1965).

3.2.3 Activated Carbon Characterization

3.2.3.1 Proximate Analysis

Proximate analysis determines the biochar decanter cake by calculating the weight percent of moisture content, ash content, volatile matter, and fixed carbon content (Makshut *et al.*, 2020). Fixed carbon was calculated by difference (Wahi *et al.*, 2022). Determination of moisture content, ash content, volatile matter, and fixed carbon content was done in three replications.

i. Moisture Content

An empty, dried crucible (W_e) was weighed. Three replicates of 0.1 g of each sample were added to the crucible, weighed, and labeled (W_s). The sample was dried at 105°C for 24 hours. The crucible will not be covered during the heating process. After heating, the crucible was removed and cooled in a desiccator. After the cooling process, the dried sample was weighed again and denoted as W_d . The moisture content of the sample was calculated by using Equation 3.1:

$$\text{Moisture Content (\%)} = \frac{W_s - W_d}{W_s - W_e} \times 100\% \quad \text{Equation 3.1}$$

ii. Volatile Matter

An empty, dried crucible (W_e) was weighed. Three replicates of 0.1g of each sample were added into the crucible, closed with a lid, weighed, and labeled (W_s). the sample was dried for 7 minutes in a furnace at 500°C. Then, the crucible was cooled in a desiccator. After the cooling process, the dried samples were weighed and denoted as W_v . The volatile matter content of the sample was calculated by using Equation 3.2:

$$\text{Volatile Matter (\%)} = \frac{W_s - W_v}{W_s - W_e} \times 100\% \quad \text{Equation 3.2}$$

iii. Ash Content

An empty, dried crucible (W_e) was weighed. The sample was kept dry for 24 hours in a desiccator before the ashing process. Three replicates of 0.1g of each sample were placed into the crucible and were weighed (W_s). The samples were burned in a furnace at 500°C for 3 hours. During the heating process, the crucible was left open. The crucible was cooled in a desiccator. After the cooling process, the crucible with the dried sample was weighed and labeled (W_a). The ash content was calculated by using Equation 3.3:

$$\text{Ash Content (\%)} = \frac{W_s - W_a}{W_s - W_e} \times 100\% \quad \text{Equation 3.3}$$

iv. Fixed Carbon Content

The fixed carbon content (FCC) in the sample was calculated by using Equation 3.4:

$$\text{FCC (wt\%)} = 100 - (\% \text{ Moisture Content} + \% \text{ Volatile Matter} + \% \text{ Ash Content})$$

Equation 3.4

3.2.4 C, N, and Organic Matter using CHNS

About 2.5 mg of ground soil was placed on the machine's loading head. Samples were combusted at 1000°C, and the readings of total C and N were obtained directly from computer software. The loss of weight presented the weight of C, and the organic matter content was estimated by multiplying the organic matter value; 58% of organic matter is carbon (Cheftetz *et al.*, 1996). The reading was recorded from computer software, namely Flash Smart Elemental Analyzer (Thermo ScientificTM).

3.2.5 Characterization of Fourier Transform Infrared Spectroscopy (FTIR)

Decanter cake biochar has been characterized by using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups by quantifying the absorption or transmission of light across a sample, concerning wavelength, employing a KBr pellet. The sample range was recorded from 4000 cm⁻¹ to 500 cm⁻¹ at a resolution of 4 cm⁻¹ (Wahi *et al.*, 2018). The decanter cake biochar was mixed with KBr, then put pressure using a hydraulic press at 10 t for 10 seconds before the analysis. The FTIR was recorded in the 400-500 cm⁻¹ range at a resolution of 4 cm⁻¹.

3.2.6 Scanning Electron Microscope (SEM)

The macroaggregate slices were scanned for the distribution of carbon to reveal the interaction between the macroaggregates and incorporated biochar. The carbon mapping within macroaggregates can show the spatial distribution of biochar directly. The spatial distribution of carbon was analyzed by a scanning electron microscope with a JSM-IT500HR. The decanter cake biochar was observed under a scanning electron microscope and used to evaluate porosity and pore size distribution from scanning electron microscope images. The decanter cake biochar was prepared by spreading the powdered sample holder with double-sided carbon tape. It was then plated with a thin layer of gold on the sample's surface.

3.3. Results and Discussions

3.3.1 Chemical Properties of Decanter Cake Biochar

The chemical characterization of decanter cake biochar is summarized in Table 3.1. The biochar exhibited an alkaline pH of 9.40 (KCl) and 9.00 (water), organic matter of 35.56%, total carbon of 61.16%, exchangeable ammonium of 29.18%, and available nitrate of 19.84. The primary macronutrients, such as nitrogen, phosphorus, and potassium, were 3.33%, 0.40%, and 2.50%, respectively, while the C/N ratio was 18.36. These chemical characteristics suggest that decanter cake biochar contains essential plant nutrients, possesses high carbon stability, and may enhance soil fertility, nutrient retention, and sustainable agricultural productivity.

Table 3.1: Selected chemical properties of decanter cake biochar

Properties	Decanter Cake Biochar
pH (KCl)	9.40 ± 0.03
pH (Water)	9.00 ± 0.10
Organic Matter (%)	35.56 ± 0.41
Total Carbon (%)	61.16 ± 0.71
Exchangeable ammonium (%)	29.18 ± 4.67
Available Nitrate	19.84 ± 3.08
Total Nitrogen (%)	3.33 ± 0.05
Total Phosphorus (%)	0.40 ± 0.18
Total Potassium (%)	2.50 ± 0.02
C/N Ratio	18.36 ± 0.76

Note: Means (value ± standard error)

The alkaline pH (~9) of decanter cake biochar makes it particularly effective in neutralizing acidic soils and enhancing nutrient availability. This property is valuable for improving soil fertility in acidic environments common to tropical regions (Zubairu et., 2023). Furthermore, its pH contributes to better soil structure, microbial activity, and moisture retention, ultimately supporting crop growth (Ahmed *et al.*, 2023).

The biochar contained 35.56% organic matter and 61.16% total carbon, both critical for soil fertility and long-term carbon storage. The high organic matter content improves nutrient retention, water-holding capacity, and microbial activity (Wang *et al.*, 2022).

Meanwhile, the stable carbon fraction contributes to carbon sequestration, reducing CO₂ emissions and mitigating climate change (State & Co, 2013). Its porous structure further enhances aeration, reduces compaction, and supports root development (Bagheri Novair *et al.*, 2023).

Decanter cake biochar is a notable source of macronutrients. The relatively high nitrogen content (3.33%) enhances vegetative growth by supporting amino acid, protein, and chlorophyll synthesis (Bagheri Novair *et al.*, 2023). Although the phosphorus level (0.40%) is modest, it plays a key role in root development, seed formation, and energy transfer processes (Hasanuzzaman *et al.*, 2018). The potassium content (2.50%) supports photosynthesis, water regulation, enzyme activation, and improves plant tolerance against drought and disease (Hasanuzzaman *et al.*, 2018). Together, these nutrients position biochar as a slow-release organic fertilizer capable of sustaining crop productivity.

The C/N ratio of 18.36 suggests a balanced nutrient profile that supplies carbon while avoiding nitrogen immobilization. This ratio supports microbial activity and soil structure improvement, creating a favourable environment for crop growth (Singh *et al.*, 2022). The balance between carbon and nitrogen is especially important for long-term soil fertility management and ensures efficient nutrient cycling (Rohith, 2023). Beyond nutrient supply, decanter cake biochar serves broader environmental functions. Its alkaline pH and porous structure facilitate the immobilization of heavy metals, thereby reducing their bioavailability in contaminated soils (Zhang *et al.*, 2013). This remediation potential highlights the dual role of decanter cake biochar in agriculture and environmental management. Decanter cake biochar demonstrates high potential as a soil amendment due to its alkaline pH, nutrient

composition, balanced C/N ratio, and stable organic matter content. These properties enhance soil fertility and crop productivity and contribute to carbon sequestration and environmental remediation.

3.3.2 Proximate Analysis

The proximate analysis of decanter cake biochar is depicted in Table 3.2. Decanter cake biochar with a volatile matter content of 23.55% indicates the proportion of organic compounds and carbonaceous materials that can vaporize at high temperatures (Abioye *et al.*, 2023a). This volatile matter affects biochar properties, such as porosity, density, and chemical composition (Tomeczyk *et al.*, 2020). The volatile matter content is crucial in assessing biochar quality and its potential applications, such as soil improvement and carbon sequestration (Yadav *et al.*, 2023).

Table 3.2: Proximate analysis results of decanter cake biochar

Proximate Analysis	Decanter Cake Biochar
Moisture content (%)	11.00 ± 0.57
Volatile matter content (%)	0.57 ± 0.01
Ash Content (%)	0.43 ± 0.01
Fixed carbon (%)	88.00 ± 0.56

Note: Means (value ± standard error)

Decanter cake biochar contained 23.55% volatile matter, reflecting the proportion of thermally labile organic compounds and carbonaceous fractions. This parameter strongly influences porosity, surface chemistry, and nutrient release potential (Tomczyk *et al.*, 2020). A relatively higher volatile matter fraction enhances biochar reactivity and the gradual release of nutrients into soils (Ding *et al.*, 2016), which is advantageous for soil amendment. Comparable values have been reported in palm oil residues (20–30%), supporting its potential as a nutrient-releasing soil conditioner (Abioye *et al.*, 2023a). The biochar exhibited a low ash content of 0.43%, signifying minimal inorganic residue after combustion. Low ash fractions indicate higher purity and reduced risks of heavy metal accumulation in soils (Aller, Bakshi, & Laird, 2017). In contrast, animal-manure biochars often display high ash contents (>20%), which may elevate salinity and limit application in sensitive soils (Khan *et al.*, 2024). Thus, the low ash fraction of decanter cake biochar enhances its environmental compatibility and suitability for long-term soil application.

The fixed carbon fraction of 88% was substantially greater than the range typically reported for crop-residue biochars (50–70%) (Yadav *et al.*, 2023). Fixed carbon represents biochar's stable carbon backbone, determining both soil persistence and its role in long-term carbon sequestration (Li & Tasnady, 2023). A higher fixed carbon percentage improves soil water-holding capacity, enhances microbial habitat stability, and supports prolonged fertility improvements (Aller *et al.*, 2017). The high value obtained here suggests that decanter cake biochar has strong potential as a climate-change mitigation tool through carbon stabilization. The moisture content (11.00%) was within the acceptable range for biochar storage and application. Excessive moisture reduces biochar's calorific value and storability, whereas

moderate moisture content prevents dust formation and facilitates soil mixing (Tomczyk *et al.*, 2020).

3.3.3 Ultimate Analysis of Decanter Cake Biochar

The elemental composition of decanter cake biochar determined through ultimate analysis in terms of carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) content is summarized in Table 3.3. This analysis is crucial for understanding the biochar's nutrient content and potential in agricultural applications. Biochar is primarily composed of carbonaceous material due to pyrolysis, which results in volatilizing elements like hydrogen during production. The nitrogen content of decanter cake biochar indicates its potential as a nitrogen source for plant growth and soil improvement.

Table 3.3: Elementary composition of decanter cake biochar

Element	Content (wt%)
Carbon (C)	35.56 $\pm$ 0.05
Hydrogen (H)	0.00
Nitrogen (N)	3.33 $\pm$ 0.05
Sulphur (S)	0.00

Note: Means (value $\pm$ standard error)

The decanter cake biochar contained 35.56 wt% carbon, reflecting its richness in carbonaceous material. High carbon levels enhance soil fertility, water-holding capacity, and microbial activity, while also providing long-term carbon sequestration potential (Singh Yadav *et al.*, 2023; Lehmann *et al.*, 2011). Compared with other agricultural biochars such as rice husk (28–32% C) and palm kernel shell biochar (40–45% C), decanter cake biochar falls within a moderate range (Zhang *et al.*, 2020; Fidel *et al.*, 2018). This indicates both good structural stability and significant potential for soil amendment and carbon storage.

The hydrogen content was recorded as 0%, suggesting that almost all volatile organic fractions were removed during pyrolysis. This points to a highly stable biochar structure with limited degradability, ensuring long-lasting persistence in soil (Tomczyk *et al.*, 2020). The absence of hydrogen differentiates it from other biochars, such as coconut shell biochar (1–2% H) and wood-derived biochar (1.5–3% H) (Méndez *et al.*, 2013; Ippolito *et al.*, 2020). Such structural stability is advantageous for applications targeting long-term carbon sequestration and soil conditioning.

The biochar contained 3.33 wt% nitrogen, which is relatively high compared to many agricultural biochars that typically range from 0.2% to 2% (Embrandiri *et al.*, 2013; Abioye *et al.*, 2023b). This nitrogen enrichment suggests that decanter cake biochar is a promising organic nitrogen source, particularly in nitrogen-deficient soils. Nitrogen is essential for amino acids, proteins, and chlorophyll synthesis, and its presence in biochar has been linked to improved crop growth and yields (Hisham & Ramli, 2021; Xu *et al.*, 2020). Similar findings were reported by Beesigamukama *et al.* (2020), where nitrogen-rich biochars significantly enhanced maize nitrogen uptake and biomass accumulation.

No sulphur was detected (0%), indicating that decanter cake biochar does not directly supply sulphur to soils. While sulphur is an essential macronutrient for crops, excessive sulphur in biochar can contribute to acidification and potential nutrient imbalances (Santos *et al.*, 2019). Therefore, the absence of sulphur may be beneficial in maintaining soil pH stability, though supplementary sulphur sources may be required in sulphur-deficient soils (Liang *et al.*, 2021).

3.3.4 Functional Group Analysis of Decanter Cake Biochar

The Fourier Transform Infrared (FTIR) spectra of decanter cake biochar, Figure 3.3, reveal the presence of key functional groups that influence its chemical reactivity and soil amendment potential. The broad absorption band around 3400 cm^{-1} indicates O–H stretching vibrations, associated with hydroxyl groups in alcohols or phenolic compounds. Peaks near 2920 cm^{-1} correspond to C–H stretching in aliphatic hydrocarbons, while the prominent band around 1700 cm^{-1} suggests C=O stretching, typical of carbonyl or carboxylic groups. The absorption in the region of 1600 cm^{-1} can be attributed to aromatic C=C stretching, indicating lignin-derived structures. Bands between $1000\text{--}1100\text{ cm}^{-1}$ represent C–O stretching vibrations, linked to polysaccharides or silicates. These functional groups confirm that decanter cake biochar retains oxygenated surface chemistry, which enhances cation exchange capacity and nutrient retention when applied to soil.

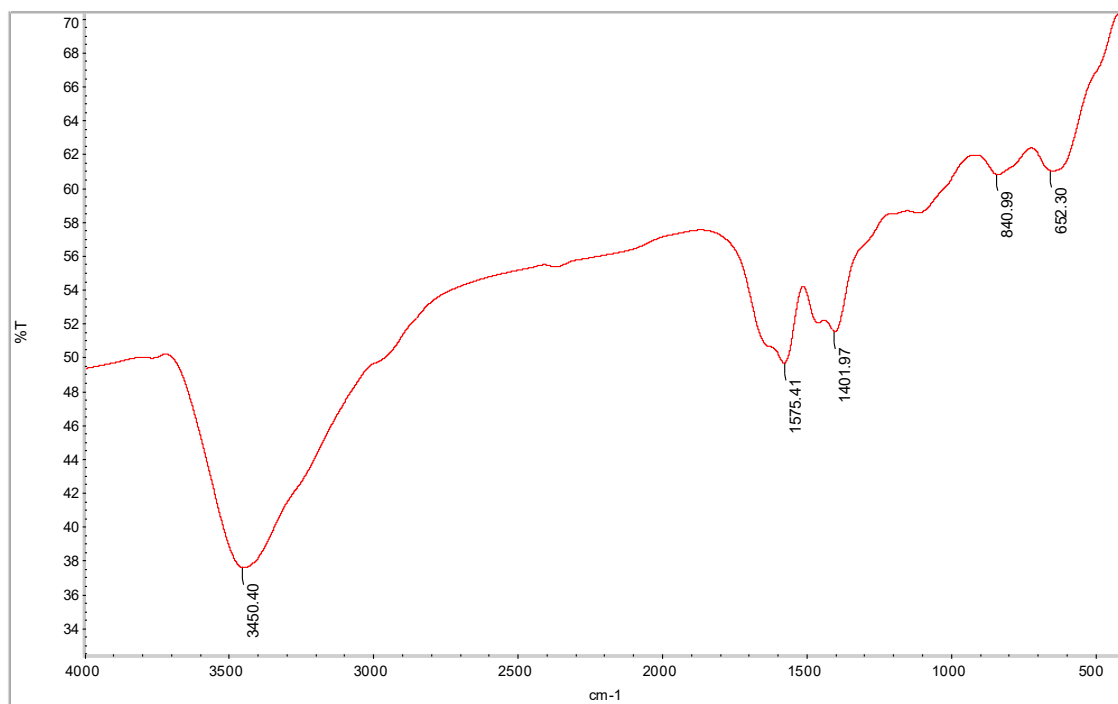


Figure 3.4: The FTIR spectra of decanter cake biochar

The broad absorption band observed near 3450.40 cm^{-1} is attributed to O–H stretching vibrations. This signal typically originates from hydroxyl groups (–OH) in alcohols, phenols, or carboxylic acids. In some cases, overlapping N–H stretching vibrations from amines or amides may also contribute to this region, particularly when hydrogen bonding is less pronounced (Zhang *et al.*, 2021). The broadness of this peak suggests extensive hydrogen bonding, a feature consistent with biochar derived from lignocellulosic feedstocks (Shaaban *et al.*, 2013).

A weaker band near 2900 cm^{-1} corresponds to C–H stretching vibrations of aliphatic groups (–CH₂), associated with hemicellulose-derived compounds. The diminishing intensity of this peak with increasing pyrolysis temperature indicates the thermal degradation of aliphatic components, particularly hemicellulose and cellulose fractions (Li *et al.*, 2022).

The 1600–1700 cm^{-1} region shows distinct absorption bands, attributed to C=O stretching vibrations from carbonyl or quinone functional groups. These peaks are typically more pronounced in raw biomass but progressively decrease with carbonization, reflecting the transition from oxygenated functional groups to more stable, aromatic carbon structures (Ahmad *et al.*, 2014).

At lower wavenumbers, bands between 1100–1500 cm^{-1} are associated with C–O stretching of carboxylic acids, esters, and carbonate groups. The attenuation of these peaks at higher pyrolysis temperatures highlights the decomposition of oxygen-containing groups and the enrichment of aromatic structures in the biochar matrix (Keiluweit *et al.*, 2010). These observations are consistent with findings reported in other biochar studies, where the simplification of FTIR spectra with rising pyrolysis temperature indicates the progressive elimination of volatile matter and oxygenated groups (Shaaban *et al.*, 2013; Qambrani *et al.*, 2017). Notably, quinone-related bands around 1550–1680 cm^{-1} persist at higher temperatures, suggesting that biochar retains certain basic functional groups with proton-accepting capacity, potentially enhancing its cation exchange properties (Wu *et al.*, 2019).

The transformation of functional groups in decanter cake biochar indicates a clear temperature-dependent structural evolution where at the lower pyrolysis temperatures, biochar retains more oxygenated functional groups, enhancing its potential for nutrient retention, ion exchange, and soil interaction (Qambrani *et al.*, 2017). While, at the higher pyrolysis temperatures, biochar becomes increasingly aromatic and carbon-rich, improving stability and longevity in soils but reducing reactive functional sites (Keiluweit *et al.*, 2010; Zhang *et al.*, 2021). Thus, the FTIR analysis demonstrates how tailoring pyrolysis conditions

can modulate the surface chemistry of decanter cake biochar, thereby influencing its effectiveness as a soil amendment, adsorbent, or carbon sequestration agent.

3.3.5 Surface Morphology of Decanter Cake Biochar

The structure of decanter cake (DC) biochar observed through Scanning Electron Microscopy (SEM) typically reveals a porous and heterogeneous morphology characterized by interconnected networks of pores (Figure 3.4). SEM imaging provides insights into the surface topography and pore distribution, highlighting the physical properties that underpin its potential applications in environmental remediation and agriculture (Khan *et al.*, 2024). The porosity of DC biochar is critical for enhancing water and nutrient retention, thereby minimizing nutrient leaching and improving plant uptake efficiency (Azzi *et al.*, 2024; Weng *et al.*, 2015). Such porous structures are advantageous for soil fertility enhancement and remediation practices.

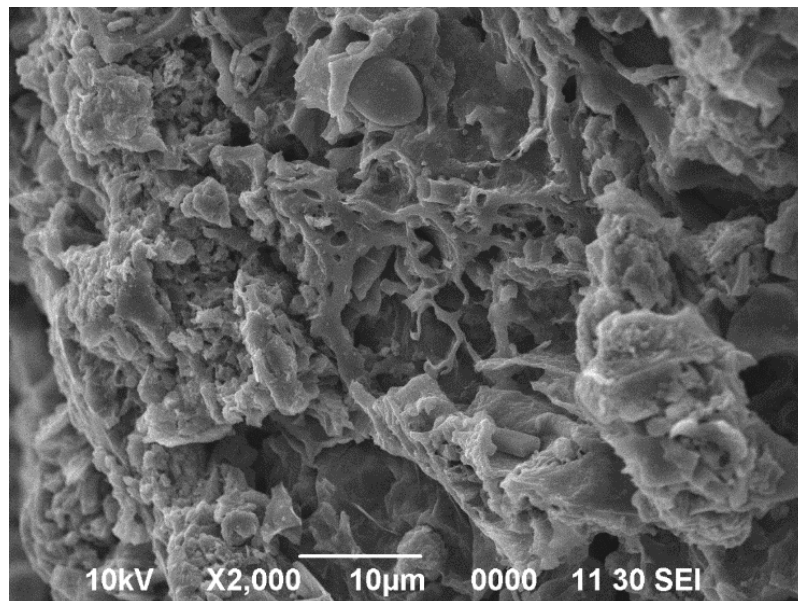


Figure 3.5. The SEM image of decanter cake biochar at x2000

SEM analysis reveals a highly heterogeneous surface, with a network of voids and microfractures contributing to an increased surface area (Ayadi *et al.*, 2020). This roughness enhances the biochar's adsorptive capacity, making it suitable for soil amendments, pollutant capture, and microbial colonization. Previous studies indicate that these properties are essential for improving carbon sequestration and soil health (Lehmann *et al.*, 2011). The production conditions, particularly pyrolysis temperature, significantly influence DC biochar morphology. SEM observations show that raw residues, initially smooth, develop well-defined pores at elevated temperatures such as 300°C (C300) and 700°C (C700) due to organic volatilization (Nepal *et al.*, 2023). At C700, the pore volume can be three times greater than at C300, with higher pyrolysis temperatures also promoting a more orderly arrangement of carbon atoms, thus increasing carbon density and structural integrity (Aldarmon *et al.*, 2015). These features enhance root penetration, microbial habitats, and overall soil functionality.

The morphological features of DC biochar highlight its utility as a multifunctional amendment. Its porous structure, high surface area, and enhanced carbon stability allow for improved soil aeration, increased cation exchange capacity, and elevated organic carbon levels (Domingues *et al.*, 2020; Toková *et al.*, 2020). Furthermore, such properties align with findings that biochar not only improves soil physicochemical characteristics but also facilitates long-term waste valorization and sustainable resource management (Rongwang, Polprasert, & Kanchanasuta, 2017; Ahmad Parveez *et al.*, 2022).

3.4 Conclusion

In summary, Chapter 3 has demonstrated the successful transformation of decanter cake (DC), a palm oil milling by-product, into biochar (DC biochar), thereby achieving the primary objective of this study was to valorise agricultural waste into a sustainable soil amendment. The ultimate and proximate analyses confirmed that DC biochar is a carbon-rich, structurally stable material with high porosity and surface area, directly supporting its role in improving soil properties. The results highlighted that DC biochar significantly enhances soil fertility by increasing water retention and phosphorus availability, while reducing the fixation of aluminium and iron ions in acidic tropical soils. Its measurable nitrogen content further contributes to soil nutrition, whereas its porous structure facilitates aeration, root growth, and microbial activity. These benefits collectively improve soil health, enhance crop productivity, and increase resilience under environmental stresses such as drought. In addition, producing biochar from decanter cake successfully addresses two critical challenges: effective waste management by converting a problematic residue into a value-added product and sustainable soil management by providing a long-lasting amendment that reduces dependency on chemical fertilizers. This aligns with circular economy principles and supports the transition toward eco-friendly and resource-efficient agriculture. By achieving the objective of producing biochar from decanter cake, this study validates its potential as a multifunctional soil amendment that improves soil fertility and crop growth and contributes to waste valorisation, carbon sequestration, and sustainable farming practices. The insights gained here establish a foundation for future research on the long-term field performance, scalability, and integration of DC biochar into holistic soil fertility management strategies.

CHAPTER 4

CHARACTERIZATION OF FRASS YIELD FROM BLACK SOLDIER FLY CO-BIOCONVERSION OF SAGO *HAMPAS* AND DECANter CAKE

4.1 Introduction

The palm oil and sago industries in Malaysia are major contributors to the agro-industrial sector but simultaneously generate significant quantities of lignocellulosic residues, particularly decanter cake and sago *hampas* (Ali *et al.*, 2021; Khasanah & Purnamasari, 2022). Decanter cake, a semi-solid by-product from palm oil milling, is produced in large volumes and, if left unmanaged, poses risks of soil and water contamination due to its high organic and oil content (Ahmed *et al.*, 2020). Similarly, sago *hampas*, the fibrous residue from sago starch extraction, is often discharged into water bodies along with effluents, contributing to high biological oxygen demand (BOD) levels and severe aquatic pollution, which threatens ecosystem integrity (Ling *et al.*, 2021).

Conventional composting has been explored as a low-cost method for managing these residues (Siles *et al.*, 2022). However, traditional composting processes are time-consuming, typically requiring several weeks to months for stabilization, thereby limiting their scalability for large-volume waste streams (Sánchez-Monedero *et al.*, 2018). At the same time, the growing demand for organic fertilizers driven by consumer health concerns and the premium market value of organically grown produce necessitates faster, more efficient, and sustainable waste-to-fertilizer solutions (Hernandez *et al.*, 2021).

Black Soldier Fly Larvae (*Hermetia illucens* L.) bioconversion has emerged as a promising approach for organic waste management. BSFL are highly efficient decomposers capable of rapidly degrading diverse organic substrates, including fibrous agricultural by-products, while producing two value-added products: larval biomass, which can serve as a protein source for animal feed, and frass (residual substrate), which is nutrient-rich and can be utilized as an organic fertilizer (Purnamasari & Khasanah, 2022; Meneguz *et al.*, 2018). Compared to conventional composting, BSFL bioconversion significantly shortens decomposition time, making it an ideal option for managing high-volume residues such as decanter cake and sago *hampas* (Gold *et al.*, 2020).

The frass produced through BSFL bioconversion is particularly noteworthy due to its content of essential macronutrients (N, P, K) and beneficial micronutrients, which enhance soil fertility, improve structure, and support beneficial microbial activity (Barragán-Fonseca *et al.*, 2017; Beesigamukama *et al.*, 2020).

Thus, the second objective (in Chapter 4) focuses on the co-bioconversion of decanter cake and sago *hampas* using BSFL, specifically characterizing frass yield and its physicochemical properties. Achieving this objective offers insights into transforming agro-industrial residues into sustainable soil amendments, addressing waste management challenges, and the growing demand for eco-friendly fertilizers.

4.2 Materials and Methods

Figure 4.1. Flowchart illustrating the overall methodology employed in this study to analyse the chemical and physical properties of black soldier fly larvae (BSFL) frass derived from *sago hampas* and decanter cake. The process begins with the collection of essential materials, including BSF eggs, decanter cake, and *sago hampas*.

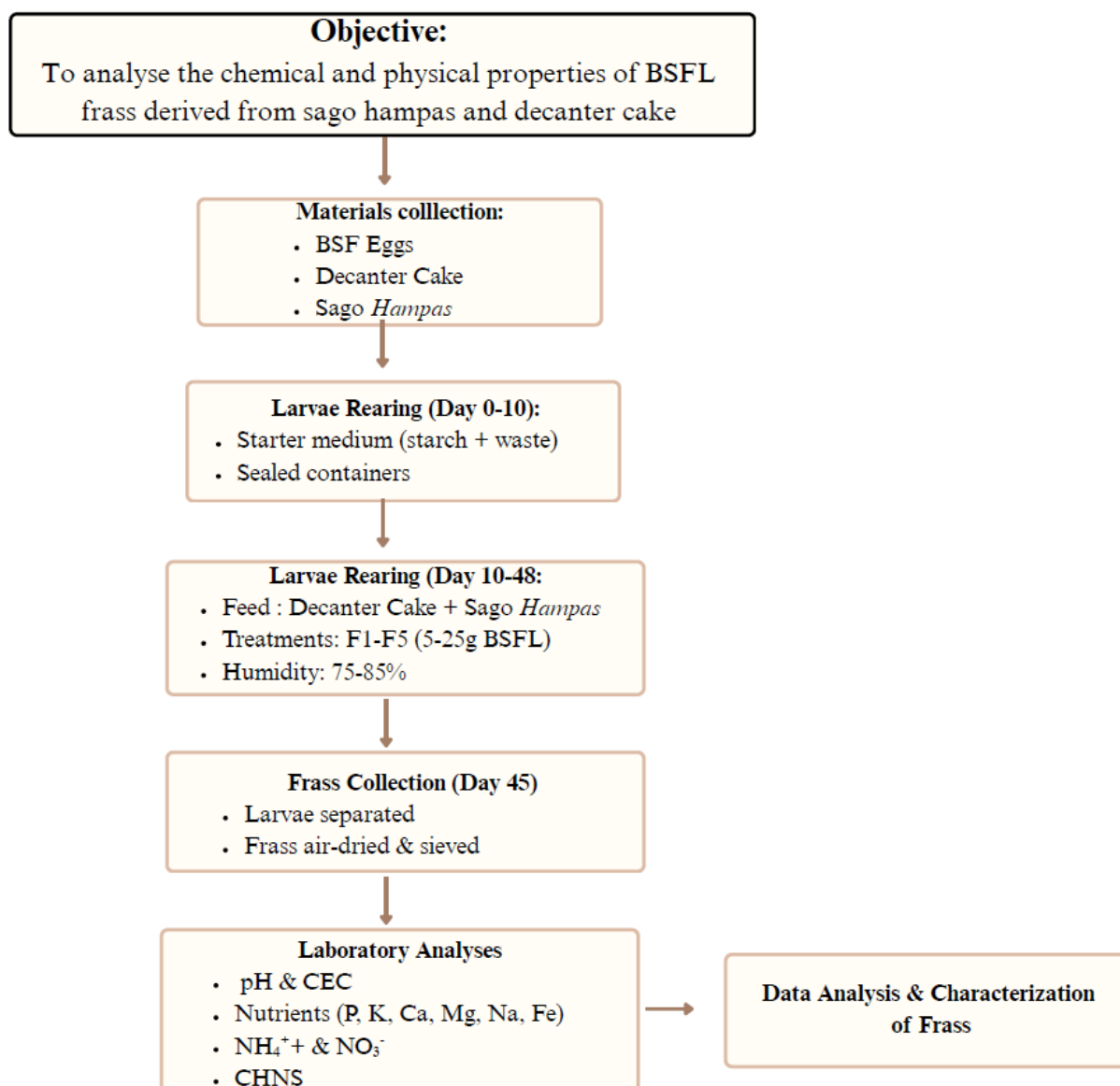


Figure 4.1: Overall methodological flowchart for the study on black soldier fly larvae (BSFL) frass derived from *sago hampas* and decanter cake.

4.2.1 Materials

The black soldier fly egg was bought from BSF Borneo Asajaya, Kota Samarahan, Sarawak, Malaysia, and collected in the egg stage. The decanter cake was collected from Felcra Jaya Samarahan in Kota Samarahan, Sarawak, Malaysia, and Sago *Hampas* was collected from Sago-Link in Mukah, Sarawak, Malaysia.



Figure 4.2: Sago *hampas* collected from Sago-Link in Mukah, Sarawak, Malaysia.
(Image by Deborah Renting Jimmy, 2025).



Figure 4.3: Decanter cake from oil generated in a palm oil mill.
(Image by Deborah Renting Jimmy, 2025).

4.2.2 The Bioconversion of Black Soldier Fly Frass

All apparatus, materials, and samples are stored in three 30cm x 60cm containers for the larvae starter-rearing procedure. A mosquito net is positioned in the centre of a plastic container with its base removed; this net functions as a tripod to prevent the egg from becoming damp. To avoid the departure of the larvae, a buffer zone was constructed using double tape and fine wood husk, which was positioned one inch above the level of the starter food in the tray. Subsequently, a starter diet consisting of water and rejected sago starch in a ratio of 2:1 (1 kilogram of sago starch to 500 milliliters of plain water) was added to the tray.

Subsequently, the container containing 5g of *H. illucens* is positioned in the middle of the tray, and its top is sealed to prevent the introduction of any extraneous matter into the egg stand. The containers were assigned the designations F1, F2, F3, F4, and F5 with 3 replications for each treatment. After that, the containers were refrigerated at room temperature with limited air circulation and light exposure to prevent the starter media from drying out too quickly. A repellent against ants was applied around the containers to prevent their access to the starter culture tray. The rearing process will take around three weeks, starting from the day the larvae hatch and are recorded as one-day-old larvae until they reach 45 days old after reaching the adult phase. Further procedures, such as physical, chemical, and biological tests, were done to determine the stabilization rate of sago frass produced by the *H. illucens* larvae.

4.2.3 Characterization of BSFL Frass, Sago *Hampas*, Decanter Cake, and Biochar

i. pH analysis and CEC

The glass electrode has been used to measure the pH levels of BSFL frass. 10 g of each of the samples was weighed and placed in disposable vials. 20 mL of distilled water and KCl were introduced individually and agitated at a speed of 180 rpm for 15 minutes, as described by Peech in 1965. The KCl readings were acquired following a 15-minute settling period for the samples, whereas the pH in water was measured after 24 hours. The pH measurement was recorded using a digital pH meter, namely the Thermo Scientific EutechTM Expert pH Pocket Tester model.

The CEC of the BSFL frass and biochar in this study was determined using the CsCl method (Ming and Dixon, 1986). The procedure is similar to that for soil CEC determination, but 5 g of BSFL frass and Biochar instead of 10 g were used.

ii. Total phosphorus and potassium analysis

The aqua regia technique was employed to measure the concentration of total phosphorus in the soil. The solution was obtained by combining the soil samples with a combination of acids (HCl and HNO₃) in a ratio of 3:1. The ratio of the mixture to the soil samples was 1:10, and the mixture was prepared in a 250 mL volumetric flask. Subsequently, the samples were subjected to heat on a hot plate until the solution became devoid of colour. The solution was then allowed to cool before being filtered into a 50 mL volumetric flask using Advantec filter paper No. 2. The concentration of phosphorus in the soil was measured

using a UV-Vis spectrophotometer (Perkin Elmer Lambda 25, USA) at a wavelength of 882 nm, following the emergence of a blue hue as described by Murphy and Riley in 1962. The colour development process involved the preparation of a standard P solution (1000 mg L⁻¹) (standard solution 1). This solution was made by dissolving 4.39 g of oven-dried (105 °C), high-quality potassium dihydrogen phosphate (KH₂PO₄) in 1 L of distilled water. Subsequently, a volume of 5 mL from standard solution 1 was transferred using a pipette into a volumetric flask with a capacity of 1000 mL to achieve a dilution of 5 parts per million (ppm), resulting in the creation of standard solution 2 (Murphy and Riley, 1962).

The acid molybdate stock solution, also known as Reagent A, was created by combining 12 g of ammonium molybdate [(NH₄)₆Mo₇O₂₇] with 500 mL of distilled water and 148 mL of pure sulphuric acid (H₂SO₄). After cooling the solution to room temperature, 0.29 g of potassium antimony tartrate (KSbOC₄H₄O₄) was added, followed by dilution with distilled water. On the day of the colour development, Reagent B was made by dissolving 1.32 g of ascorbic acid in 250 mL of Reagent A. A working standard solution spanning from 0 to 0.7 ppm was prepared using standard solution 2. A volume of 1 to 7 mL of standard solution 2 was transferred into a 50 mL volumetric flask using a micropipette. The blue hue of the sample solution was created by adding eight milliliters of Reagent B.

The extraction of nutrients (Total K, Ca, Mg, Na, and Fe) from above-ground biomass and root biomass of maize plants was carried out using a single dry ashing method, as described by Cottenie in 1980. Before this, the maize plant was divided into above-ground biomass (leaves and stems) and root biomass at the time of harvest. Subsequently, the samples were subjected to oven drying at a temperature of 60 °C until a consistent weight

was achieved. Subsequently, the samples were ground before chemical analysis. The plant samples underwent a process of desiccation at a temperature of 60 °C for 24 hours to eliminate any moisture content. A 1 g plant tissue sample was measured and placed in a silica or porcelain dish (crucible).

The dish was then placed in a muffle furnace at an initial temperature of 300 °C for 1 hour. The temperature was initially increased to 520 °C and maintained for 4 to 5 hours. The samples were chilled to around 35 °C before examination. Subsequently, they were moved onto a heated plate, onto which a small amount of distilled water was added, followed by 2 mL of concentrated HCl. The samples were then heated until all moisture evaporated in a fume chamber. Subsequently, 10 mL of a 20% nitric acid (HNO₃) was introduced to the samples and subjected to heat until 50% of the solution evaporated. Subsequently, the samples were strained through Advantec filter paper No. 2 into a 100 mL volumetric flask and topped up with distilled water. The cations K, Ca, Mg, Na, and Fe were measured using Atomic Absorption Spectrometry (AAS). The blue colour was produced following the procedure outlined by Murphy and Riley (1962), and the amount of phosphorus (P) was determined using a UV-Vis Spectrophotometer (Perkin Elmer Lambda 25, USA) at a wavelength of 882 nm.

iii. Determination of Exchangeable Ammonium (NH₄⁺) and Available Nitrate (NO₃⁻)

The Keeney and Nelson (1982) method was employed to extract exchangeable NH₄⁺ and accessible NO₃⁻ ions, and their concentrations were measured using steam distillation. A 5 g BSFL frass sample was subjected to extraction with 50 mL of a 2 M KCl solution. The

mixture was agitated for one hour on a mechanical shaker and subsequently filtered using Whatman filter paper No. 2. The concentration of NH_4^+ ions that can be exchanged was measured by transferring 20 mL of extractant into a distillation tube, then adding 0.2 g of MgO and distilling the mixture for 5 minutes. A solution containing 10 mL of boric acid and bromocresol green, and methyl red indicators was utilized to capture NH_4^+ . Subsequently, the distillation process was extended by introducing 0.2 g of Devarda's alloy to the sample, and the distillation continued for an additional 5 minutes. The NH_4^+ and NO_3^- distillates were titrated using a 0.01 M HCl solution.

iv. CHNS Analysis

BSFL frass of C, N, and organic matter was determined using CHNS. A 2.5 mg ground soil was placed on the loading head of the machine. Samples were combusted at 1000°C . and the readings of total C and N were obtained directly from computer software. The weight loss presented the weight of C, and the organic matter content was estimated by multiplying the organic matter value, 58% of organic matter is carbon (Cheftetz et al., 1996). The reading was recorded using computer software, Flash Smart Elemental Analyzer (Thermo ScientificTM).

4.2.4 Rearing Black Soldier Fly Larvae for Frass Production

The eggs of BSF were obtained from BSF Borneo, Kota Samarahan, Sarawak, Malaysia, while sago *hampas* were from Mukah, Sarawak, Malaysia (Figure 4.1) and decanter cake was collected from Felcra Jaya, located in Kota Samarahan (Figure 4.2). Table

4.1 presents the experimental treatments used for frass production, where different amounts of Black Soldier Fly Larvae (BSFL) were applied to organic substrates. 10 g of BSF eggs were placed in a plastic tray with a dimension of 40 cm length $\times$ 30 cm width $\times$ 10 cm depth, which was laid along with discarded sago starch as a starter medium for the diet of BSFL. It was observed that the juvenile larvae could not consume a coarse solid diet at the first instar. In this study, the larvae were fed with starter diets consisting of rejected sago starch and kitchen waste (e.g., expired oats, fruit peels, and ground coffee waste) for 10 days. Then, from day 10 to day 48, the BSFL were fed with 3 kg of DC and SH as the primary feeding substrate with different amounts of BSFL as given in the following:

Table 4.1: Treatments of frass production

Treatments	BSFL (g)
F1	5
F2	10
F3	15
F4	20
F5	25

Note: BSFL application from 5 g to 25 g across treatments F1 to F5

An egg stand was placed on a tray for rearing the black soldier fly larvae. A dry wooden husk was positioned around the tray before the eggs were transferred, ensuring the eggs were contained within the tray. The larvae were fed rice from day 1 to day 5, and then oats were given from day 6 to day 7. The larvae were on day 1 when they started to hatch from the eggs, and this continued until they reached their adult phase on day 45

At day 7, the larvae were divided among the treatments that used a mixture of decanter cake and sago *hampas*. Each treatment was misted daily to maintain the level of humidity, as it has been found that organic waste treatment with BSF larvae works best at 75% to 85% relative humidity. The complete rearing process typically takes around three weeks. At 45 days, the black soldier fly frass was air-dried to prevent the growth of fungus. The frass was then sieved using a 2mm sieve to remove the larvae for laboratory analysis. The frass samples were analysed for pH, exchangeable NH_4^+ , and available NO_3^- . The method of determining soil pH was as previously stated. Keeney and Nelson (1982) provided the method to extract soil exchangeable NH_4^+ and available NO_3^- . The treatments were assigned in a completely randomized design (CRD), with three replications being performed for each treatment.



Figure 4.4: Treatment of frass production from decanter cake and sago *hampas*.
(Image by Deborah Renting Jimmy, 2025)

4.3 Results and Discussions

4.3.1 The Chemical Properties of Decanter Cake and Sago *Hampas*

The chemical characterization of decanter cake and sago *hampas* revealed notable differences in their nutrient composition (Table 4.2). The pH values indicated that the decanter cake was near neutral (pH 6.80 in water), whereas sago *hampas* was strongly acidic (pH 4.20 in water).

Table 4.2: The chemical properties of decanter cake and sago *hampas*

Properties	Decanter cake (DC)	Sago <i>hampas</i> (SH)
pH (KCl)	6.53 ± 0.33	3.73 ± 0.03
pH (Water)	6.80 ± 0.03	4.20 ± 0.01
Organic Matter (%)	63.31 ± 1.00	58.46 ± 2.51
Total Carbon (%)	36.80 ± 0.58	33.99 ± 1.46
Exchangeable ammonium (%)	17.51 ± 0	15.17 ± 1.16
Available Nitrate	19.84 ± 1.167	16.34 ± 1.16
Total Nitrogen (%)	3.00 ± 0.12	0.90 ± 0.02
Total Phosphorus (%)	3.00 ± 0.02	1.02 ± 0.88

Note: All analyses are based on dry weight

The chemical properties of decanter cake (DC) and sago *hampas* (SH) showed clear differences that influence their potential as substrates for Black Soldier Fly Larvae (BSFL) rearing and frass production. The pH values revealed that DC was close to neutral (6.80 in water), while SH was strongly acidic (4.20 in water). The acidity in SH is likely attributed to residual starch hydrolysis and fermentation during processing, which may limit its direct

use in soil amendment without neutralization. In contrast, the near-neutral pH of DC makes it more favorable for both microbial activity and larval development.

Both DC and SH were rich in organic matter (63.31% and 58.46%, respectively) and carbon content (36.80% and 33.99%), indicating their suitability as carbon-rich feedstocks to sustain microbial metabolism and larval growth (Paritosh *et al.*, 2020). High organic matter also enhances soil fertility when applied as amendments, contributing to better soil structure and water-holding capacity. The nutrient analysis has highlighted significant imbalances. DC recorded a total nitrogen content of 3.00%, whereas SH contained only 0.90%, which is considered insufficient for supporting optimal plant growth or larval protein requirements. Similarly, exchangeable ammonium and available nitrate were higher in DC than in SH, confirming its superior nitrogen availability. Previous studies emphasize that low-nitrogen substrates, such as SH, may require co-feeding with nitrogen-rich materials to improve BSFL biomass yield and frass quality (Surendra *et al.*, 2016). Phosphorus levels followed the same trend, with DC containing 3.00% compared to only 1.02% in SH.

Overall, the findings suggest that DC is a nutrient-rich substrate with higher nitrogen and phosphorus contents, while SH provides substantial organic matter but limited macronutrients. Their complementary characteristics support the combined use of DC and SH in BSFL rearing and frass production, where DC supplies essential nutrients and SH contributes bulk organic material, ultimately producing a balanced organic amendment for soil fertility improvement.

Table 4.3: Selected chemical properties of frass (sago *hampas* and decanter cake) after 52 days of rearing

Variables	T1	T2	T3	T4	T5
Colour	very dark brown	very dark brown	very dark brown	very dark brown	very dark brown
pH in water	7.4 ± 0.06a	7.40 ± 0.0ab	7.40 ± 0.03ab	7.30± 0.0bc	7.16± 0.03c
pH in KCl	7.8 ± 0.0a	7.66 ± 0.03ab	7.63 ± 0.03b	7.63± 0.33b	7.46± 0.03c
Cation exchange capacity (cmol ₍₊₎ kg ⁻¹)	4.0 ± 0.32a	14.6 ± 2.53a	8.56 ± 0.788a	25.55 ± 0.44a	10.33 ± 1.31a
Electrical conductivity (µS cm ⁻¹)	3.03 ± 13.33a	2.77 ± 5.77b	2.71 ± 8.82b	2.96 ± 41.76a	2.97 ± 52.06a
Total organic carbon (%)	23.57 ± 0.04a	22.30 ± 0.54ab	20.21 ± 0.49b	24.24 ± 0.63a	22.47 ± 0.38a
Total organic matter (%)	40.54 ± 0.07a	38.37 ± 0.94ab	34.76 ± 0.84b	41.70 ± 1.09a	38.65 ± 0.66a
Total nitrogen (%)	2.83 ± 0.06ab	2.66 ± 0.12b	2.31 ± 0.04c	2.62 ± 0.02bc	3.31 ± 0.02a
C/N ratio	8.32 ± 0.04ab	8.43 ± 0.54ab	8.73 ± 0.49a	11.68 ± 2.85a	14.66 ± 2.04b
Total phosphorus (mg kg ⁻¹)	0.12 ± 0.00b	0.12 ± 0.0b	0.12 ± 0.00b	9.23 ± 0.63b	7.16 ± 0.38a
Total potassium (mg kg ⁻¹)	251 ± 0.02a	206.8 ± 0.04a	186.9 ± 0.02a	204.2 ± 0.3a	286.0 ± 0.04a

Note: All analyses are based on dry weight. Means (value ± standard error)

4.3.2 Effect of Larval Density on BSF Frass Properties

The production of frass from decanter cake and sago *hampas* significantly affected the frass pH after 45 days of BSFL rearing. The pH in KCl showed distinct variations among treatments. Treatment F1 (5 g larvae) recorded the highest pH compared to other treatments (F2, F3, F4, and F5). Treatment F2 (10 g larvae) was significantly higher than F3, F4, and F5, but lower than F1. There was no significant difference between F3 (15 g larvae) and F4 (20 g larvae), both of which were higher than F5 but lower than F1 and F2. Treatment F5 (25 g larvae) showed the lowest pH among all treatments. These results suggest that larval density influences frass alkalinity, with higher larval biomass leading to reduced pH. Although all treatments used the same feed substrate (decanter cake + sago *hampas*), the larval density (biomass per unit feed) significantly influenced frass pH due to metabolic, microbial, and nutrient transformation dynamics. Higher larval densities (F4, F5) accelerate feed consumption and stimulate intensive microbial fermentation, accumulating organic acids (such as lactic, acetic, and formic acids), which lower the pH. At lower densities (F1, F2), the rate of acid accumulation is slower, maintaining a relatively higher frass pH. This agrees with reports that larval density affects fermentation intensity and acid formation in frass (Parodi *et al.*, 2020; Klammsteiner *et al.*, 2020). Larval density shapes the microbial community in frass. Lower densities promote balanced microbial activity, whereas high densities favor acidogenic microbes due to oxygen depletion and rapid substrate turnover. This microbial shift is linked with reduced frass pH in high-density treatments (Gold *et al.*, 2020; Lalander *et al.*, 2019). Even with identical feed, larval density altered the balance between alkalizing factors (ammonia release, buffering minerals) and acidifying processes (organic acid accumulation, microbial fermentation). Lower densities (F1, F2) favored

alkalinity, while higher densities (F4, F5) promoted acidification, explaining the observed pH differences.

The treatment effect on total carbon (TC) and organic matter (OM) (Figure 3) showed that F1, F4, and F5 had significantly higher TC and OM compared to F2 and F3. F2 was higher than F3 but lower than F1. Treatment F3 had the lowest TC and OM among all treatments. This aligns with previous findings that BSF frass properties vary with substrate and larval density, where diet composition influences the frass nutrient profile and pH (Beesigamukama *et al.*, 2020; Basri *et al.*, 2022; Daniel Gärttling & Hannes, 2021). BSFL metabolism drives organic carbon loss through CO₂ emission. At moderate densities (F2, F3), active feeding accelerates respiration and microbial degradation, thereby reducing residual TC and OM. At higher densities (F4, F5), overcrowding may reduce individual feeding efficiency, leaving more undecomposed organic residues, which explains the elevated TC and OM compared to F2 and F3. This pattern aligns with Basri *et al.* (2022), who reported that larval feeding intensity influences carbon stabilization in frass.

The effect of treatments on total nitrogen (N), phosphorus (P), and potassium (K) (Table 4.3) further confirmed the nutrient-rich nature of BSF frass. Treatment F5 (25 g larvae) recorded the highest N and P compared to all other treatments (F1–F4). F1 was significantly higher than F2, F3, and F4 but lower than F5. F4 was higher than F3 but significantly lower than F1, F2, and F5. F3 showed the lowest N among all treatments. For phosphorus, F5 again showed the highest value, while no significant differences were observed among F1–F4. For potassium, no significant difference was observed across all treatments. These results are consistent with Beesigamukama *et al.* (2020) and Anyega *et al.*

(2021), who highlighted BSF frass as a nitrogen- and phosphorus-rich organic fertilizer that improves crop yield and soil fertility. The highest N and P content in F5 can be attributed to intense substrate processing at high larval density. With more larvae, a larger fraction of the feed was rapidly metabolized, releasing nitrogen and phosphorus compounds into the frass. High larval biomass accelerates microbial mineralization and excretion of nitrogenous waste (ammonium, uric acid) and phosphate compounds, resulting in nutrient-rich frass (Beesigamukama *et al.*, 2020; Anyega *et al.*, 2021). However, this also coincided with lower pH, suggesting that higher metabolic activity increased acidification, which helped solubilize more P into available forms. Despite the low larval biomass, F1 recorded N and P levels almost comparable to F5. This is explained by lower consumption efficiency and reduced nutrient uptake by larvae, meaning that more nutrients remained unassimilated in the frass. With fewer larvae competing for nutrients, the feed was underutilized, and undegraded organic material retained more nitrogen and phosphorus, giving rise to relatively high nutrient concentrations in the frass. This pattern reflects an inverse relationship where both very low and very high larval densities can produce nutrient-rich frass, but through different mechanisms, nutrient conservation in low density (F1) versus accelerated nutrient release in high density (F5). At moderate larval densities (10–20 g), nutrients were more efficiently assimilated into larval biomass, leaving less available N and P in the frass. F3 (15 g larvae) recorded the lowest N, reflecting optimal uptake by larvae, consistent with reports that medium larval densities maximize nutrient conversion into biomass rather than frass (Gold *et al.*, 2020; Beesigamukama *et al.*, 2020).

The effect of treatments on aluminum (Al), calcium (Ca), and zinc (Zn) (Figure 5) revealed that there were no significant differences in Al and Ca across all treatments (F1–F5). However, zinc content was significantly highest in F5, followed by F4, then F3, with F1 and F2 showing the lowest Zn concentrations. Zinc is essential for plant enzymatic processes (Hassan *et al.*, 2020), while calcium improves soil structure and organic carbon stabilization (Bronick & Lal, 2005). The presence of these micronutrients in BSF frass highlights its importance as an organic amendment in enhancing soil fertility and plant growth (García-Sánchez *et al.*, 2014; Zhu *et al.*, 2020).

The results demonstrate that BSFL bioconversion of decanter cake and sago *hampas* produces frass with improved nutrient availability, stable organic matter, and a near-neutral pH. This transformation addresses the disposal challenge of agro-industrial wastes and creates a sustainable organic fertilizer. The improved nutrient profile of frass aligns with the objectives of sustainable soil management in tropical regions, where soils are often acidic and nutrient-depleted (Jien & Wang, 2013). The co-utilization of DC and SH ensures a balance of carbon and nitrogen, supporting larval growth while producing a frass that enhances soil fertility. Moreover, the increased CEC and stable organic matter content indicate potential long-term benefits for soil health, water retention, and crop productivity (Agegnehu *et al.*, 2017).

This study validates the role of BSFL as a sustainable bioconversion agent for agroindustrial residues by achieving the objective of producing frass from decanter cake and sago *hampas*. It also supports circular bioeconomy initiatives by turning waste into valuable

biofertilizer, reducing reliance on synthetic fertilizers, and mitigating environmental pollution (Paritosh *et al.*, 2020; Gold *et al.*, 2020).

4.4 Conclusion

In summary, the findings of this study affirm the potential of agro-industrial by-products, specifically decanter cake and sago *hampas*, as valuable resources for sustainable soil management when transformed into biochar and frass. The production of decanter cake biochar (DC biochar) successfully achieved the objective of generating a soil amendment with favorable physicochemical properties, including high porosity, enhanced water retention, and increased nutrient-holding capacity. Its ability to reduce aluminum and iron toxicity while improving phosphorus availability is particularly effective for ameliorating nutrient-deficient tropical acid soils. Similarly, the bioconversion of decanter cake and sago *hampas* through black soldier fly larvae (BSFL) yielded nutrient-enriched frass with a near-neutral pH, improved cation exchange capacity, and balanced C/N ratios, meeting the requirements of an efficient organic fertilizer. Among the treatments, frass from T5 emerged as the most promising formulation, showing the highest total nitrogen (3.31%), phosphorus (7.16 mg kg⁻¹), and potassium (286 mg kg⁻¹), alongside a stable pH and favorable C/N ratio. These attributes highlight T5 frass as the most effective organic fertilizer candidate for improving soil fertility and supporting crop growth. These results demonstrate the effectiveness of both DC biochar and BSFL-derived frass in improving soil fertility, water retention, and overall soil health, contributing to healthier root systems, enhanced crop yields, and greater resilience against soil degradation and drought stress. Beyond soil improvement, these transformations provide an integrated waste management strategy that

aligns with circular bioeconomy principles, converting agricultural residues into high value biofertilizers while minimizing environmental impact. Thus, the outcomes of Chapter 4 underscore the dual role of biochar and frass, particularly the recommended T5 frass, as sustainable solutions for addressing soil fertility challenges in tropical agriculture, paving the way for their broader application in sustainable farming systems.

CHAPTER 5

CO-APPLICATION OF BLACK SOLDIER FLY FRASS, DECANter CAKE BIOCHAR, AND CHEMICAL FERTILIZERS FOR THE GROWTH OF MAIZE (*ZEa MAYS L.*) CULTIVATION

5.1 Introduction

Agricultural wastes such as decanter cake (DC) and sago *hampas* present critical management and sustainability challenges for agro-industrial sectors in Southeast Asia. OPDC, a fibrous by-product generated during palm oil milling, is produced in substantial quantities and is often disposed of through land application or open dumping, leading to soil and water contamination (Ong, Hamzah, & Che Man, 2021). Similarly, sago *hampas*, the starchy residue from sago starch extraction, accumulates in large volumes, posing risks of fermentation and greenhouse gas emissions if improperly managed (Ghodake *et al.*, 2021). These lignocellulosic residues are rich in organic matter and nutrients, making them promising candidates for valorization as soil amendments or bio-based products. Recent studies have explored their use in biofuel production and as bioactive compound sources; however, technological and economic barriers such as high processing costs, low productivity, and product inhibition limit large-scale utilization (Ghodake *et al.*, 2021; Ong *et al.*, 2021). Therefore, converting DC and sago *hampas* into value-added products, such as biochar and organic fertilizers, offers a sustainable strategy to reduce environmental burdens while improving soil health and supporting circular bioeconomy initiatives.

In this context, the Black Soldier Fly Larvae (BSFL) bioconversion process has emerged as a promising biotechnology for agricultural waste valorisation. Studies have shown that BSFL can efficiently convert diverse organic residues into nutrient-rich frass and larval biomass (Liu *et al.*, 2018; Ravi *et al.*, 2020). This process not only reduces the environmental burden of agricultural waste but also generates valuable inputs for farming. Research by Peguero *et al.* (2022) further demonstrated that pretreatment strategies could enhance the efficiency of BSFL-mediated bioconversion, while Purnamasari and Khasanah (2022) reported that BSFL bioconversion releases fewer greenhouse gases compared to conventional composting methods, making it a more environmentally sound approach.

The frass derived from BSFL has attracted considerable attention as a potential organic fertilizer. According to Basri *et al.* (2022) emphasized that BSF frass, particularly when sourced from food waste, contains beneficial properties that can improve soil fertility and plant growth. Similarly, Menino *et al.* (2021) demonstrated its positive effects on ryegrass cultivation, while Lopes *et al.* (2022) critically reviewed its role in sustainable soil management. Several experimental studies further support these findings, highlighting the potential of BSF frass to enhance nutrient availability and crop productivity when applied as a soil amendment (Chiam *et al.*, 2021; Susanto *et al.*, 2022; Rejeki *et al.*, 2023; Arabzadeh *et al.*, 2022; Naser El Deen *et al.*, 2023).

Complementary to frass, biochar derived from decanter cake has also been recognized as a soil amendment capable of improving soil structure, nutrient retention, and cation exchange capacity. When applied in combination with organic and chemical fertilizers, biochar can enhance soil health while reducing nutrient leaching losses. Thus,

integrating BSF frass with decanter cake biochar and conventional fertilizers presents a novel co-application strategy for sustainable crop cultivation. Given the global significance of maize (*Zea Mays L.*) as a staple food and feed crop, exploring this integrated approach in maize cultivation holds great promise. Co-application of frass, biochar, and chemical fertilizers is expected to not only improve maize growth performance but also address the dual challenge of waste management and soil fertility enhancement.

In Chapter 5, the third objective of the study was conducted, which is to investigate the effectiveness of this co-application strategy, aiming to assess its potential as a sustainable solution for both agricultural waste valorisation and crop productivity improvement.

5.2 Materials and Methods

Figure 5.1 shows the flowchart of the overall methodology outlining the sequential processes involved in the study. It begins with soil sampling and preparation, soil characterization, and fertilizer amendment, followed by the laboratory incubation study, pot experiment, harvesting, and subsequent soil and plant analyses.

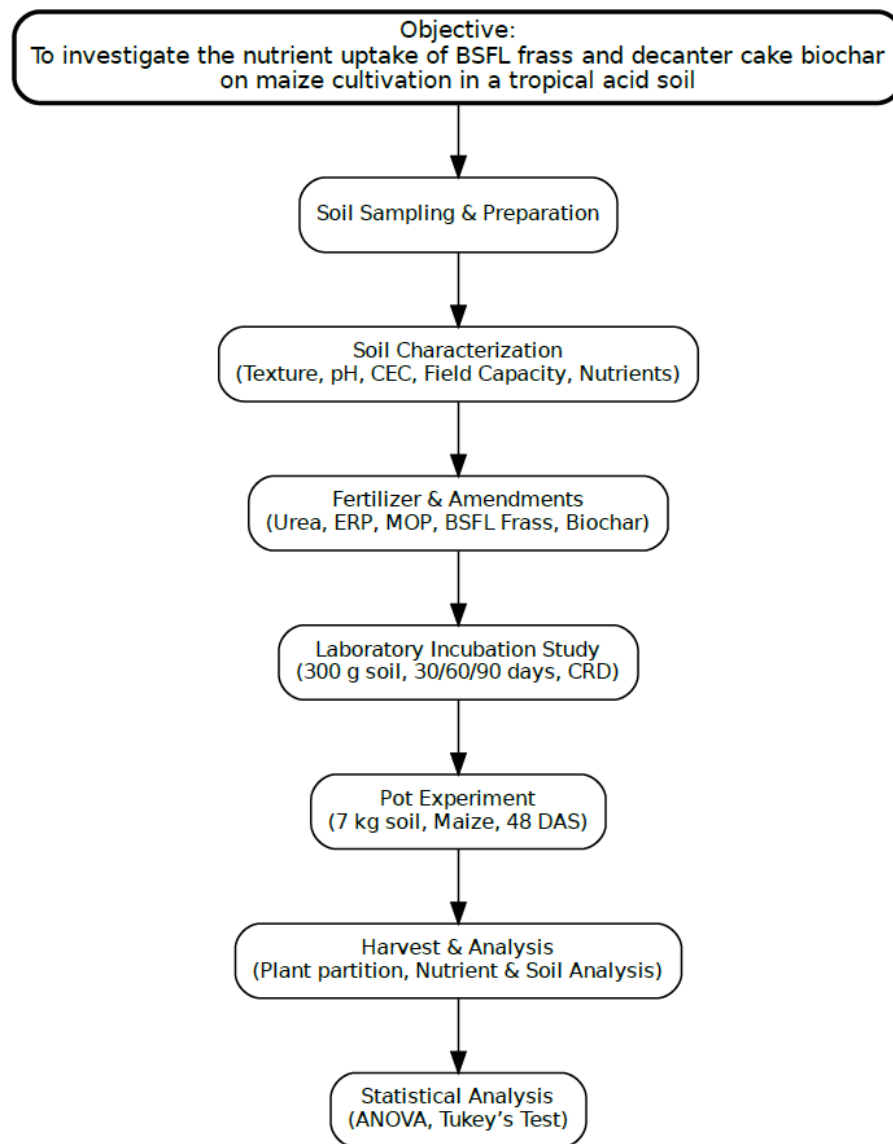


Figure 5.1: Methodology flowchart for BSFL frass, biochar, and fertilizer effects on maize cultivation.

5.2.1 Soil Sampling and Preparation

Soil sampling, BSF frass, and the sources of NPK fertilizers were used. The application of Urea (46% N), Egyptian Rock Phosphate (ERP) (28% P_2O_5), and Muriate of Potash (MOP) (60% K_2O) was applied at 60 kg N ha⁻¹, 60 kg P_2O_5 ha⁻¹, and 40 kg K_2O ha⁻¹. These rates were based on the recommendation of MARDI (1993). These fertilizers were chosen because they supply the primary macronutrients required for maize (*Zea Mays L.*) production for nitrogen (N), phosphorus (P), and potassium (K). Nitrogen is vital for leaf development and chlorophyll formation, phosphorus supports root growth and grain development, while potassium enhances stress tolerance, water-use efficiency, and kernel quality. Soil texture was determined using the hydrometer method (Bouyoucos, 1962), while its field capacity and bulk density were determined following Tan (2005). The pH of the soil was determined in a ratio of 1:2 (soil: distilled water) suspension and 1 M KCl solution using a glass electrode (Peech, 1965).

5.2.2 Determination of Soil Texture

The Bouyoucos Hydrometer Method (Bouyoucos, 1962) was employed in determining soil texture. A 50 g soil sample was weighed and placed in a blender cup. Distilled water was introduced into the sample, filling it up to a height of 10 cm from the top. Then, 4 drops of a 3 M NaOH solution were added and stirred. The combination was agitated incessantly until the soil suspension reached a pH of 10. Subsequently, the concoction was agitated mechanically for 15 minutes. Following this, it was transferred to a measuring cylinder with a capacity of 1000 mL, and the volume was adjusted to get a final

measurement of 1130 mL. The dirt suspension was agitated incessantly to achieve a uniform mixing. Subsequently, a hydrometer was employed to ascertain the initial measurement after 40 seconds.

The suspension was agitated six times, and after 40 seconds, the hydrometer was introduced into the suspension to get the subsequent measurement. The suspension temperature was measured after removing the hydrometer from the suspension. The average of two measurements yielded the quantities of silk and clay in grams for the soil sample. After allowing the suspension to settle for 2 hours, it was thoroughly agitated, and the third measurement was taken to determine the quantity of clay in grams. The suspension's temperature was promptly measured after immersing the hydrometer into it for each reading, as the hydrometer was calibrated at 20°C.

5.2.3 Determination of Soil Field Capacity

Field capacity is the quantity of water that remains in the soil after preventing any further soaking of the soil sample (Tan, 2005). The soil field capacity was measured using a graduated cylinder (Tan, 2005). This approach entails computing the water percolation in a graduated cylinder. A 50 g substance was filtered using a funnel and collected in a measuring cylinder with 50 mL of pure water. The water removed from the soil due to gravitational forces was defined as the soil's field water capacity.

5.2.4 Determination of Cation Exchange Capacity (CEC) of Soil

The soil CEC was assessed by extracting the soil samples with 100 mL of a 1 M NH_4OAc buffer solution, which was adjusted to a pH of 7.0 for 5 to 6 hours (Cottenie, 1980). A sheet of Whatman filter paper No. 2 was positioned at the base of a leaching tube. Subsequently, a 10 g soil sample was deposited into the tube and coated with another layer of filter paper. Subsequently, the soil sample was rinsed with 30 mL of 95% ethanol, and the resulting liquid was gathered in a 100 mL volumetric flask and filled to its maximum capacity.

10 mL of the sample (from leachate) was pipetted into the distillation flask, and then 10 mL of 40% NaOH was added. The samples underwent a 5-minute distillation process and were then collected using 10 mL of a solution containing 2% boric acid, along with bromocresol green and methyl red indicators. Next, the distillate was titrated using a 0.01 M hydrochloric acid (HCl) solution.

5.2.5 Determination of pH

The glass electrode was used to measure soil pH levels, BSFL frass, and biochar. 10 g of each m were weighed and placed in disposable vials. 20 mL of distilled water and KCl were introduced individually and agitated at a speed of 180 rpm for 15 minutes, as described by Peech in 1965. The KCl readings were acquired following a 15-minute settling period for the samples, whereas the pH in water was measured after 24 hours. The pH measurement

was recorded using a digital pH meter, the Thermo Scientific Eutech TM Expert pH Pocket Tester model.

5.2.6 Determination of Total Carbon (TC), Total Nitrogen (N), and Organic Matter (OM)

Soil, BSFL frass, and biochar of C, N, and organic matter were determined using CHNS. A 2.5 mg ground soil was placed on the loading head of the machine. Samples were combusted at 1000°C. and the total C and N readings were obtained directly from computer software. The loss of weight presented the weight of C, and organic matter content was estimated by multiplying organic matter value; 58% of organic matter is carbon (Cheftetz *et al.*, 1996). The reading was recorded using the computer software Flash Smart Elemental Analyzer (Thermo ScientificTM).

5.2.7 Determination of Available Phosphorus (P)

The Double Acid Method (Tan, 2005) has been used to extract phosphorus (P). 5 g of soil, BSFL frass, and biochar were measured and deposited into a 250 mL Erlenmeyer flask. The user added a 20 mL extraction solution and mechanically shook it at 180 rpm for 10 minutes. Subsequently, the liquid portion was passed through a Whatman filter paper No.2. A pipette transferred 4 mL of the supernatant into a 50 mL volumetric flask.

Stock solutions of acid molybdate (Reagent A) and ascorbic acid (Reagent B) were produced for the colour development operation. Two standard solutions, 1 and 2, were created and utilized to create working solutions with concentrations ranging from 0 to 0.6 parts per million (ppm). Using a micropipette, 0, 1, 2, 3, 4, 5, and 6 mL of standard solution 2 were transferred into a 50 mL volumetric flask. 8mL of Reagent B was introduced into the blue standard solution.

4 mL of the extract was transferred into a 50 mL volumetric flask and combined with a solution of ammonium molybdate ($(\text{NH}_4)_6\text{MO}_7\text{O}_{24}$) containing H_2SO_4 , as well as 4 mL of the antimony-ascorbic acid combination. The solution was diluted with distilled water, and the development of the maximum blue hue was permitted (Murphy & Riley, 1962). The measurement of absorbance was conducted at a wavelength of 840 nm. A standard curve was generated by transferring 0, 1, 2, 3, 4, 5, and 6 mL of the P standard solution into seven sets of 50 mL volumetric flasks using a pipette. The spectrophotometry technique was used to measure the samples, which included a standard solution (Murphy & Riley, 1962). The reading was recorded using computer software, and a Cary 60 UV-Vis spectrophotometer was used to determine the P concentration.

5.2.8 Determination of Exchangeable Potassium (K)

The Ammonium acetate Method (Tan, 2005) has been used to ascertain the levels of exchangeable potassium (K), calcium (Ca), and magnesium (Mg) in the soil. A 10 g soil, BSFL frass, and biochar sample were introduced into a leaching tube and subjected to

leaching using a 100 mL solution of NH_4OAc for 5 to 6 hours. Subsequently, the soil was rinsed with 95% ethanol and leached again using a 100 mL solution of 0.1 M K_2SO_4 . The levels of exchangeable calcium (Ca), magnesium (Mg), and potassium (K) were measured using atomic absorption spectrophotometry using the Analyst 800 instrument from Perkin Elmer Instruments, located in Norwalk, CT.

5.2.9 Determination of Exchangeable Ammonium (NH_4^+) and Available Nitrate (NO_3^-)

The Keeney and Nelson (1982) method was employed to extract exchangeable NH_4^+ and accessible NO_3^- ions, and their concentrations were measured using steam distillation. A 5 g soil sample was subjected to extraction with 50 mL of a 2 M KCl solution. The mixture was agitated for one hour on a mechanical shaker and subsequently filtered using Whatman filter paper No. 2. The concentration of NH_4^+ ions that can be exchanged was measured by transferring 20 mL of extractant into a distillation tube, then adding 0.2 g of MgO and distilling the mixture for 5 minutes. A solution containing 10 mL of boric acid and bromocresol green, and methyl red indicators was utilized to capture NH_4^+ . Subsequently, the distillation process was extended by introducing 0.2 g of Devarda's alloy to the sample, and the distillation continued for an additional 5 minutes. The NH_4^+ and NO_3^- distillates were titrated using a 0.01 M HCl solution.

5.2.10 Statistical Analysis

Experimental designs were arranged in a completely randomized design (CRD) with three replications for each treatment. Statistical Analysis System software version 9.4, one-way analysis of variance (ANOVA) was used to detect treatment effects, and Tukey's test was employed to compare treatment means at P 0.05.

5.2.11 Laboratory Incubation Study

A soil incubation experiment was conducted in the Environmental Laboratory II at the Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS). From the bulked soil, 300 g of air-dried soil was weighed for each replicate and placed in a plastic container (14 cm diameter $\times$ 8.5 cm height). Fertilizers were applied following MARDI's (1993) recommendation at 60 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹ using urea (46% N), ERP (28% P₂O₅), and MOP (60% K₂O). BSF frass and decanter cake biochar were applied at 10 t ha⁻¹ and 20 t ha⁻¹, respectively, based on recommendations for maize cultivation (Zhang *et al.*, 2012; John *et al.*, 2013) with treatments fixed at 50% and 100% in Table 5.1. The fertilizers and frass were thoroughly mixed with soil, alongside a control (F0B0C0) and a treatment with only urea, MOP, and ERP (F0B0C1). The incubation study consisted of three batches (30, 60, and 90 days) with eight treatments each, arranged in a completely randomized design (CRD) and replicated three times.

Table 5.1: Set up and layout of laboratory incubation study

Treatments	Soil (g)	BSFF (g)	DC Biochar (g)	Urea (g)	ERP (g)	MOP (g)
F0B0C0	300	0	0	0	0	0
F0B0C1	300	0	0	5 g	8.24 g	2.58 g
F1B0C0	300	14.40 g	0	0	0	0
F0B1C0	300	0	28.80 g	0	0	0
F2B2C2	300	7.20 g	14.40 g	2.5 g	4.12 g	1.29 g
F2B0C2	300	7.20 g	0	2.5 g	4.12 g	1.29 g
F0B2C2	300	0	14.40 g	2.5 g	4.12 g	1.29 g
F2B2C0	300	7.20 g	14.40 g	0	0	0



Figure 5.2: The treatment arrangement of the incubation study in the laboratory
(Image by Deborah Renting Jimmy, 2025)

5.2.12 Pot Study Set-up

A pot experiment was conducted in a net house at the Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS), using Thai Super Sweet hybrid F1 maize (*Zea Mays* L.) as the test crop due to its sensitivity in reflecting nutrient uptake, recovery, efficiency, and deficiency response. Each pot (22 × 30 × 30 cm) was filled with 7 kg of bulked soil sieved to 5 mm. Fertilizers were applied following MARDI's (1993) recommendation at 60 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹ using urea (46% N), ERP (28% P₂O₅), and MOP (60% K₂O), split between 10 and 28 days after sowing. BSF frass and decanter cake biochar were applied at 10 t ha⁻¹ and 20 t ha⁻¹, respectively, based on recommendations for maize cultivation (Zhang *et al.*, 2012; John *et al.*, 2013). The fertilizer rates in Table 5.2 were reduced to 50% to test the potential of frass and biochar as partial substitutes for chemical fertilizers, to sustain crop growth while improving soil fertility, nutrient use efficiency, and reducing the environmental and economic costs of conventional fertilizer use.

Table 5.2: Treatments evaluated in the pot experiment

Treatments	Soil (kg)	BSFF (g)	DC Biochar (g)	Urea (g)	ERP (g)	MOP (g)
F0B0C0	7	0	0	0	0	0
F0B0C1	7	0	0	5 g	8.24 g	2.58 g
F1B0C0	7	14.40 g	0	0	0	0
F0B1C0	7	0	28.80 g	0	0	0
F2B2C2	7	7.20 g	14.40 g	2.5 g	4.12 g	1.29 g
F2B0C2	7	7.20 g	0	2.5 g	4.12 g	1.29 g
F0B2C2	7	0	14.40 g	2.5 g	4.12 g	1.29 g
F2B2C0	7	7.20 g	14.40 g	0	0	0

The soil, urea, ERP, MOP, compost, and biochar were thoroughly mixed. Maize seeds were soaked in water for 24 hours before sowing. This was done to ensure good germination and plant establishment. The sowing depth was 4 cm. The seeds were sown in planting holes (1 seed per hole), after which the holes were partially covered with loose soil. Five seeds were sown per pot and thinned to two seven days after sowing (DAS). The pot experiment was conducted in a completely randomized design with three replications. The soil moisture was maintained at 70% field capacity throughout the pot experiment. The plants were monitored for 48 days. At the tasseling stage (48 DAS), the plants were harvested and partitioned into leaves, stems, and roots. The plant parts were oven-dried at 60°C until constant weight was attained, after which their dry weight was determined using a digital balance. At tasseling (48 DAS), soil samples were collected, air-dried, crushed, and sieved to pass through a 2 mm sieve. Afterward, the soil samples were analyzed for pH, exchangeable Al, total N, total P, available P, and cations (K, Ca, Mg, and Fe) using previously cited methods. The single dry ashing method (Cottenie, 1980) was used to extract P, K, Ca, and Mg in the plant tissues (roots, leaves, and stems). The filtrates for K, Ca, and Mg were analyzed using AAS. Phosphorus was determined using the blue method (Murphy & Riley, 1962). Total N was determined using the micro-Kjeldahl method (Bremner & Lees, 1949). The concentrations of N, P, K, Ca, and Mg in roots, leaves, and stems were multiplied by the respective dry weight of the plant parts to obtain the amounts of N, P, K, Ca, and Mg taken up by the maize plants.

5.2.13 Harvesting of Maize Plant

During the tasselling stage, the maize plants were collected and divided into their respective components: leaves, stems, and roots. The various components of the maize plant were subjected to oven drying at 60 °C until a consistent weight was achieved. Subsequently, the dry weight of each component was measured using a digital scale. The process involved the collection of soil samples, which were then dried in the air, powdered, and passed through a sieve with a 2 mm mesh size.



Figure 5.3: Harvesting of the maize plant at 52 days.

(Image by Deborah Renting Jimmy, 2025)

5.3 Results and Discussions

5.3.1 Initial Soil Chemical Properties

The selected physico-chemical properties of the soil used in both the incubation (Chapter 4) and pot experiment (Chapter 5) are presented in Table 5.3. The soil texture was classified as sandy loam with 33.8% sand, 46.0% silt, and 20.2% clay. Sandy loam soils generally exhibit moderate water-holding capacity and good aeration, which are suitable for maize growth but typically require additional nutrient inputs due to relatively low inherent fertility compared to clay-rich soils (Brady & Weil, 2016). The soil pH in water was 6.6 (near neutral), while the pH in KCl was 4.66, reflecting the presence of exchangeable acidity. This condition is common in tropical soils, where aluminum ions (Al^{3+}) occupy exchange sites and lower the effective pH (Gillman & Sumner, 1987).

Table 5.3: Selected physico-chemical properties of soil

Properties	Value Obtained
Soil texture	Sand: 33.8% Silt: 46.0% Clay: 20.2% Sandy Loam
pH in water	6.6 $\pm$ 0.0
pH in KCl	4.66 $\pm$ 0.02
Total Carbon (%)	2.3 $\pm$ 0.88
Total Nitrogen (%)	0.07 $\pm$ 1.58
Total Phosphorus (%)	0.03 $\pm$ 1.00
Total Potassium (%)	0.02 $\pm$ 0.58
C: N ratio	32.85 $\pm$ 2.58
Available Phosphorus (mg kg ⁻¹)	4.5 $\pm$ 1.88
CEC (cmol (+) kg ¹)	4.40 $\pm$ 0.66
Exchangeable Al (mg kg ⁻¹)	0.32 $\pm$ 0.32
Exchangeable Fe (mg kg ⁻¹)	0.03 $\pm$ 0.64
Exchangeable K (mg kg ⁻¹)	0.4 $\pm$ 0.04
Exchangeable Ca (mg kg ⁻¹)	0.20 $\pm$ 0.02
Exchangeable Na (mg kg ⁻¹)	0.03 $\pm$ 0.99

Note: Values are expressed on a dry-weight basis (mean $\pm$ standard error).

The total carbon content (2.3%) suggests a moderate level of soil organic matter, which improves soil structure, microbial activity, and water retention (Lal, 2020). However, the C:N ratio of 32.85 is relatively high, indicating potential nitrogen immobilization during organic matter decomposition, which could temporarily limit N availability to crops (Fageria, 2012).

Nutrient concentrations were generally low. Total nitrogen (0.07%), total phosphorus (0.03%), and total potassium (0.02%) indicate limited reserves of essential macronutrients. Available phosphorus was also low (4.5 mg kg⁻¹), consistent with the strong P-fixation tendencies in acidic tropical soils (Sanchez, 2019). Similarly, the cation exchange capacity (CEC) of 4.40 cmol (+) kg⁻¹ is considered low, suggesting limited capacity to retain and supply essential nutrients such as Ca²⁺, Mg²⁺, and K⁺ (Hazelton & Murphy, 2016).

Exchangeable cations provided further insights into soil fertility. Exchangeable aluminum (0.32 cmol (+) kg⁻¹) confirmed the acidic nature of the soil and the risk of aluminum toxicity to root development if unmanaged (von Uexküll & Mutert, 1995). Potassium (0.40 cmol (+) kg⁻¹) and calcium (0.20 cmol (+) kg⁻¹) were present at low to moderate levels, insufficient for sustaining nutrient-demanding crops such as maize (Dobermann & Fairhurst, 2000). Sodium (0.03 cmol (+) kg⁻¹) was very low, which is beneficial since excessive Na can deteriorate soil structure and permeability (Rengasamy, 2010).

Therefore, the initial soil characteristics suggest that while the soil has a favorable texture and near-neutral pH in water, it is nutrient-deficient with low CEC and high C:N ratio. These limitations highlight the need for external nutrient inputs, including chemical fertilizers (urea, MOP, ERP) and organic amendments (BSFL frass, biochar), to enhance soil fertility and sustain maize production.

5.3.2 Selected Chemical Properties of BSFL Frass and Decanter Cake Biochar

The chemical characteristics of BSFL frass and decanter cake biochar are presented in Table 5.4. The pH of BSFL frass in KCl and water was 7.46 and 7.16, respectively, indicating a near-neutral reaction. When applied to soil, frass with this pH can help buffer slightly acidic or alkaline soils, thereby creating a more favourable environment for nutrient availability and microbial activity. In contrast, the biochar exhibited a much higher pH, with values of 9.40 in KCl and 9.00 in water, reflecting strong alkalinity. Such alkaline biochar is particularly beneficial for ameliorating acidic soils by raising soil pH, reducing aluminium toxicity, and enhancing the solubility of key nutrients like phosphorus.

Table 5.4: Selected chemical properties of BSFL frass and decanter cake biochar

Properties	BSFL Frass	DC Biochar
pH (KCl)	7.46 ± 0.03	9.40 ± 0.03
pH (dH ₂ O)	7.16 ± 0.03	9.00 ± 0.1
Organic Matter (%)	38.65 ± 0.66	35.56 ± 0.41
Total Carbon (%)	22.47 ± 0.38	61.16 ± 0.71
Exchangeable ammonium (%)	nd	29.18 ± 4.67
Available Nitrate	nd	19.84 ± 3.08
Cation Exchange Capacity (cmol) (%)	10.33 ± 0.02	nd
Total Nitrogen (%)	3.13 ± 0.02	3.33 ± 0.05
Total Phosphorus (%)	4.40 ± 0.02	0.40 ± 0.18
Total Potassium (%)	4.50 ± 0.06	2.50 ± 0.02

Note: Values are based on dry weight; mean ± standard error. nd is not determined.

The organic matter (OM) content of BSFL frass (38.65%) was slightly higher than that of decanter cake biochar (35.56%), although the total carbon (C) content of biochar (61.16%) was nearly three times greater than that of frass (22.47%). This reflects a fundamental difference in their roles: BSFL frass primarily functions as a nutrient source, whereas biochar contributes more towards long-term carbon sequestration, improved soil structure, and enhanced cation exchange capacity (CEC) (Lehmann & Joseph, 2015; Beesley *et al.*, 2011).

Notably, frass exhibited a CEC of 10.33 cmol (+) kg⁻¹, indicating its ability to hold and exchange essential cations, which benefits nutrient retention and reduces leaching losses (Nyambo *et al.*, 2021). Nutrient content further differentiates the two amendments. The nitrogen (N), phosphorus (P), and potassium (K) concentrations for BSFL frass were 3.13%, 4.40%, and 4.50%, respectively, compared with 3.33%, 0.40%, and 2.50% in biochar. Thus, frass provides a more balanced NPK profile, especially in terms of phosphorus and potassium, which are critical for maize growth (Fageria, 2012). The relatively higher phosphorus in frass (4.40%) makes it a particularly valuable organic input for tropical soils, which are often phosphorus-deficient (Sanchez, 2019).

Conversely, decanter cake biochar contained much lower available phosphorus but contributed to nutrient stability through its high carbon content and pH-buffering properties (Glaser *et al.*, 2002). When compared with the nutrient requirement for maize (60 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹), BSFL frass demonstrates strong potential as a supplementary fertilizer. Its balanced NPK profile suggests it could partly replace or

complement synthetic fertilizers, especially in meeting phosphorus and potassium demands, which are essential for root development, grain filling, and overall yield (Dobermann & Fairhurst, 2000).

On the other hand, decanter cake biochar is less effective as a direct nutrient source but plays a key role in enhancing fertilizer use efficiency by improving soil properties for nutrient uptake (Lehmann *et al.*, 2011). This synergy between frass and biochar indicates that their combined application could simultaneously address immediate nutrient supply and long-term soil fertility management in maize production systems (Schulz & Glaser, 2012).

5.3.3 Incubation Study

i. Effect of Black Soldier Fly Frass (BSFF), decanter cake biochar, and chemical fertilizers on soil pH

The interaction between the fertilizer treatments and incubation period significantly influenced soil pH in KCl Table 5.4. As shown in Figure 5.4, soils amended with decanter cake biochar (F2B2C2, F0B2C2, and F2B2C0) consistently exhibited the highest pH values across incubation periods compared to other treatments. This alkalizing effect can be attributed to the liming capacity of biochar, which reduces soil acidity by neutralizing exchangeable aluminium (Al^{3+}) and iron (Fe^{3+}). Suppressing Al and Fe hydrolysis decreases H^+ ion release, while the concurrent release of OH^- ions elevate soil pH (Ch'ng *et al.*, 2014a; Tang *et al.*, 1999). In addition to the liming effect, the decomposition of biochar may have

released phenolic and humic-like substances, which contributed organic anions that consumed H^+ ions, further increasing soil pH (Narambuye & Haynes, 2006; Haynes, 2001). This explains why treatments with higher biochar rates (F0B0C1, F2B2C2, and F0B2C2) showed a more pronounced increase in pH compared to those without biochar.

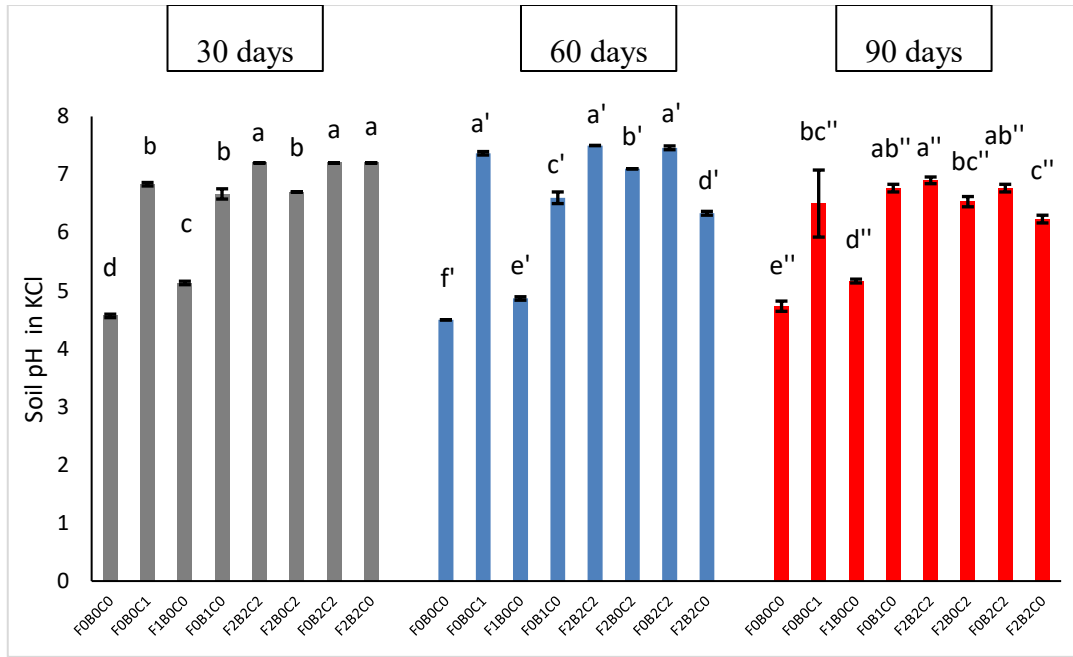


Figure 5.4: Effect of treatments on soil pH (KCl) at 30, 60, and 90 days after incubation (DAI). Different letters above the bars indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$). Error bars represent the mean $\pm$ standard error (SE).

The soil pH patterns observed after 60 and 90 days of incubation largely followed the same trends as those at 30 days, suggesting that the effects of biochar and frass on soil acidity were sustained over time. In particular, the treatments incorporating BSFL frass (F2B0C0 and F2B2C0) maintained moderately higher pH compared to the control (F0B0C0), which can be linked to the mineralization of organic N and the subsequent release of basic cations (Ca^{2+} , Mg^{2+} , K^+) from frass during decomposition. In the early stage (30 days), rapid mineralization of labile organic matter from BSFL frass releases NH_4^+ , Ca^{2+} ,

Mg²⁺, and K⁺, which can temporarily increase pH and CEC. Over time (60–90 days), continued decomposition releases more stabilized forms of nutrients, while microbial activity drives nitrification (NH₄⁺ → NO₃⁻), which produces H⁺ ions, slightly lowering soil pH (Beesigamukama *et al.*, 2020; Basri *et al.*, 2022). Microbial populations adapt to fresh organic inputs within 30 days, but by 60–90 days, microbial succession alters nutrient cycling rates. For instance, fungi tend to dominate later, contributing to lignin and cellulose breakdown, releasing more stabilized organic matter that sustains CEC and soil pH buffering (Lehmann *et al.*, 2011).

The results confirm that biochar serves as a strong pH regulator, while BSFL frass contributes to gradual nutrient-driven alkalization. The combination of frass, biochar, and chemical fertilizers (F2B2C2) provided the most balanced effect, enhancing soil pH buffering capacity while also contributing essential nutrients required for maize cultivation. Therefore, the results confirm that biochar serves as a strong pH regulator, while BSFL frass contributes to gradual nutrient-driven alkalization. The combination of frass, biochar, and chemical fertilizers (F2B2C2) provided the most balanced effect, enhancing soil pH buffering capacity while also contributing essential nutrients required for maize cultivation.

ii. Effect of Different Amounts of Black Soldier Fly Frass, Decanter Cake Biochar, and Chemical Fertilizers on Soil Cation Exchange Capacity (CEC)

As shown in Figure 5.5, the application of BSF frass, decanter cake biochar, and chemical fertilizers had a significant effect on soil CEC across 30, 60, and 90 days of incubation. Among all treatments, F2B2C2 consistently recorded the highest CEC values,

reaching approximately 22.7 cmol/kg at day 90, which was almost double the CEC of the control (F0B0C0). This demonstrates the synergistic effect of frass and biochar, which enhances the retention and exchange of essential cations in soil (Carroll *et al.*, 2023; Mubekaphi *et al.*, 2024).

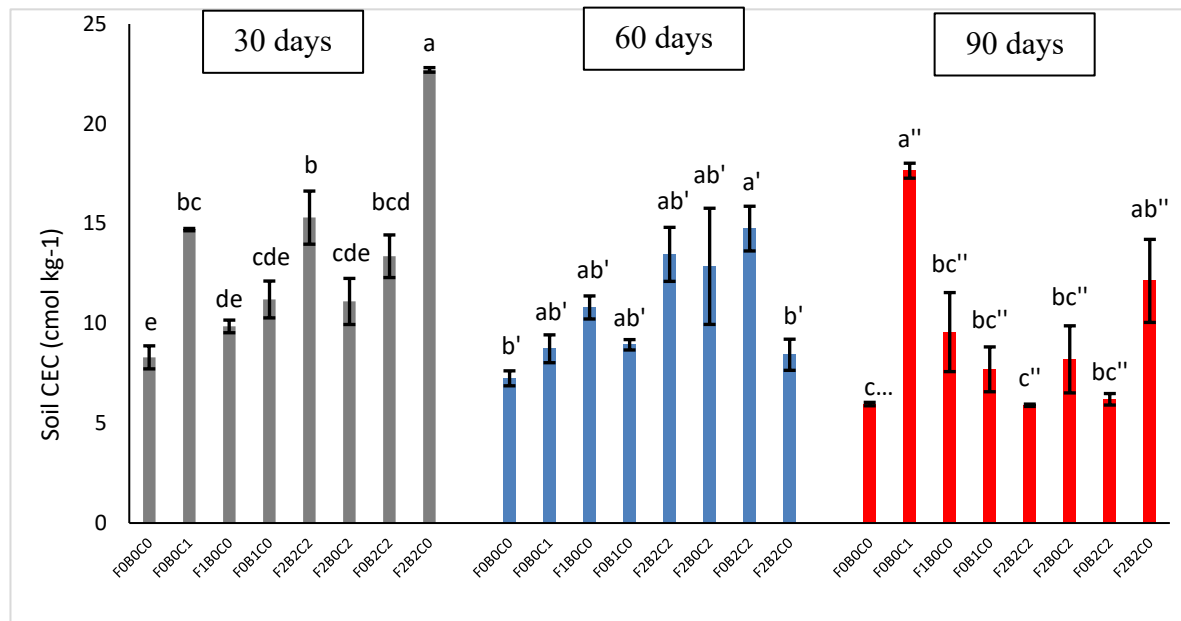


Figure 5.5: Effect of treatments on soil **Cation Exchange Capacity (CEC)** at 30, 60, and 90 days after incubation (DAI). Different letters above the bars indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$). Error bars represent the mean $\pm$ standard error (SE).

In contrast, the control treatment (F0B0C0) exhibited the lowest CEC values throughout the incubation period, with only 9.85 cmol/kg at 60 days. This highlights that chemical fertilizers alone are insufficient in improving the soil's ability to retain cations. By comparison, biochar provides a porous structure and a high surface area capable of adsorbing and retaining nutrient cations such as Ca^{2+} , Mg^{2+} , and K^{+} , which are crucial for plant growth (Abdo *et al.*, 2004).

The application of BSF frass, decanter cake biochar, and chemical fertilizers significantly affected soil CEC across 30, 60, and 90 days of incubation (Figure 5.4). Among all treatments, F2B2C2 consistently recorded the highest CEC values, reaching approximately 22.7 cmol/kg on day 90, which was almost double the CEC of the control (F0B0C0). This demonstrates the synergistic effect of frass and biochar, which enhances the retention and exchange of essential cations in soil (Carroll *et al.*, 2023; Mubekaphi *et al.*, 2024). In contrast, the control treatment (F0B0C0) exhibited the lowest CEC values throughout the incubation period, with only 9.85 cmol/kg at 60 days. This highlights that chemical fertilizers alone are insufficient in improving the soil's ability to retain cations. By comparison, biochar provides a porous structure and a high surface area capable of adsorbing and retaining nutrient cations such as Ca^{2+} , Mg^{2+} , and K^{+} , which are crucial for plant growth (Abdo *et al.*, 2004).

Importantly, the variation in soil pH, CEC, and other measured parameters across 30, 60, and 90 days reflects the dynamic nature of soil–amendment interactions. At 30 days, rapid mineralization of BSF frass released exchangeable cations and readily available nutrients, contributing to an early increase in pH and CEC. By 60 days, biochar's liming effect and surface oxidation processes began to play a stronger role, sustaining soil pH and enhancing CEC through the development of functional groups on biochar surfaces (Liang *et al.*, 2006; Mukherjee & Lal, 2013). At 90 days, the influence of microbial nitrification and gradual nutrient leaching moderated soil pH, yet treatments containing both frass and biochar (e.g., F2B2C2) maintained significantly higher CEC due to their combined effects of nutrient supply and retention. This indicates that frass acts as a source of fast-acting nutrients that

support microbial activity, while biochar contributes to the long-term stabilization and conservation of nutrients within the soil matrix (Agegnehu *et al.*, 2017).

For instance, F0B2C2 (biochar + chemical fertilizer, without frass) recorded a steadily high CEC of 17.6 cmol/kg at 90 days, demonstrating biochar's role in sustaining nutrient retention even without organic frass inputs. The pattern observed confirms that frass and biochar act complementarily: frass supplies nutrients that are immediately available to plants and microbes, whereas biochar buffers nutrient losses and improves the soil's cation storage capacity over time. From a crop perspective, higher soil CEC is particularly important for maize production, as it ensures a stable nutrient supply throughout the growing season. Soils with improved CEC are better able to buffer nutrient fluctuations, reduce leaching losses, and support consistent nutrient uptake. Therefore, treatments such as F2B2C2, which combine frass, biochar, and balanced chemical fertilizers, create an optimal soil environment for sustained fertility and maize productivity.

From a crop perspective, an increase in soil CEC is particularly important for maize production, as it ensures a more stable supply of essential nutrients throughout the growing season. Soils with higher CEC are better able to buffer nutrient fluctuations, reducing nutrient losses from leaching and supporting consistent nutrient uptake by maize. Therefore, treatments like F2B2C2, which combine frass, biochar, and balanced chemical fertilizers, create an optimal soil environment for sustained fertility and maize productivity.

iii. Effect of Different Amounts of Black Soldier Fly Frass, Decanter Cake Biochar, and Chemical Fertilizers on Soil Exchangeable Ammonium and Available Nitrate

Figure 5.6 shows the effects of Black Soldier Fly (BSF) frass, decanter cake biochar, and chemical fertilizers on soil exchangeable ammonium (NH_4^+) and available nitrate (NO_3^-) after 30, 60, and 90 days of incubation. The temporal progression highlights how each treatment influenced nitrogen dynamics, availability, and retention over time.

During 30 days of incubation, the treatment with 100% chemical fertilizers (F0B0C1) recorded the highest exchangeable ammonium. This indicates that chemical fertilizers act as an immediate and concentrated source of NH_4^+ in soil, particularly at the initial stage. However, nitrate availability remained relatively low at this stage, suggesting that the conversion of ammonium to nitrate (nitrification) had not yet fully progressed. In contrast, treatments integrating BSF frass and biochar, such as F2B2C2, showed a more balanced nutrient profile, with moderate ammonium and nitrate. The gradual mineralization of organic nitrogen from frass, combined with the adsorption capacity of biochar, provided a steady release of ammonium while preventing excessive leaching losses (Klammsteiner *et al.*, 2020; Zhang *et al.*, 2023).

By 60 days, a clear shift was observed. F0B0C1 still exhibited the highest ammonium levels, reflecting the persistence of fertilizer-derived NH_4^+ . However, nitrate levels under this treatment declined compared to 30 days, possibly due to nitrification being offset by leaching losses or microbial immobilization in the absence of sufficient organic matter to retain nutrients. In contrast, frass–biochar combinations such as F2B2C2 sustained higher nitrate concentrations. This indicates that frass mineralization was still ongoing, supplying

nitrogen gradually, while biochar's porous structure and functional groups reduced nitrate leaching and stabilized nitrogen forms in the soil (Carroll *et al.*, 2023). The combination of organic and inorganic sources thus provided a more sustained nitrogen release pattern than chemical fertilizers alone.

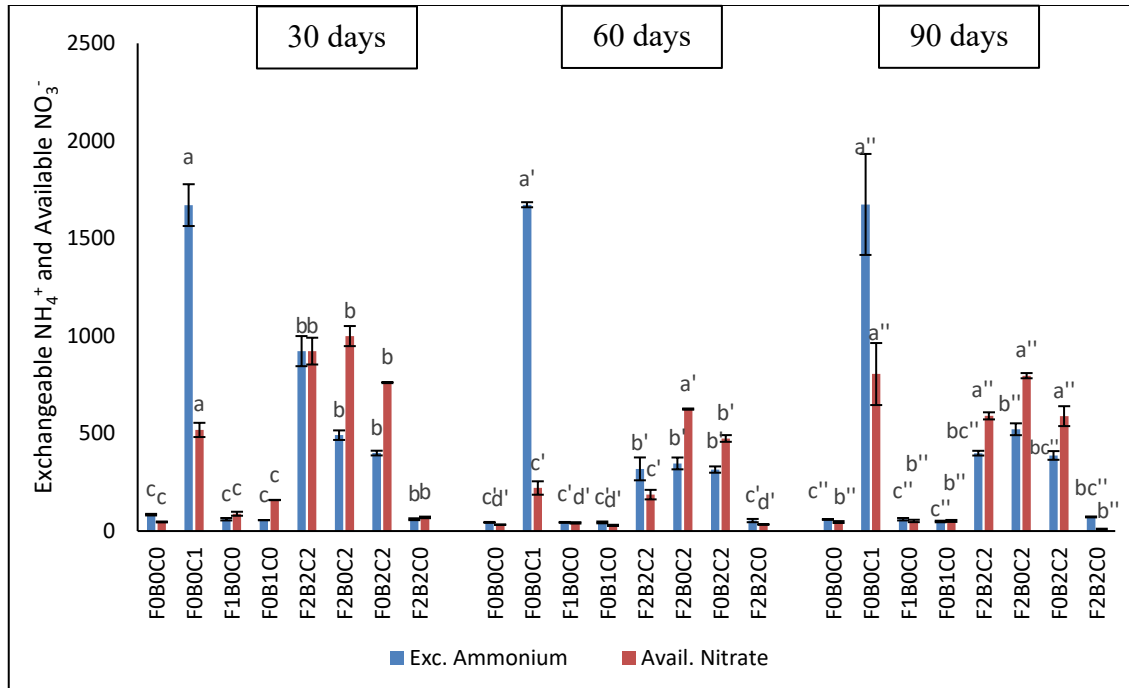


Figure 5.6: Effect of treatments on **exchangeable ammonium and available nitrate** at 30, 60, and 90 days after incubation (DAI). Different letters above the bars indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$). Error bars represent the mean $\pm$ standard error (SE).

At 90 days, the dynamics of nitrogen transformation became more evident. F0B0C1 continued to have the highest ammonium concentration, but levels plateaued, reflecting declining fertilizer efficiency and possible losses through volatilization or leaching. Conversely, F2B2C2 maintained relatively high nitrate levels, highlighting the long-term benefits of combining frass and biochar. The organic matter from frass promoted continuous mineralization and nitrification, while biochar stabilized the released nitrate, limiting losses.

This finding supports previous reports that biochar not only enhances nitrogen use efficiency but also prolongs nutrient availability in the soil (Lehmann *et al.*, 2011; Agegnehu *et al.*, 2017).

The differences observed across 30, 60, and 90 days can therefore be explained by nitrogen transformation processes. In the early stage (30 days), chemical fertilizers dominate through rapid NH_4^+ release, while frass begins slow mineralization. By 60 days, nitrification and leaching reduce fertilizer-derived nitrate, but frass–biochar treatments sustain release through ongoing mineralization and adsorption effects. By 90 days, chemical fertilizer efficiency declines, while frass–biochar combinations continue to provide a stable supply of nitrate, ensuring long-term fertility and reducing nutrient losses.

The control treatment (F0B0C0) remained nutrient-poor across all incubation periods, emphasizing the necessity of amendments for soil fertility improvement. Overall, while chemical fertilizers provided a rapid but short-lived nutrient boost, the combination of BSF frass and biochar ensured sustained nitrogen availability through mineralization, nutrient retention, and reduced leaching losses. This synergistic effect is particularly valuable in maize production, where a continuous nitrogen supply is critical for optimal growth and yield.

5.3.4 Pot Study

Table 5.5: Soil selected physico-chemical properties at fifty-two (52) days after planting

Treatments								
Chemical Properties	F0B0C0	F0B0C1	F1B0C0	F0B1C0	F2B2C2	F2B0C2	F0B2C2	F2B2C0
pH in water	5.60± 0.05c	4.63±0.05d	6.20±0.15b	7.20±0.25a	6.20±0.15b	4.50±0.11d	5.60±0.20c	6.90±0.11a
CEC (cmol (+) kg ⁻¹)	18.95±2.35a	11.60±2.45a	14.86±3.35a	17.03±5.31a	12.85±2.85a	16.3±6.02a	19.00±4.5a	16.5±4.3a
Total organic carbon (%)	37.61±1.15a	37.31±3.88a	37.57±6.37a	34.49±1.36a	35.07±1.33a	34.83±1.80a	34.94±0.95a	35.44±1.15a
Total organic matter (%)	64.68±1.15a	64.17±3.88a	64.62±6.37a	59.32±1.36a	60.32±1.33a	59.9±1.80a	60.08±0.95a	60.95±1.15a
Total nitrogen (%)	1.74±0.02b	3.38±0.34a	2.70±0.32ab	2.14±0.30b	2.85±0.50ab	3.40±0.54a	2.75±0.29ab	1.59±0.62b
Exchangeable ammonium (mg kg ⁻¹)	22.18±2.02b	53.70±2.02a	21.01±3.50b	21.01±0.00b	22.18±2.02b	24.15±3.50b	22.18±2.02b	21.01±3.50b
Available nitrate (mg kg ⁻¹)	31.52±3.50cd	171.62±21.015a	33.85±5.35cd	26.68±4.04d	65.38±2.02b	64.79±8.75b	57.20±12.30bc	23.35±4.04d
Available phosphorus (mg kg ⁻¹)	0.18±0.10c	1.14±0.66a	0.04±0.02c	0.31±0.18c	1.30±0.75b	0.08±0.04cb	0.87±0.503cb	0.04±0.02c
Available potassium (mg kg ⁻¹)	0.06±0.18b	0.43±11.80ab	0.33±15.74ab	0.85±3.18ab	0.88±33.41a	0.33±14.04ab	0.51±23.30ab	0.73±6.71ab

Note: All analyses are based on dry weight. Means (value ± standard error)

Table 5.5 summarizes the soil physico-chemical properties at 52 days after planting across different treatments combining BSF frass, decanter cake biochar, and chemical fertilizers. The observed variations in pH, CEC, and nutrient availability reflect the distinct contributions of these amendments (Lehmann & Joseph, 2015; Nobile *et al.*, 2020). Soil pH ranged from 4.50 (F2B0C2) to 7.20 (F0B1C0). Treatments containing biochar without chemical fertilizers, such as F0B1C0 and F2B2C0, recorded significantly higher pH (7.20 and 6.90, respectively) due to biochar's liming effect, which neutralizes soil acidity by releasing basic cations like Ca^{2+} and Mg^{2+} (Zhang *et al.*, 2019). Conversely, treatments with chemical fertilizers but no biochar (F0B0C1 and F2B0C2) showed lower pH values (< 5.0), likely due to the acidifying effect of urea hydrolysis and nitrification (Guo *et al.*, 2010). These results confirm biochar's role in improving pH buffering capacity (Lehmann & Joseph, 2015).

CEC values varied between 11.60 cmol (+) kg^{-1} (F0B0C1) and 19.00cmol (+) kg^{-1} (F0B2C2). Treatments with higher biochar content (F0B2C2 and F2B2C2) consistently exhibited improved CEC compared to treatments without biochar. This is attributed to biochar's porous structure and high surface charge, which enhance nutrient retention and reduce leaching (Glaser *et al.*, 2002; Chen *et al.*, 2019). The relatively lower CEC in F0B0C1 reflects the lack of organic amendments in that treatment. Total organic carbon (TOC) and total organic matter (TOM) remained high across treatments (TOC: 34.49–37.61%), reflecting the overall organic input from frass and biochar. Treatments F1B0C0 (frass only) and F0B2C2 (high biochar) slightly improved TOC, indicating both amendments contribute to long-term soil carbon sequestration (Lehmann *et al.*, 2021). The stability of organic matter

levels suggests that the amendments were not fully mineralized within 52 days, providing a sustained nutrient reservoir (Gwenzi *et al.*, 2015).

Total nitrogen (N) content ranged from 1.59% (F2B2C0) to 3.40% (F2B0C2). Treatments with chemical fertilizer (urea) and frass, such as F2B0C2, recorded higher N availability, showing the additive effect of organic and inorganic N sources (Kasozi *et al.*, 2010). Exchangeable ammonium (NH_4^+) was highest in F0B0C1 (53.70 mg kg⁻¹), which contained only chemical fertilizers, suggesting rapid urea hydrolysis. However, nitrate (NO_3^-) was highest in F0B0C1 (171.62 mg kg⁻¹) and moderately high in combined treatments like F2B0C2 and F2B2C2, indicating active nitrification (Ju *et al.*, 2009). Frass-only treatment (F1B0C0) maintained moderate N levels, confirming frass as a slow-release nitrogen source compared to urea (Purnamasari & Khasanah, 2022). Available phosphorus (P) was generally low (< 1.30 mg kg⁻¹) but improved in treatments with ERP and frass, such as F2B2C2 (1.30 mg kg⁻¹). This indicates that ERP and frass synergistically enhance P availability (Liang *et al.*, 2016), although fixation in acidic treatments (F0B0C1, F2B0C2) likely limited overall P solubility (Zhao *et al.*, 2020). Available potassium (K) ranged from 0.06 mg kg⁻¹ (F0B0C0) to 0.88 mg kg⁻¹ (F2B2C2). Treatments receiving MOP in combination with frass and biochar (F2B2C2, F0B2C2) demonstrated the highest K availability. Biochar likely improved K retention by reducing leaching losses and providing exchange sites for K^+ (Major *et al.*, 2010).

The results indicate that treatments combining frass, biochar, and chemical fertilizers (F2B2C2) optimized nutrient availability and improved soil chemical properties. Biochar effectively increased pH and CEC, while frass supplied organic matter and slow-release

nitrogen. Chemical fertilizers contributed to immediate nutrient availability but risked soil acidification when applied alone (F0B0C1). The integration of these amendments, particularly in balanced proportions, presents a sustainable strategy for improving soil fertility and nutrient cycling.

5.4 Dry Weight of Maize Plant

Figure 5.7 compares maize plant dry weights across treatments involving different combinations of BSF frass, decanter cake biochar, and NPK fertilisers. Notably, treatments F0B0C1 (recommended chemical NPK only), F2B2C2 (BSF frass + biochar + NPK), and F2B0C2 (frass + NPK only) delivered the highest dry weights, ranging from approximately 16–20 g per plant, and were statistically indistinguishable. These treatments performed significantly better than others, illustrating the clear benefit of fertiliser inputs when paired with organic amendments.

Maize typically requires approximately 60 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹ to sustain vigorous growth and high yield. In the F0B0C1 treatment, the full complement of NPK fertilisers delivered this targeted nutritional supply, supporting robust vegetative growth. In F2B2C2 and F2B0C2, BSF frass contributed nitrogen, phosphorus, potassium, and organic matter, enhancing nutrient availability and retention. Biochar in F2B2C further improved cation retention and soil structure, helping to reduce nutrient losses and support sustained nutrient uptake throughout the growth period.

Conversely, the control (F0B0C0) produced only 2 g dry weight, underscoring the critical role of nutrient inputs. Treatments featuring sole organic amendments or incomplete nutrient profiles, such as F1B0C0 (frass only at a lower rate) and F0B2C2 (biochar + NPK without frass), improved performance modestly but did not meet the nutritional demands of maize for optimal biomass production. Interestingly, F2B2C0 (frass + biochar without NPK) achieved intermediate dry weight gains. This suggests that substantial organic inputs alone (frass plus biochar) can partially meet the maize nutrient demand, though still not achieving the peak performance of treatments complemented with chemical fertilisers.

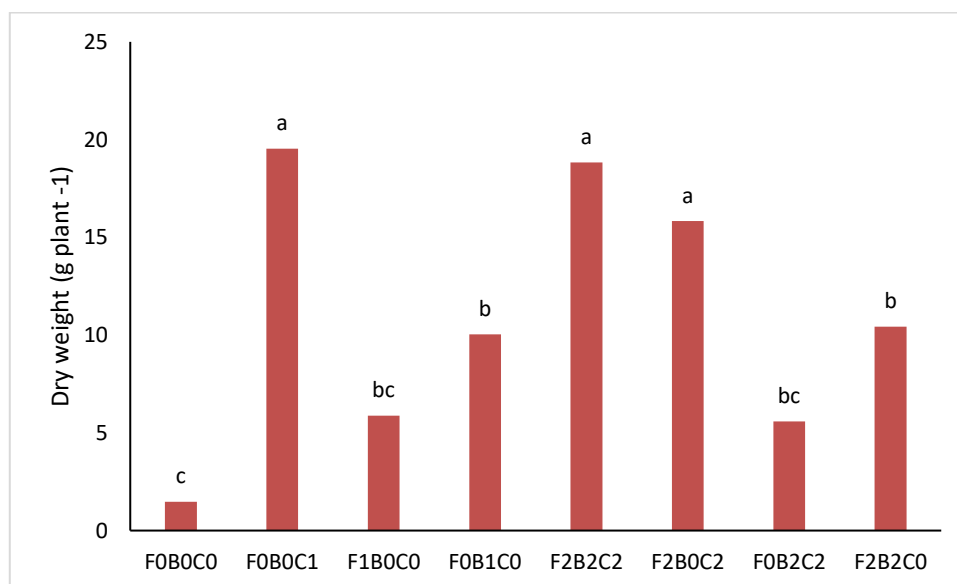


Figure 5.7: Effect of treatments on **Dry Weight** of the plant after 52 Days. Different letters above the bars indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$). Error bars represent the mean $\pm$ standard error (SE).

5.5 Effect of Treatments on concentration of Nitrogen (N), Phosphorus (P), Potassium (K) in Maize Leaves, Stems, and Roots

Table 5.6 presents the concentrations of nitrogen, phosphorus, and potassium in the roots, stems, and leaves of maize under different treatment combinations of BSF frass, decanter cake biochar, and chemical fertilisers.

Table 5.6: NPK concentration of roots, stems, and leaves

Plant Part	Treatments	N	P	K
Root	F0B0C0	0.0002 ± 0.00a	0.0001 ± 0.00a	0.007 ± 0.00a
	F0B0C1	0.0003 ± 0.00ab	0.0002 ± 0.00a	0.019 ± 0.02a
	F1B0C0	0.0002 ± 0.00a	0.0001 ± 0.00a	0.019 ± 0.00a
	F0B1C0	0.0002 ± 0.00a	0.0002 ± 0.00a	0.022 ± 0.00a
	F2B2C2	0.0003 ± 0.00a	0.0002 ± 0.00a	0.038 ± 0.00a
	F2B0C2	0.0003 ± 0.00a	0.0002 ± 0.00a	0.009 ± 0.00b
	F0B2C2	0.0002 ± 0.00a	0.0002 ± 0.00a	0.025 ± 0.00a
	F2B2C0	0.0002 ± 0.00a	0.0002 ± 0.00a	0.028 ± 0.00a
Stem	F0B0C0	0.000 ± 0.00a	0.000 ± 0.00a	0.028 ± 0.00b
	F0B0C1	0.000 ± 0.00a	0.001 ± 0.00a	0.291 ± 0.12ab
	F1B0C0	0.000 ± 0.00a	0.001 ± 0.00a	0.401 ± 0.00ab
	F0B1C0	0.000 ± 0.00a	0.002 ± 0.00a	0.427 ± 0.04ab
	F2B2C2	0.000 ± 0.00a	0.001 ± 0.00ab	0.378 ± 0.03a
	F2B0C2	0.000 ± 0.00a	0.001 ± 0.00a	0.248 ± 0.03b
	F0B2C2	0.000 ± 0.00a	0.001 ± 0.00a	0.310 ± 0.10ab
	F2B2C0	0.000 ± 0.00a	0.001 ± 0.00a	0.306 ± 0.04ab
Root	F0B0C0	0.000 ± 0.00a	0.000 ± 0.00b	0.114 ± 0.01a
	F0B0C1	0.000 ± 0.00a	0.001 ± 0.00ab	0.123 ± 0.01a
	F1B0C0	0.000 ± 0.00a	0.000 ± 0.00ab	0.186 ± 0.01a
	F0B1C0	0.000 ± 0.00a	0.001 ± 0.00a	0.170 ± 0.02a
	F2B2C2	0.000 ± 0.00a	0.001 ± 0.00ab	0.178 ± 0.02a
	F2B0C2	0.000 ± 0.00a	0.001 ± 0.00a	0.156 ± 0.01a
	F0B2C2	0.000 ± 0.00a	0.001 ± 0.00ab	0.162 ± 0.02a
	F2B2C0	0.000 ± 0.00a	0.001 ± 0.00a	0.150 ± 0.02a

In roots, N and P concentrations showed only slight variation across treatments, with most values statistically similar. However, K displayed a more pronounced response. The highest root K concentration was observed in F2B2C2 (0.038 ± 0.00^a), indicating that the integrated application of frass, biochar, and NPK enhanced K uptake and retention in the root zone compared to the control (F0B0C0, 0.007 ± 0.00^a). Interestingly, F2B0C2 recorded a lower root K concentration (0.009 ± 0.00^b), suggesting that the absence of biochar reduced nutrient holding capacity despite the presence of frass and fertiliser.

In stems, while N and P concentrations in stems remained relatively constant across treatments, K concentrations varied substantially. Treatments such as F0B1C0 (0.427 ± 0.04^{ab}) and F1B0C0 (0.401 ± 0.00^{ab}) recorded higher K levels, while F2B0C2 showed comparatively lower accumulation (0.248 ± 0.03^b). The increase in stem K with organic inputs suggests that frass and biochar may improve nutrient mobility and enhance K transport from roots to shoots.

In leaves, being the primary photosynthetic organs, accumulated higher concentrations of K relative to N and P. Treatments such as F1B0C0 (0.186 ± 0.01^a) and F2B2C2 (0.178 ± 0.02^a) demonstrated increased K concentrations compared to the control (F0B0C0, 0.114 ± 0.01^a). Phosphorus in leaves was slightly elevated in treatments with biochar and frass (0.001 ± 0.00), highlighting their contribution to nutrient availability. However, N concentrations across treatments remained negligible, possibly due to rapid N turnover and limited accumulation in vegetative tissues at the sampling stage.

Overall, the results indicate that potassium was the most responsive macronutrient across all plant parts, with the greatest enhancement seen in treatments combining frass, biochar, and chemical fertiliser. This suggests a synergistic effect of integrated nutrient management, which improves both uptake and translocation of K within the plant. Phosphorus and nitrogen concentrations, by contrast, showed minimal variation, likely reflecting soil fixation effects for P and rapid assimilation and cycling of N. therefore, these findings align with previous studies showing that biochar can improve nutrient retention and cation exchange capacity, while frass provides readily available nutrients and organic matter, together supporting more efficient nutrient utilisation in maize (Glaser *et al.*, 2015; Houben *et al.*, 2020).

5.6 Effect of Treatments on nutrient uptake of Nitrogen (N), Phosphorus (P), Potassium (K) in Maize Leaves, Stems, and Roots

Table 5.7 presents the uptake of nitrogen, phosphorus, and potassium in the roots, stems, and leaves of maize under different treatment combinations of BSF frass, decanter cake biochar, and chemical fertilisers.

Table 5.7: The NPK uptake of roots, stems, and leaves

Plant Part	Treatments	N	P	K
Root	F0B0C0	0.001 ± 0.00a	0.000 ± 0.00a	0.002 ± 0.00a
	F0B0C1	0.005 ± 0.00a	0.000 ± 0.00a	0.023 ± 0.00a
	F1B0C0	0.001 ± 0.00a	0.000 ± 0.00a	0.007 ± 0.00a
	F0B1C0	0.001 ± 0.00ab	0.000 ± 0.00a	0.016 ± 0.00a
	F2B2C2	0.004 ± 0.00ab	0.000 ± 0.00a	0.052 ± 0.02a
	F2B0C2	0.003 ± 0.00ab	0.000 ± 0.00a	0.001 ± 0.00a
	F0B2C2	0.003 ± 0.00ab	0.000 ± 0.00a	0.020 ± 0.01a
	F2B2C0	0.003 ± 0.00a	0.000 ± 0.00a	0.030 ± 0.01a
Stem	F0B0C0	0.000 ± 0.00cd	0.000 ± 0.00a	0.009 ± 0.01c
	F0B0C1	0.002 ± 0.00ab	0.001 ± 0.00a	1.761 ± 0.03ab
	F1B0C0	0.000 ± 0.00abc	0.000 ± 0.00a	0.635 ± 0.14abc
	F0B1C0	0.001 ± 0.00bcd	0.001 ± 0.00a	1.490 ± 0.11abc
	F2B2C2	0.002 ± 0.00ab	0.010 ± 0.00a	2.007 ± 0.61a
	F2B0C2	0.002 ± 0.00a	0.012 ± 0.00a	1.574 ± 0.27abc
	F0B2C2	0.002 ± 0.00bcd	0.006 ± 0.00a	1.740 ± 1.25bc
	F2B2C0	0.000 ± 0.00d	0.001 ± 0.00a	1.614 ± 0.45abc
Root	F0B0C0	0.000 ± 0.00d	0.000 ± 0.00d	0.100 ± 0.01d
	F0B0C1	0.005 ± 0.00ab	0.015 ± 0.00ab	1.443 ± 0.06ab
	F1B0C0	0.002 ± 0.00bcd	0.004 ± 0.00bcd	0.731 ± 0.05bcd
	F0B1C0	0.002 ± 0.00bcd	0.009 ± 0.00a	0.979 ± 0.07bcd
	F2B2C2	0.004 ± 0.00a	0.015 ± 0.00abc	2.082 ± 0.23a
	F2B0C2	0.003 ± 0.00abc	0.012 ± 0.00abc	1.300 ± 0.21abc
	F0B2C2	0.002 ± 0.00bcd	0.006 ± 0.00bcd	0.791 ± 0.14bcd
	F2B2C0	0.001 ± 0.00cd	0.006 ± 0.00cd	5.575 ± 0.45cd

In roots, the nutrient uptake in roots was generally lower compared to the aboveground parts due to limited biomass. However, treatment differences were evident, particularly for potassium. The F2B2C2 treatment recorded the highest root K uptake (0.052 ± 0.02^a), while other treatments, such as F2B0C2, showed very low K uptake (0.001 ± 0.00^a). This highlights the positive role of combined frass, biochar, and fertilizer in improving K retention and availability in the root zone.

In the stem, nutrient uptake showed striking variation, especially for potassium. The F2B2C2 treatment achieved the highest K uptake (2.007 ± 0.61^a), followed closely by F0B2C2 (1.740 ± 1.25^{bc}) and F2B0C2 (1.574 ± 0.27^{abc}). Nitrogen and phosphorus uptake also increased under integrated treatments, with notable improvements in F2B0C2 (N = 0.002 ± 0.00^a ; P = 0.012 ± 0.00^a). This suggests that biochar and frass synergize with fertilizer inputs to enhance nutrient capture and stem biomass development.

In leaves exhibited the highest nutrient uptake among all tissues, particularly for potassium. The F2B2C2 treatment recorded the highest leaf K uptake (2.082 ± 0.23^a), while F0B0C0 (control) showed minimal uptake (0.100 ± 0.01^d). Leaf N and P uptake also improved under integrated treatments, with F2B2C2 reaching 0.004 ± 0.00^a (N) and 0.015 ± 0.00^{abc} (P). Interestingly, the F2B2C0 treatment also showed a pronounced effect on K uptake (5.575 ± 0.45^{cd}), reflecting the strong responsiveness of maize leaves to biochar-inclusive amendments.

5.7 Conclusion

The integration of Black Soldier Fly (BSF) frass and biochar presents a sustainable and innovative strategy for improving soil fertility while mitigating the environmental challenges posed by conventional fertilizers. BSF frass, rich in essential nutrients such as nitrogen, phosphorus, and potassium, not only supports robust plant growth but also contributes to circular economy practices by converting organic waste into a valuable fertilizer, thereby reducing waste volume and greenhouse gas emissions. Complementarily, biochar enhances the agronomic value of frass by improving nitrogen retention, stabilizing nutrients, and reducing leaching losses, particularly of potassium. Its role in enhancing soil structure, microbial activity, and seed germination further underscores its potential as a soil amendment. BSF frass and biochar foster efficient nutrient cycling, suppress soil-borne diseases, and promote higher crop yields while reducing reliance on synthetic inputs. This study highlights the promise of integrated organic amendments in achieving resilient and sustainable agricultural systems. However, future research should refine application rates, investigate long-term soil health impacts, and explore crop-specific responses across different agroecosystems to fully harness the potential of BSF frass–biochar combinations in advancing sustainable food production.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study demonstrates that the combined use of Black Soldier Fly (BSF) frass and decanter cake biochar provides a sustainable strategy to enhance soil fertility and maize productivity, while reducing dependence on chemical fertilizers. Applying biochar significantly improved soil structure, nutrient retention, cation exchange capacity (CEC), and soil pH. Its porous nature facilitated the adsorption and slow release of key nutrients, particularly potassium (K) and phosphorus (P), making them more available for maize uptake. Meanwhile, as a nutrient-rich organic amendment, BSF frass supplied essential macronutrients (N, P, K) in a slow-release form. This supported sustained plant growth and resulted in a higher dry weight of maize plants, confirming its effectiveness as a biofertilizer. In this study, compared to the untreated control (F0B0C0), soils amended with BSF frass and biochar (F2B2C2) recorded a 41% increase in total nitrogen, a 58% enhancement in phosphorus, and a 22% improvement in potassium availability. Moreover, micronutrient availability improved: zinc concentration increased by 37%, while calcium and aluminum remained stable across treatments. These improvements translated into significantly enhanced soil fertility and nutrient cycling capacity for maize cultivation. The integrated treatment F2B2C2 (BSF frass + biochar + chemical fertilizer) emerged as the most effective, producing the highest maize biomass due to its balanced nutrient supply. This indicates the importance of integrated soil fertility management, where organic amendments complement chemical fertilizers for enhanced crop performance. Notably, using 50% BSF frass with biochar and reduced chemical fertilizer improved phosphorus recovery, nutrient-use

efficiency, and maize yield on nutrient-depleted tropical soils. This finding demonstrates that reliance on synthetic inputs can be reduced without compromising productivity, contributing to more sustainable farming systems. While 100% chemical fertilizer provided rapid nutrient release, particularly for exchangeable P and K in the first 30 days, its effects were short-lived. In contrast, biochar and frass improved long-term nutrient retention, soil quality, and sustained maize growth. Therefore, the study achieved its objectives by showing that integrating BSF frass and biochar with chemical fertilizers enhances soil fertility, optimizes nutrient availability, and improves maize growth more effectively than chemical fertilizers alone. This approach addresses soil degradation and sustainable nutrient management, offering a viable pathway toward resilient and eco-friendly agriculture.

6.2 Recommendations

Future research should prioritize long-term field trials to validate the benefits of BSF frass and biochar under real farming conditions and across various soil types. Optimizing application rates is crucial, as synergistic effects indicate that reduced chemical fertilizer inputs can be effectively combined with organic amendments for sustainable maize production. Studies should also extend beyond early growth stages to assess nutrient uptake during the later phases of maize development when nutrient demand peaks after 55 days. Besides, future investigations should explore using different biochar feedstocks, such as chicken litter or rice husk, to understand their impact on soil nutrient dynamics. Research should also examine the role of microbial interactions, disease suppression from BSF frass, and environmental benefits like carbon sequestration and greenhouse gas mitigation.

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APPENDICES

Appendix A: Journal Publications

Jimmy, D.R., Omar, L., Maikol, N., Wahi, R. (2024). Nitrogen Availability Following Application of Urea and Decanter Cake/Palm Kernel Expeller Frass Produced from Black Soldier Fly Larvae. *International Journal of Nanoelectronics and Materials*, 17 (Dec 2024). 139-146.

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