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Growth Performance of Clonal Sago Palm Seedlings Following Application of NPK Green and Black Soldier Fly Larvae Frass Cultivated in Bekenu Series Soil

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ABSTRACT
The development of clonal sago palm seedlings at the nursery stage is crucial to ensure vigorous establishment and subsequent field performance. A 120-day pot experiment was conducted at Sungai Talau Research Station, Dalat, Sarawak, Malaysia, to evaluate the growth response of four-month-old clonal sago palm seedlings to black soldier fly larvae (BSFL) frass and NPK Green fertilizer in Bekenu Series soil, a highly weathered tropical soil with low inherent fertility. Clonal sago palm seedlings were subjected to six treatments: unamended soil (S0), NPK Green alone (SN1), BSFL frass alone (SF), and three combinations of NPK Green with increasing rates of BSFL frass (SFN1, SFN2, SFN3). Results indicated that neither sole NPK Green nor the tested combinations achieved an optimum nutrient regime for significant improvement in seedling growth within the 120-day period. However, BSFL frass alone (SF) and its combined application with reduced NPK Green (SFN3) showed potential to enhance nutrient availability and soil fertility, suggesting that organic amendments can partially substitute inorganic fertilizer inputs in Bekenu Series soil. The lack of significant improvement in N, P, and K uptake and chlorophyll content at this early stage suggests that nutrient assimilation is constrained by limited root development. Thus, fertilizer regimes for clonal sago palm seedlings in Bekenu soil require reconsideration, with longer observation periods beyond 120 days recommended to fully assess the benefits of BSFL frass as a soil fertility enhancer.

Keywords: Clonal palm, larvae frass, organic fertilizer, nursery stage, nutrient uptake

INTRODUCTION
Sago palm (*Metroxylon sagu* Rottb.) is a starch-producing palm commonly grown in the Mukah region in Sarawak. Sago palm is a clustering palm well adapted to swampy tropical lowland ecosystems. Each axis of a clump undergoes a single reproductive cycle, flowering once at the end of its life after accumulating substantial quantities of starch in the trunk. Traditionally, the starch is harvested by cutting the palm stem, pulverizing the pith, and leaching out the starch with water, which can then be utilized for both food and non-food purposes. It remains a staple food in parts of Sarawak (Eastern Malaysia), Indonesia and Papua New Guinea, where it is largely extracted from semi-managed stands. Beyond its traditional role, sago palm holds significant promise as a plantation crop owing to its high starch yield potential as a perennial species, its ability to thrive in niche wetland habitats unsuitable for many other crops, and its prospective use as a sustainable raw material for bioethanol production. To fully realize this potential, however, a stronger scientific foundation is needed

to determine the optimal fertilization ensuring maximum yield and efficient utilization. The hardy nature of this palm prompted the Sarawak government to establish commercial sago plantations as a strategy to stimulate the local economy (Mohammad *et al*., 2016).

The tissue culture of sago palm for superior clone production has been established by CRAUN Research Sdn. Bhd., Kuching, Sarawak, Malaysia, as a large-scale propagation method to increase planting materials and boost sago starch yield. When clonal sago palms are introduced into new environments, their early development in the nursery stage is critical to ensure vigorous growth and successful establishment in the field (Samsul, 2016). At this stage, proper nutrient management is particularly important, as nutrient deficiencies can hinder clonal sago palm seedlings vigor and compromise long-term productivity. Controlled release and compound fertilizers such as NPK Green have been widely applied to clonal sago palm seedlings to supply essential macronutrients for root and shoot development, while also serving as a growth booster during field establishment. Properly managed clonal sago palm seedlings at nursery stage did not only favor continuous starch production but also have the potential to store large amounts of carbon sustainably (Sasaki *et al*., 2024).

Balanced fertilization involves more than the sole use of chemical inputs. Excessive dependence on inorganic fertilizers often fails to correct nutrient imbalances in low-fertility soils such as the Bekenu Series. This soil is characterized by high acidity, low base saturation, and the dominance of aluminium (Al) and iron sesquioxides, which restrict nutrient availability to plants (Shamsuddin & Anda, 2012). To address these limitations, the combined application of organic amendments and inorganic fertilizers has been recognized as a sustainable approach to enhance soil fertility, improve nutrient retention, and support the growth of clonal sago palm seedlings. Among promising organic inputs, black soldier fly larvae (BSFL) frass has recently attracted attention due to its considerable content of macronutrients, micronutrients, and organic matter. In our earlier study, frass derived from BSFL reared on water hyacinth was found to contain appreciable amounts of nitrogen (N), phosphorus (P), potassium (K), and organic matter, making it an effective amendment for improving crop performance during the early growth stages (Hassan et al., 2023). Frass is the BSFL excretion after the larvae digested feeding substrate during the completion of larvae stage in the black soldier fly life cycle (Hassan *et al*., 2023).

Integrating BSFL frass with NPK Green could reduce reliance on chemical fertilizers while simultaneously enhancing nutrient cycling and soil health in Bekenu Series soil. Therefore, a pot experiment was undertaken to evaluate the growth performance of clonal sago palm seedlings cultivated in Bekenu Series soil under different application rates of BSFL frass in combination with NPK Green. The study aimed to identify an optimum fertilization regime that integrates the advantages of both organic and inorganic nutrient sources, thereby improving soil fertility, enhancing nutrient availability and retention, and promoting vigorous seedling growth at the nursery stage. Establishing such a regime is essential not only for reducing dependence on chemical fertilizers but also for ensuring sustainable nutrient management in low-fertility tropical soils, ultimately contributing to the successful establishment and long-term productivity of clonal sago palm plantations.

MATERIALS AND METHODS

The BSFL frass used in this study was produced and characterized for its nutrient composition as reported in our earlier work (Hassan *et al*., 2023). Four-month-old clonal sago palm seedlings were supplied by CRAUN Research Sdn. Bhd., Kuching, Sarawak. A pot experiment was conducted at the Sungai Talau Research Station, Dalat, Sarawak, using Bekenu Series soil, the properties of which have been described previously (Hassan *et al*., 2023). The Bekenu series (*Typic Paleudults*) was selected for this pot study because the soil is a typical acid soil (pH < 5) which is commonly grown with diverse crops such as sago palm, oil palm and black pepper, despite having a high P fixation rate due to excessive aluminium and iron levels and lack of organic matter. According to Paramananthan (2021), the Bekenu series soil is a fine loamy soil composed of silica with an isohyperthermic temperature regime. The soil sample was collected in a secondary forest area which has not been cultivated with any crops at the Universiti Putra Malaysia Sarawak (UPMS), Sarawak, Malaysia (3°12′20″ N, 113°04′20″ E). Soil samples were collected both before planting and after the pot experiment and analyzed for physicochemical properties, including electrical conductivity (EC), pH, total organic carbon (TOC), and total organic matter (TOM) using standard procedures described by Tan (2005). In addition, macronutrients and fertility indicators were quantified, namely total N, exchangeable ammonium (NH_4^+), available nitrate (NO_3^-), cation exchange capacity (CEC), available P, and exchangeable K.

The physical growth parameters of clonal sago palm plantlets, including height, stem diameter, and root length, were measured prior to the acclimatization process in the nursery shade-house. The recommended NPK Green fertilizer (SN1) from CRAUN Research was applied in two split doses at 30 days after planting (DAP) and 90 DAP, while BSFL frass in all relevant treatments was incorporated once, prior to transplanting (**Table 1**). Clonal sago palm seedlings were irrigated twice daily using a sprinkler system to maintain adequate soil moisture. Growth monitoring and chlorophyll measurements were conducted at regular intervals, specifically at 1 DAP (baseline), 40 DAP, 80 DAP, and 120 DAP.

Table 1: Treatment composition

Treatments	Composition
S0	Soil only (control) No fertilizer
SF	10 kg soil + 10 g BSFL frass Standard recommendation for BSFL frass (100%)
SN1	10 kg soil + 10 g NPK green (15:15:15) Craun research recommendation (NPK green 100%)
SFN1	10 kg soil + BSFL frass 10 g + 10 g NPK green (15:15:15) Frass 100% and NPK green 100%
SFN2	10 kg soil + BSFL frass 10 g + 8 g NPK green (15:15:15) 20% reduction of frass and 20% reduction of NPK Green
SFN3	10 kg soil + BSFL frass 10 g + 6 g NPK green (15:15:15) Frass 100% and 40% reduction of NPK Green

A pot study was conducted at the Sungai Talau Research Station, Dalat, Sarawak, to evaluate the growth performance of clonal sago palm seedlings under combined applications of BSFL frass and NPK Green fertilizer (15:15:15) (**Table 1**). The study was established within a 6 m × 4 m nursery bed, arranged with eight treatments and five replications per treatment. Prior to the experiment, the nursery site was cleared and lined with silver shine plastic to prevent seedling roots from penetrating the underlying soil and to suppress weed growth. The fertilizer application rates were scaled down to reflect the nutrient requirements of clonal sago palm seedlings at the nursery stage. The pots were arranged in a completely randomized design (CRD) with five replications per treatment. Seedlings were grown for 120 days, during which they were monitored regularly for growth and physiological performance.

Growth parameters recorded included seedling height, stem diameter, and root length, measured with a measuring tape. Chlorophyll content was assessed using a SPAD-502 chlorophyll meter**.** At the end of the growth period, sago palm seedlings were harvested by cutting the shoots 1.5 cm above the soil surface using a sterilized sharp knife. The above ground of clonal sago palm seedlings was partitioned into leaves and stems, while the below ground (roots) was manually separated from the soil, thoroughly washed with tap water followed by distilled water, and then dried. Plant tissues (leaves, stems, and roots) were oven-dried at 60 °C to constant weight (Selvarajh & Ch'ng, 2021). The dried samples were ground to a fine powder using a laboratory blender. Nutrient analyses were conducted following the single dry ashing method **(**Tan, 2005), with total N, P, and K determined from digested extracts. A pot study was arranged in a completely randomized design (CRD). Data were analyzed using one-way analysis of variance (ANOVA) to evaluate treatment effects, and mean comparisons were performed with Tukey's test at a significance level of $P \leq 0.05$. All statistical analyses were conducted using SAS software, version 9.4 (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

Selected initial chemical properties of clonal sago palm seedling

The initial nutrient composition and growth characteristics of the clonal sago palm seedlings are presented in **Table 2**. On average, clonal sago palm seedlings recorded a height of 36.4 cm, a stem diameter of 1 cm, and a root length of 14.7 cm, indicating uniform early growth performance. This consistency across individuals confirms the suitability of the clonal sago palm seedlings as reliable test material prior to the application of different rates of fertilizer treatments. Sago palm seedling tissue nutrient analysis further demonstrated that the clonal seedlings shared a similar baseline composition across plant parts. Total N concentrations were uniformly low, with 0.06% in leaves, 0.08% in stems, and 0.07% in roots. Likewise, total P levels were closely aligned, with 32.48 mg kg^{-1} in leaves, 29.15 mg kg^{-1} in stems, and 32.49 mg kg^{-1} in roots, reflecting balanced internal nutrient allocation. Potassium distribution also showed consistency, with 2.12 mg kg^{-1} in leaves, 1.47 mg kg^{-1} in stems, and 2.12 mg kg^{-1} in roots. The uniformity in both growth traits and nutrient content highlights that the clonal sago palm seedlings, in their unfertilized state, provide an accurate and stable baseline for evaluating the effects of different fertilizer application rates. This ensures that subsequent variations observed can be attributed primarily to treatment effects rather than initial plant variability.

Selected initial physico-chemical analyses of Bekenu series soil

The Bekenu Series soil used in this study was classified as sandy loam, comprising 47.4% sand, 29.6% silt, and 23.0% clay, with a bulk density of 1.50 g cm^{-3} (**Table 3**). The soil was moderately acidic, with pH values of 4.21 (H_2O) and 4.01 (KCl), a condition typical of highly weathered tropical soils that are strongly leached, nutrient-depleted, and dominated by sesquioxides (Shamsuddin & Anda, 2012). The soil CEC was relatively low at 4.67 cmol$_{(+)}$ kg^{-1}, reflecting poor nutrient retention and buffering capacity. Nitrogen availability was particularly limiting, with total N at 0.24%, exchangeable NH_4^+ at 0.014 mg kg^{-1}, and available NO_3^- at 0.004 mg kg^{-1}. Soil organic matter status was moderate, with TOM at 6.43% and TOC at 3.74%. Electrical conductivity was 22.4 dS m^{-1}, indicating minimal soluble salts, while exchangeable K was also low at 17.32 mg kg^{-1}, consistent with the low base saturation characteristic of Bekenu soils. The deep, coarse-textured, and well-drained nature of this soil further exacerbates nutrient leaching losses, thereby limiting its inherent fertility. Overall, the combination of soil acidity, low CEC, poor nitrogen status, and insufficient exchangeable bases demonstrates that Bekenu Series soil has low inherent productivity. Consequently, nutrient supplementation through fertilization is essential to support optimal clonal sago palm seedlings growth and development on this soil type.

Table 2. Selected initial growth parameters of clonal sago palm seedling

Parameters	Mean ± S.E.
Height (cm)	36.4
Stem diameter (cm)	1
Root length (cm)	14.7
Total N in leaf (%)	0.06 ± 0.01
Total N in stem (%)	0.08 ± 0.00
Total N in root (%)	0.07 ± 0.00
Total P in leaf (mg kg^{-1})	32.48 ± 1.70
Total P in stem (mg kg^{-1})	29.15 ± 0.16
Total P in root (mg kg^{-1})	32.49 ± 1.7
Total K in leaf (mg kg^{-1})	2.12 ± 0.12
Total K in stem (mg kg^{-1})	1.47 ± 0.12
Total K in root (mg kg^{-1})	2.12 ± 0.12
Chlorophyll content	62.1

Note: Mean value followed by ± standard error

Table 3. Selected Initial chemical properties of Bekenu series used for pot study

Chemical properties	Soil initial properties (Mean ± S.E)
pH in water	4.21 ± 0.01
pH in KCl	4.01 ± 0.02
Cation exchange capacity (cmol(+) kg^{1})	4.67 ± 0.96
Electrical conductivity (ds m^{-1})	22.14±2.14
Total organic carbon (%)	3.74 ± 0.74
Total organic matter (%)	6.43 ± 1.21
Total nitrogen (%)	0.24 ± 0.04
C:N ratio	12:1 ± 1.46
Exchangeable ammonium (mg kg-^{1})	0.014 ± 0.002
Available nitrate (mg kg-^{1})	0.004 ± 0.001
Available phosphorus (mg kg-^{1})	0.755 ± 0.085
Available potassium (mg kg-^{1})	17.32 ± 1.32
Soil texture	Sandy loam
Bulk density (g cm^{-3})	1.50 ± 0.34

Selected chemical properties of bekenu series soil after pot study

The pH of Bekenu Series soil showed no significant differences among treatments after 120 DAP (**Table 4**). Nevertheless, a slight increase in soil pH was observed in the treatment SF1 (5.10), where BSFL frass was co-applied with NPK Green. This suggests that the incorporation of BSFL frass contributed to the amelioration of soil acidity. The effect can be attributed to the alkaline nature of BSFL frass (pH 7.64), as reported in our previous study (Hassan *et al*., 2023). Through gradual mineralization, BSFL frass releases basic cations that buffer soil acidity and enhance cation retention in the soil matrix. Over time, this process helps moderate soil acidity while simultaneously improving nutrient availability. These findings, as presented in Table 4, highlight the potential role of BSFL frass as a complementary amendment to chemical fertilizers in sustaining soil fertility under acidic soil conditions.

Soil EC of the Bekenu Series soil in the pot study increased markedly with the co-application of BSFL frass and NPK Green, ranging from 6.38 to 8.49 dS m^{-1}, which exceeds the permissible threshold of 4 dS m^{-1} (**Table 4**). According to Ng *et al*. (2021), elevated EC levels can suppress crop growth and microbial activity, suggesting that while BSFL frass contributes beneficial cations, its excessive application may pose salinity-related risks. This highlights the importance of balancing BSFL frass application rates to avoid detrimental effects on plant and soil interactions. Soil CEC improved significantly with BSFL frass incorporation, reaching 5.80 $cmol_{(+)}$ kg^{-1} in SFN1, 6.70 $cmol_{(+)}$ kg^{-1} in SFN2, and 5.43 $cmol_{(+)}$ kg^{-1} in SFN3, compared to only 1.53 $cmol_{(+)}$ kg^{-1} under NPK Green alone (SN1). This improvement demonstrates the role of BSFL frass in enhancing the soil's capacity to retain and exchange essential nutrients, counteracting to some extent the low inherent fertility of Bekenu soils. However, despite improvements in CEC, the soil TOM and TOC contents did not differ significantly among treatments. This suggests that BSFL frass primarily influences soil chemical reactivity (cation retention and buffering capacity) rather than substantially increasing the soil's organic carbon pool within the 120-day experimental period.

Overall, while BSFL frass shows clear potential in ameliorating soil acidity and enhancing CEC, its contribution to elevated EC levels warrants careful management. Optimizing BSFL frass application rates is therefore critical to maximize soil fertility benefits while minimizing salinity risks that could offset gains in crop growth and microbial activity.

Total N content of treatments with BSFL frass, SF (0.12%), SFN1 (0.09%), and SFN2 (0.07%) was significantly higher than soils without frass (S0, 0.04%) and NPK Green alone (SN, 0.03%) at 120 DAP. This clearly demonstrates that BSFL frass acts as a supplementary N source, whereby its organic matter content promotes the decomposition and mineralization of organic N into plant-available forms. The presence of organic matter also enhances the number of negatively charged sites in the soil, improving the retention of soil exchangeable NH_4^+. This effect was reflected in the higher exchangeable NH_4^+ levels in frass-amended soils namely 0.0033 mg kg^{-1} in SFN1 and SFN2, and 0.0044 mg kg^{-1} in SFN3 as compared to other treatments. These results suggest that BSFL frass addition did not only supplies N but also reduces potential N losses through leaching, as soil exchangeable NH_4^+ is adsorbed to soil colloids. In contrast, soil available NO_3^- levels were relatively low in treatments combining BSFL frass with NPK Green, SF1 (0.0021 mg kg^{-1}), SFN1 (0.0026 mg kg^{-1}), and SN (0.0030 mg kg^{-1}). Interestingly, higher rates of frass alone (SFN2) with 0.0037 mg kg^{-1} NO_3^- and SFN3mwith 0.0049 mg kg^{-1} NO_3^- resulted in comparatively greater NO_3^- accumulation. This trend indicates that co-application with NPK Green accelerates nitrification, but also increases soil acidification, as each nitrified NH_4^+ generates two hydrogen ions, thereby lowering soil pH and limiting the persistence of NO_3^- in acidic conditions. BSFL frass, with its moderately alkaline pH (7.64) (Hassan *et al*., 2023), was expected to buffer this acidification; however, the limited increase in soil NO_3^- suggests that BSFL frass mineralization primarily favors NH_4^+ retention rather than sustaining NO_3^- availability under acidic soil environments. The findings highlight the dual role of BSFL frass: while it enhances total N and stabilizes NH_4^+ pools, its effectiveness in supporting NO_3^- accumulation is constrained when used with ammonium-based fertilizers in acid soils such as the Bekenu Series. This indicates that optimizing the ratio of BSFL frass to NPK fertilizer is essential. Low amount of BSFL frass fails to counteract acidification, while excessive frass may shift N dynamics towards NH_4^+ retention at the expense of NO_3^- availability. From a management perspective, frass could be strategically applied not only as a nutrient source but also as a buffering amendment to improve soil acidity and enhance long-term N retention efficiency. After 120 DAP, soil available P increased markedly with higher rates of BSFL frass application, as observed in SF1 (5.75 mg kg^{-1}) and SFN1 (5.32 mg kg^{-1}), which were significantly higher compared to SFN2, SFN3, and S0 (0.37–1.27 mg kg^{-1}) (**Table 4**). The increase in available P under higher BSFL frass rates can be attributed to improvements in soil pH, as BSFL frass with alkaline nature (pH 7.64) buffered soil acidity. By reducing the concentration of H^+ ions, frass minimized the hydrolysis of Al^{3+} and Fe^{3+} ions, thereby suppressing the formation of insoluble Al–P and Fe–P complexes. This reaction enhanced the solubility of phosphate ions, making P more available for plant uptake. The findings emphasize the role of BSFL frass which did not only serve as a direct nutrient source but also as an amendment that modifies soil chemical reactions to improve P bioavailability, particularly in acidic soils such as the Bekenu Series whereby P fixation is otherwise a major constraint to crop growth. For sago palm, improved soil P availability is especially critical as P supports vigorous root development, enhances tillering capacity, and facilitates efficient energy transfer, ultimately influencing starch accumulation in the trunk. Thus, the observed improvement in soil P under frass application directly supports physiological processes essential for sago palm growth and productivity.

In contrast, soil available K was significantly higher in the NPK Green-only treatment (SN: 198.33 mg kg^{-1}) compared with all BSFL frass-amended treatments (17.67–45.33 mg kg^{-1}) (**Table 4**). This reflects the high solubility and immediate release of K from inorganic fertilizer compared to the slower, more gradual release from organic amendments. The lower K levels in BSFL frass-treated soils may also indicate rapid crop uptake or potential leaching losses due to the coarse texture and low CEC of Bekenu soils. While this highlights the strength of NPK Green in providing readily available K, it also underscores the importance of synchronizing nutrient release from organic amendments such as BSFL frass to reduce nutrient loss and improve efficiency. For sago palm, potassium plays a central role in carbohydrate metabolism and the translocation of assimilates to the trunk, where starch is stored. Insufficient K supply could therefore limit starch accumulation even when other nutrients are adequate, reinforcing the need to complement frass application with targeted K inputs (Jimmy *et al*., 2024).

From a crop perspective, improved P availability supports root development and starch biosynthesis in sago palm seedlings, while adequate K supplementation remains essential to maximize carbohydrate translocation and trunk starch accumulation. The challenge, therefore, lies in optimizing the combined use of BSFL frass and NPK Green to maximize N and P benefits while ensuring sufficient K supply for sustaining sago palm growth and productivity in Bekenu Series soil.

Table 4. Soil Selected physico-chemical properties at one hundred and twenty (120) days after planting

Variables	S0	SF	SN1	SFN1	SFN2	SFN3
pH	4.80 ± 0.06^{b}	5.10 ± 0.06^{ab}	4.89 ± 0.06^{ab}	4.96 ± 0.10^{ab}	5.02 ± 0.03^{ab}	4.98 ± 0.12^{ab}
CEC ($cmol_{(+)}\ kg^{1}$)	6.17 ± 0.64^{ab}	3.67 ± 0.17^{cd}	1.53 ± 0.20^{d}	5.80 ± 0.42^{abc}	6.70 ± 0.72^{a}	5.43 ± .58^{abc}
EC (ds m^{-1})	15.32 ± 0.46^{a}	7.87 ± 0.30 ^{c}	6.38 ± 0.46^{c}	8.49 ± 0.33^{b}	9.52 ± 0.11^{c}	6.90 ± 0.48^{d}
TOC (%)	3.07 ± 0.16^{ab}	3.59 ± 0.03^{a}	3.57 ± 0.36^{a}	2.55 ± 0.27^{ab}	1.75 ± 0.17^{b}	3.35 ± 0.43^{ab}
TOM (%)	5.30 ± 0.27^{ab}	6.19 ± 1.09^{a}	6.15 ± 0.62^{a}	4.40 ± 0.46^{ab}	3.01 ± 0.29^{b}	5.78 ± 0.74^{ab}
Total N (%)	0.04 ± 0.01^{cd}	0.07 ± 0.01^{ac}	0.03 ± 0.00^{d}	0.09 ± 0.01^{ab}	0.07 ± 0.01^{ab}	0.04 ± 0.01^{cd}
NH_4^+ (mg kg^{-1})	0.0016 ± 0.0002^{c}	0.0023 ± 0.0002^{bc}	0.0019 ± 0.0002^{c}	0.0033 ± 0.0002^{b}	0.0033 ± 0.0002^{b}	0.0044 ± 0.0002^{a}
NO_3^- (mg kg^{-1})	0.0023 ± 0.0002^{c}	0.0021 ± 0.0000^{c}	0.0030 ± 0.0002^{bc}	0.0026 ± 0.0002^{bc}	0.0037 ± 0.0005^{ab}	0.0049 ± 0.0000^{a}
P (mg kg^{-1})	0.71 ± 0.04^{c}	5.75 ± 0.04^{a}	4.43 ± 0.36^{b}	5.32 ± 0.36^{ab}	0.37 ± 0.02^{c}	0.90 ± 0.08^{c}
K (mg kg-^{1})	18.33 ± 1.45^{b}	21.00 ± 3.79^{b}	198.3 ± 19.22^{a}	31.83 ± 2.52^{b}	33.83 ± 5.09^{b}	45.33 ± 2.46^{b}

Note: CEC is cation exchange capacity; TOC is total organic carbon; TOM is total organic matter; S0 is soil only, SF is standard recommendation for black soldier fly larvae frass (100%); SN1 is Craun research recommendation (NPK green 100%) SFN1 is black soldier fly larvae frass (100%) and NPK green (100%); SFN2 is black soldier fly larvae frass (80%) and NPK green (80%); SFN3 black soldier fly larvae frass (100%) and NPK green (40%); The values given are means followed by ± standard error.

Height, stem, and roots development of clonal sago palm seedlings

The standard fertilization regime with NPK Green alone (SN1) did not improve clonal sago palm seedling growth performance, as reflected in the lowest values of palm height, stem diameter, and root development compared to all other treatments (**Table 5**). This poor response can be attributed to the highly acidic and nutrient-deficient nature of Bekenu Series soil, whereby the exclusive use of soluble inorganic fertilizer promotes nutrient losses through leaching and soil acidification, thereby limiting nutrient uptake efficiency. In contrast, the incorporation of BSFL frass, either in combination with NPK Green (SFN1, SFN2, SFN3) or as a sole amendment (SF), consistently enhanced growth parameters. The improvements in palm height, stem diameter, and root development indicate that BSFL frass supplied not only essential nutrients but also organic matter that improved soil chemical properties and nutrient retention. The presence of organic matter seemingly buffered soil acidity, reduced Al^{3+} toxicity, and enhanced cation exchange capacity, thereby increasing nutrient availability in forms more accessible to sago palm seedlings. This synergistic effect of organic input explains the effectiveness of BSFL frass-amended treatments consistently outperformed the sole application of NPK Green.

Notably, the unfertilized control (S0) recorded better growth performance than the NPK-only treatment (SN1), underscoring the inefficiency of applying inorganic fertilizer in isolation under such soil conditions (**Table 5**). This finding suggests that, in Bekenu Series soil, chemical fertilizers alone may exacerbate soil constraints rather than alleviate them, highlighting the need for organic amendments to improve fertilizer use efficiency. Overall, these results reinforce the critical role of BSFL frass in improving seedling vigor and overcoming the inherent fertility limitations of Bekenu Series soil. By integrating BSFL frass into the fertilization regime, soil acidity can be ameliorated, nutrient cycling improved, and root development stimulated, thereby establishing stronger early growth in clonal sago palm seedlings. This points to a more sustainable fertilization strategy where organic amendments are not merely supplementary, but essential for ensuring the effectiveness of inorganic fertilizer inputs in nutrient-poor tropical soils (Latifah *et al*., 2021).

Table 5. Height, stem, and roots development of clonal sago palm seedlings following different fertilizations.

	Growth Parameters (cm)		
Treatment	Height	Stem Diameter	Roots
S0	33.33 ± 4.91ab	3.43 ± 0.29a	46.00 ± 7.81a
SN1	14.00 ± 0.58d	2.90 ± 0.06a	26.66 ± 5.33b
SFN1	32.00 ± 3.79abc	3.40 ± 0.10a	41.33 ± 4.18a
SFN2	28.33 ± 2.33bc	3.17 ± 0.43a	46.00 ± 3.06a
SFN3	28.00 ± 2.89bc	3.33 ± 0.29a	40.67 ± 4.10a
SF	32.00 ± 1.53abc	3.00 ± 0.00a	44.00 ± 6.43a

Note: Different letters within a column indicate significant difference of means using Tukey's test at $p \leq 0.05$.

Nitrogen, phosphorus and potassium uptake in clonal sago palm seedlings

Application of BSFL frass alone (SF) significantly improved N and P uptake in the leaves of clonal sago palm seedlings compared to NPK Green alone (SN1) (**Tables 6** and 7), but it did not enhance K uptake across any plant tissues (**Table 8**). The preferential increase in N and P uptake indicates that BSFL frass enhanced the immediate availability of these nutrients, particularly N, which is closely linked to leaf expansion, chlorophyll synthesis, and photosynthetic capacity. Enhanced foliar N and P status explains the observed improvements in aboveground leaf development, which typically responds more rapidly to nutrient inputs than structural tissues (**Tables 6** and **7**). However, this nutrient-driven improvement in leaf uptake did not translate into significant gains in stem diameter or root development. This disconnect suggests that while BSFL frass improved short-term nutrient supply, carbon allocation to structural growth is a slower process that requires sustained nutrient availability and a longer experimental timeframe than the 120 days assessed. Furthermore, the lack of response in root development may reflect the persistent physical and chemical limitations of Bekenu Series soil. The high acidity and low soil CEC restrict root proliferation and nutrient retention, conditions that organic amendments such as BSFL frass only gradually ameliorate through pH buffering, enhanced cation exchange, and improved soil organic matter dynamics.

The absence of improvement in K uptake across tissues also warrants critical consideration (**Table 8**). Unlike N and P, which are rapidly mineralized from organic inputs, the release of K from BSFL frass may be slower or less efficient, potentially due to its chemical binding in organic matrices or competitive interactions with NH_4^+, Ca^{2+} and Mg^{2+} at exchange sites. As K plays a crucial role in carbohydrate translocation and stem thickening, its limited availability may partly explain why structural parameters such as stem diameter remained unresponsive despite improvements in foliar nutrient status. Thus, the benefits of BSFL frass application manifest first in aboveground foliage through enhanced N and P availability, while improvements in stem and root development are contingent on longer-term soil amelioration and balanced nutrient release, particularly K. This highlights the need for integrated fertilization strategies whereby BSFL frass not only complements inorganic N and P sources but is also supplemented with targeted K inputs to support both immediate leaf productivity and long-term structural development in clonal sago palm seedlings.

Table 6. Nitrogen uptake in clonal sago palm tissues after 120 days of pot study.

	Nitrogen Uptake (mg plant^{-1})		
Treatment	Leaf	Stem	Root
S0	1.80 ± 0.14abc	2.18 ± 0.13a	0.99 ± 0.14b
SN1	1.01 ± 0.01c	1.78 ± 0.06a	0.97 ± 0.12b
SFN1	1.81 ± 0.32abc	2.29 ± 0.61a	1.32 ± 0.1ab
SFN2	1.14 ± 0.07bc	2.48 ± 0.16a	1.04 ± 0.05b
SFN3	1.93 ± 0.04abc	2.30 ± 0.31a	1.62 ± 0.30ab
SF	2.11 ± 0.14a	2.07 ± 0.22a	1.73 ± 0.27ab

Note: Different letters within a column indicate significant difference of means using Tukey's test at $p \leq 0.05$.

Table 7. Phosphorus uptake clonal sago palm tissues after 120 days of pot study.

	Phosphorus Uptake (mg plant^{-1})		
Treatment	Leaf	Stem	Root
S0	0.109 ± 0.008abc	0.211 ± 0.032abc	0.065 ± 0.011ab
SN1	0.082 ± 0.010c	0.092 ± 0.011c	0.034 ± 0.004b
SFN1	0.089 ± 0.004abc	0.124 ± 0.010abc	0.116 ± 0.013ab
SFN2	0.072 ± 0.010c	0.113 ± 0.020c	0.072 ± 0.015ab
SFN3	0.100 ± 0.013abc	0.107 ± 0.018abc	0.075 ± 0.007ab
SF	0.150 ± 0.012abc	0.102 ± 0.004abc	0.085 ± 0.011ab

Note: Different letters within a column indicate significant difference of means using Tukey's test at $p \leq 0.05$.

Nitrogen, phosphorus and potassium use efficiency of clonal sago palm seedlings

Nitrogen use efficiency (NUE) following the application of BSFL frass alone (SF), co-application with NPK Green (SFN1, SFN2, SFN3), or NPK Green alone (SN1) did not show significant improvement relative to the control (S0) (**Table 9**). However, the NUE values for SN1 were particularly poor, with –0.17 mg plant^{-1} in roots and –4.32 mg plant^{-1} in leaves. These negative values indicate that NPK Green alone was ineffective in promoting N uptake under Bekenu Series soil conditions. The likely explanation lies in the acidic soil environment (pH 4.89), which promotes NH_4^+ fixation on variable charge surfaces and enhances microbial immobilization, thereby reducing the pool of available mineral N following inorganic fertilizer application (Wang *et al*., 2019). As a result, N assimilation into foliage was strongly suppressed, explaining the negative NUE in leaves for SN1 **(Table 9)**.

Table 8. Potassium uptake clonal sago palm tissues after 120 days of pot study.

	Potassium Uptake (mg plant^{-1})		
Treatment	Leaf	Stem	Root
S0	0.005 ± 0.003	0.003 ± 0.002	0.001 ± 0.001
SN1	0.016 ± 0.006	0.006 ± 0.002	0.014 ± 0.005
SFN1	0.013 ± 0.003	0.018 ± 0.005	0.004 ± 0.001
SFN2	0.018 ± 0.009	0.015 ± 0.007	0.011 ± 0.005
SFN3	0.019 ± 0.009	0.025 ± 0.012	0.006 ± 0.003
SF	0.005 ± 0.002	0.003 ± 0.001	0.005 ± 0.002

Note: Different letters within a column indicate significant difference of means using Tukey's test at $p \leq 0.05$.

A similar trend was observed in SFN2, whereby leaf NUE was negative despite the inclusion of BSFL frass. This outcome may be attributed to transient immobilization of N during the early mineralization phase of organic matter in BSFL frass (Marzi *et al*., 2020), which temporarily restricts the availability of mineral N for crop uptake. Over time, however, the mineralization process would be expected to improve N release and uptake, suggesting that the short 120-day experimental may not fully capture the benefits of the BSFL frass application. For the unfertilized soil (S0), the negative NUE observed in roots is expected, as the absence of supplemental N inputs limited root N uptake and development (Gastal & Lemaire, 2018). Collectively, these results highlight that while BSFL frass has potential to enhance N retention and uptake, the balance between immediate N release and temporary immobilization is critical. Optimizing the application rate and timing of BSFL frass relative to crop demand may therefore be necessary to maximize NUE in clonal sago palm seedlings grown in Bekenu soils.

Table 9. Effects of treatment on clonal sago palm nitrogen efficiency (mg plant^{-1}) at one hundred and twenty (120) days after planting

	Nitrogen efficiency (mg plant^{-1})		
Treatment	Leaf	Stem	Root
S0	0.0009 ± 0.81abc	11.3990 ± 0.66ab	-0.0014 ± 0.80b
SN1	-4.3251 ± 0.32c	8.5956 ± 0.95b	-0.1729 ± 0.72b
SFN1	-0.0667 ± 1.77abc	10.9099 ± 3.27ab	1.6426 ± 0.55ab
SFN2	-3.8930 ± 0.41bc	13.2537 ± 0.90ab	0.2982 ± 0.32b
SFN3	0.7499 ± 0.21abc	12.2898 ± 1.90ab	3.7244 ± 1.77ab
SF	1.7868 ± 0.86a	11.0306 ± 1.29ab	4.3529 ± 1.56ab

Note: Mean between columns with different letters indicates significant difference tested by Tukey's test at $P \leq 0.05$. mean value ± standard error

Phosphorus use efficiency (PUE) was markedly higher in BSFL frass alone (SF: 0.09–0.18 mg plant^{-1}) compared to all other treatments, including combined applications (SFN1, SFN2, SFN3) and NPK Green alone (SN1), which recorded negative values (–0.005 to –0.009 mg plant^{-1}) (**Table 10**). The negative PUE values indicate that despite fertilizer application, P was either unavailable or not effectively utilized by the clonal sago palm seedlings. The less PUE can be attributed to the acidic nature of Bekenu Series soil (pH 4.89), whereby applied P is prone to fixation by Fe and Al oxides, thus reducing plant availability (Rasool *et al*., 2021). In

SN1, where P was directly supplied through NPK Green, most of the added P seemingly became immobilized, preventing efficient P uptake. Root PUE was also negative in both the control (S0) and SN1 (**Table 10**). For S0, this was expected owing to no external P input was provided. However, in SN1, the negative root PUE highlights the limitation of relying solely on inorganic fertilizer in acidic, low-CEC soils. In such environments, P fixation is exacerbated, and inorganic fertilizers have less effect to improve soil structure or microbial activity, both of which are important in mobilizing and solubilizing P for plant uptake (Ch'ng *et al*., 2019).

In contrast, the BSFL frass in SF contributed not only a direct source of P but also organic compounds that enhanced microbial activity and released organic acids, thereby reducing P fixation and increasing P availability (Luo *et al*., 2018). These findings emphasize that organic amendments such as BSFL frass are critical for overcoming P limitations in acidic sandy soils. The improvement in PUE under frass application indicates its role in sustaining root access to available P, which is particularly important for sago palm seedlings, where P is required for early root establishment and energy transfer processes that underpin long-term starch accumulation.

Table 10. Effects of treatment on clonal sago palm phosphorus efficiency (mg plant^{-1}) at one hundred and twenty (120) days after planting

	Phosphorus efficiency (mg plant^{-1})		
Treatment	Leaf	Stem	Root
S0	-0.0009 ± 0.049b	1.3202 ± 0.200a	-0.0013 ± 0.065a
SN	-0.0058 ± 0.002b	0.0186 ± 0.002b	-0.0063 ± 0.001a
SFN1	-0.0041 ± 0.001b	0.0257 ± 0.003b	0.0105 ± 0.002a
SFN2	-0.0096 ± 0.002b	0.0292 ± 0.005b	0.0019 ± 0.004a
SFN3	-0.0029 ± 0.005b	0.0374 ± 0.008b	0.0040 ± 0.03a
SF	0.1842 ± 0.053a	0.4516 ± 0.014a	0.0902 ± 0.053a

Note: Mean between columns with different letters indicates significant difference tested by Tukey's test at $P \leq 0.05$. mean value ± standard error

The combined application of BSFL frass and NPK Green (SFN1, SFN2, SFN3) as well as NPK Green alone (SN1) slightly affect KUE in the leaf and stem biomass of clonal sago palm seedlings compared to BSFL frass alone (SF) and the unfertilized control (S0) (**Table 11**). This suggests that the soluble K component of NPK Green was readily available for uptake, while the presence of BSFL frass may have enhanced K retention in the soil by supplying organic matter and improving soil CEC. As a result, co-application facilitated a modest increase in K assimilation into aboveground tissues. Comparable findings have been reported in maize, where application of 7.5 t ha^{-1} of BSFL frass increased K uptake by 44% during the short rainy season compared with synthetic fertilizer alone (Gärttling & Schulz, 2021).

However, the observed increase in KUE under co-application was relatively modest, indicating that K dynamics in Bekenu Series soil remain constrained. This soil, being sandy loam with inherently low exchangeable K, is prone to leaching losses, and the contribution of BSFL frass-derived K may not be sufficient to offset these losses in the short term. Moreover, sago palm seedlings may prioritize N and P acquisition for early root and leaf development, with K demand becoming more pronounced in later growth stages when osmotic regulation and carbohydrate transport play larger roles. Thus, while BSFL frass integration improves K availability relative to unfertilized or frass-only treatments, its benefits may be more evident over longer growth cycles when K is critical for starch accumulation and translocation in sago palm.

Table 11. Effects of treatment on clonal sago palm potassium efficiency (mg plant^{-1}) at one hundred and twenty (120) days after planting

	Potassium efficiency (mg plant^{-1})		
Treatment	Leaf	Stem	Root
S0	0.0028 ± 0.02b	0.00001 ± 0.01b	0.00002 ± 0.01a
SN1	0.0577 ± 0.03a	0.0159 ± 0.01a	0.0023 ± 0.01a
SFN1	0.0425 ± 0.02a	0.0758 ± 0.03a	0.00002 ± 0.01a
SFN2	0.0661 ± 0.04a	0.0608 ± 0.03a	0.0023 ± 0.01a
SFN3	0.0791 ± 0.05a	0.1193 ± 0.06a	0.00002 ± 0.01a
SF	0.0030 ± 0.01b	0.0023 ± 0.01b	0.0023 ± 0.01a

Note: Mean between columns with different letters indicates significant difference tested by Tukey's test at P ≤ 0.05. mean value ± standard error

Table 12. Chlorophyll content of clonal sago palm seedlings at 40, 80, and 120 days of pot study.

	Chlorophyll content		
Treatment	40 days	80 days	120 days
S0	63.00 ± 1.83a	65.33 ± 0.34c	63.17 ± 0.34c
SN1	56.97 ± 5.86a	68.83 ± 0.38a	86.60 ± 0.38a
SFN1	61.20 ± 2.40a	67.00 ± 0.70abc	83.23 ± 0.70ab
SFN2	62.10 ± 4.15a	65.37 ± 0.32c	75.47 ± 0.32ab
SFN3	65.47 ± 2.97a	67.23 ± 0.35abc	77.07 ± 0.35ab
SF	59.33 ± 2.10a	66.53 ± 0.24bc	71.33 ± 0.24ab

Note: Different letters within a column indicate significant difference of means using Tukey's test at p ≤ 0.05.

Chlorophyll content in clonal sago palm seedlings, measured at 40, 80, and 120 days, was not significantly influenced by fertilizer application across treatments or rates (**Table 12**). This uniformity suggests that leaf N concentrations in all treatments, whether derived from NPK Green or mineralized from BSFL frass, were sufficient to meet the minimum threshold required for chlorophyll synthesis. Consequently, SPAD readings could not resolve subtle differences in total N uptake among treatments, owing to chlorophyll content typically only responds when leaf N falls below or exceeds critical levels necessary for maintaining the photosynthetic apparatus. The consistency of chlorophyll content across treatments indicates that early N availability was adequate to maintain photosynthetic stability during the 120-day growth cycle. However, sustained crop productivity in clonal sago palm seedlings is not solely dependent on chlorophyll maintenance. Beyond meeting the basic requirement for photosynthesis, N partitioning into structural and storage tissues plays a decisive role in long-term yield potential. In particular, N allocation to the pith is crucial for supporting carbohydrate metabolism and starch accumulation, which are the primary determinants of sago palm productivity. Thus, while uniform chlorophyll levels demonstrate that seedlings were not under foliar N deficiency stress, differences in fertilizer treatments may still influence how N is distributed within the plant. This partitioning will ultimately determine the palm's capacity to support vigorous growth and starch yield over the longer cropping cycle.

CONCLUSION

The amendment of BSFL frass with NPK Green improved clonal sago palm seedlings growth performance by enhancing palm height, root development, and nutrient (N, P, and K) uptake and use efficiency, particularly under SF and SFN1 treatments. Notably, the combined use of BSFL frass with lower rates of NPK Green (SFN2 and SFN3) and sole application of BSFL frass (SF) also showed promising effects, suggesting that these regimes could be integrated into fertilizer management for clonal sago palm seedlings at four months of age. In contrast, the recommended fertilizer regime (SN1) did not significantly improve N, P, and K uptake or chlorophyll content, indicating its limited suitability for clonal sago palm seedlings cultivated in Bekenu Series soil at the nursery stage. These findings highlight the potential of BSFL frass, either alone or in combination with reduced rates of NPK Green, to serve as a sustainable fertilization strategy for clonal sago palm seedlings in acidic tropical soils. However, due to a pot study was limited to 120 days, the long-term effects of these fertilizer regimes on nutrient dynamics, biomass allocation, and starch accumulation in the palm's pith remain unclear. Extending fertilizer evaluation beyond 120 days is therefore essential to capture more pronounced responses and to establish fertilizer recommendations that optimize both early growth and long-term productivity of clonal sago palm under Bekenu Series soil conditions.

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