Malaysian Journal of Soil Science 2026 Vol. 30: 299-317
Received: 3/4/2026; Revised: 3/10/2026; Accepted: 6/11/2026; Online: 8/11/2026

Nitrogen And Phosphorus Uptake and Recovery in Maize Cultivation Following Application of Urea, Egyptian Rock Phosphate, and Black Soldier Fly Larvae Frass

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ABSTRACT

Bekenu Series has low pH, poor organic matter content, and limited basic nutrients which hindered crop production. This study evaluated the effects of combining urea, Egyptian rock phosphate (ERP), and BSFL frass on dry matter, nitrogen (N) uptake, phosphorus (P) uptake, and nutrient use efficiency. A pot experiment was conducted using maize grown in Bekenu Series soil under seven different fertilizers treatments (UP, UP_1F_1, UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3). Plants were harvested at the tasseling stage. Urea, ERP and BSFL frass combination (UP_1F_1, UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) significantly improved dry matter of maize with the range of 56.9 g plant^{-1} to 63.2 g plant^{-1} compared with UP (11.5 g plant^{-1}). Greater N uptake (0.76 to 0.88 g plant^{-1}) was achieved in all combined fertilizers with BSFL frass application compared with fertilizer only (UP) (0.17 g plant^{-1}). Higher P uptake recorded in maize fertilized with UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 (0.41 to 0.45 g plant^{-1}), compared with UP (0.09 g plant^{-1}) and UP_1F_1 (0.23 g plant^{-1}). The UP treatment did not improve nutrient use efficiency, with lower N use efficiency (9.79%) than combined fertilizers and BSFL frass. In contrast, treatments UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 recorded higher N use efficiency, ranging from 15% to 20%. Similarly, P use efficiency was higher in the combined fertilizer with BSFL frass treatments (5% to 7%) than those of fertilizer only treatment (2%). UP_2F_1, UP_2F_2, and UP_2F_3 showed best improvements in N and P uptake and use efficiency.

***Key words**: Acidification, frass, functional groups, nutrient use efficiency, organic fertilizer*

INTRODUCTION

The mineral soils of Malaysia, mainly classified as Ultisols and Oxisols, are generally acidic and characterized by low organic matter (OM) content and limited cation exchange capacity (CEC). These properties result from intense weathering and high rainfall, which promote the leaching of essential base cations (Ch'ng *et al*., 2014). The Bekenu Series soil under Oxisol order is low productivity soil with low nutrient content and not suitable for crop production but could be improved using fertilizers to supply nitrogen (N), phosphorus (P), and potassium (K) that are primary macronutrients required for plant growth and development. These essential elements are needed in relatively large quantities to support key physiological processes and achieve optimal crop productivity. However, these elements are often insufficient for crop uptake because of nutrient loss or are unavailable through numerous loss pathways. For example, the inorganic N, such as ammonium (NH_4^+) subjected to loss *via* ammonia (NH_3) volatilization and nitrate (NO_3^-) and K are lost from the soil profile due to leaching (Omar *et al*., 2021). In acidic soils, P availability is often limited because it becomes fixed through

reactions with aluminium (Al) and iron (Fe) oxides and hydroxides, reducing its accessibility for plant uptake (Johan *et al*., 2021). The approach in this study is to use soil organic amendment such as black soldier fly larvae (BSFL) frass to improve N and P retention in soil for crop uptake. Potassium is not included in this focus because the test crop (maize) is cultivated until tasselling stage and not for maize yield measurement. Frass are referred to the excretion of BSFL including the indigested feeding materials and larvae exoskeleton when BSFL metamorphosed to pupae (Hassan *et al*., 2025; David *et al*., 2024). Black soldier fly larvae (BSFL) frass is a by-product of larval digestion composed of insect excreta and residual organic matter. It is rich in organic matter as well as essential macro- and micronutrients, making it a promising soil amendment for improving soil fertility (Bortolini *et al*., 2020). According to Vickerson *et al*. (2017), BSFL frass contains approximately 5% total nitrogen (N), 2% total P, and 2% total K. Previous studies have also demonstrated that the application of BSFL frass enhances crop performance, including increased yields of maize (Beesigamukama *et al.,* 2020) and lettuce (Chiam *et al*., 2021), and kale (*Brassica oleracea* var. sabellica) (Romano *et al*, 2023).

Soil amendment such as frass or compost has been reported to improve N retention in soil and enhanced P sorption in soils, particularly in tropical acidic soils (Beesigamukama *et al*., 2020). The N retention in soil and P sorption significantly enhance soil fertility and nutrient availability, resulting in organic amendments being considered as an essential component of sustainable soil management. Beesigamukama *et al*. (2020) suggested that the application of minerals and organic fertilisers is highly recommended to improve soil fertility and crop yields. According to Hassan *et al*. (2025), combined application of BSFL frass with chemical fertilizers (NPK Green) able to enhance N, P, and K retention in soil, thus enhanced nutrient use efficiency in sago palm seedlings cultivated at main nursery stage. The combined BSFL frass with chemical fertilizers did not only optimize plant nutrient uptake and crop productivity but also mitigates nutrient losses, reduces environmental degradation associated with intensive chemical fertilizer use (Hassan *et al*., 2025). In our previous work carried out on BSFL frass production from palm oil wastes, we found that BSFL frass contains approximately 2% total N, 0.48% total P, with high organic matter which is important for decomposition of N and P (David *et al*., 2024).

There is limited information available on the combined application of BSFL frass with chemical fertilizers in maize cultivated in Bekenu Series soil. Bekenu Series soil is considered as low productivity soil but could be improved using the right fertilizer. In a study of Beesigamukama *et al*. (2020), the authors reported that BSFL frass can enhance maize growth, nutrient uptake, and grain yield due to its rich nutrient content and ability to improve soil fertility and microbial activity (Beesigamukama *et al*., 2020). Previous studies have shown that BSFL frass can enhance nitrogen uptake and increase agronomic nitrogen use efficiency in maize compared with the use of conventional fertilizers alone (Beesigamukama *et al*., 2020). Furthermore, integrating BSFL frass with NPK fertilizers has been found to improve maize growth and productivity (Beesigamukama *et al*., 2020). Similarly, Mokhtar *et al*. (2025) reported that combining organic amendments, such as ground sago bark ash, with inorganic fertilizers improved nutrient use efficiency while maintaining sustainable crop production. Despite these promising findings, information on the optimum application rate of BSFL frass for maintaining N and P availability in Bekenu Series remains limited. This study was designed to determine whether appropriate rates of BSFL frass, used as a soil amendment, could enhance dry matter production, increase N and P uptake, and improve nutrient recovery in maize grown on Bekenu Series soil. Accordingly, a pot experiment was conducted to evaluate the effects of applying urea, Egyptian rock phosphate, and BSFL frass on N and P uptake and nutrient recovery in maize cultivated in Bekenu Series soil.

Malaysian Journal of Soil Science 2026 Vol. 30: 299-317
Received: 3/4/2026; Revised: 3/10/2026; Accepted: 6/11/2026; Online: 8/11/2026

MATERIALS AND METHODS

Soil sampling, preparation and analysis

Bekenu Series soil (*Typic Paleudult)* used in this study was collected from an uncultivated site at Universiti Putra Malaysia, Sarawak (3°12′20″ N, 113°04′20″ E). Soil samples were randomly obtained from the 0–20 cm surface layer using a shovel. According to Shaliha *et al.* (2012), the Bekenu Series is classified as a fine-loamy, mixed, isohyperthermic *Typic Paleudult*, characterized by a yellowish-brown (10YR 6/4) surface horizon and a brownish yellow (10YR 6/8) subsoil throughout the remaining profile. After collection, the soil samples were air-dried, manually crushed, and sieved. Samples passed through a 2 mm sieve were used for chemical analyses and soil incubation, whereas those passed through a 5 mm sieve were reserved for the pot experiment. Selected physicochemical properties of the soil were determined before and after the incubation and pot experiments using standard analytical procedures. Soil bulk density was measured using the core method described by Dixon and Wisniewski (1995). A metal core was driven into the soil with a hammer and carefully removed to preserve the intact soil sample. Excess soil was trimmed flush with both ends of the core, which were then sealed with plastic caps. The core containing the soil sample was weighed before being oven-dried at 105 °C until a constant weight was achieved. Soil bulk density was subsequently calculated using the following equation:

$$Bulk\ density\ (g\ cm^{-3}) = oven - dry\ weight\ of\ soil\ (g)/core\ sampler\ volume\ cm^3$$

Soil texture was determined using the Bouyoucos hydrometer method (Bouyoucos, 1962). A 50 g air-dried soil sample was transferred into a blender cup, followed by the addition of distilled water to approximately 10 cm below the rim. Subsequently, 10 mL of sodium metaphosphate solution was added as a dispersing agent, and the suspension pH was adjusted to 10 by adding 4 M NaOH dropwise. The mixture was blended for 15 minutes to ensure complete dispersion of soil particles. The dispersed soil suspension was then poured into a 1 L measuring cylinder and diluted to a final volume of 1130 mL with distilled water. After mixing thoroughly, a hydrometer was carefully inserted into the suspension, and the first reading was recorded after 40 seconds. The hydrometer stem was read at the meniscus level, after which the instrument was removed, rinsed, and set aside. The suspension was mixed again before taking the second hydrometer reading, which represented the combined silt and clay fraction (g). The suspension temperature was also measured and recorded each time the hydrometer was removed. The suspension was then stirred once more and allowed to settle undisturbed for 2 hours before the final hydrometer reading and temperature were recorded. This final reading represented the clay fraction (g) in the soil sample. The percentages of sand, silt, and clay were subsequently calculated using the following equations:

$$Percentage\ of\ sand + silt + clay = 100\%$$

40 seconds reading:

$$Percentage\ of\ silt + clay = (corrected\ reading\ (g)/weight\ of\ soil\ (g))\ \times 100 = W\%$$

After 2 hours of reading:

$$Percentage\ of\ clay = (corrected\ reading\ (g)/weight\ of\ soil\ (g))\ \times 100\% = Y\%$$

By difference:

$$Percentage\ of\ silt = W - Y$$

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Soil pH was measured using the potentiometric method described by Peech (1965). The analysis was conducted in both distilled water and 1 M potassium chloride (KCl) using a soil-to-solution ratio of 1:2.5. For each determination, 10 g of air-dried soil was placed in a plastic vial and mixed with 25 mL of either distilled water or 1 M KCl. The suspensions were shaken on a mechanical shaker at 180 rpm for 15 minutes. The soil-water suspension was allowed to equilibrate for 24 hours before pH measurement, whereas the pH of the soil-KCl suspension was measured immediately after shaking using a digital pH meter (SevenEasy pH, Mettler-Toledo GmbH, Switzerland). Soil organic matter (OM) and total organic carbon (TOC) were determined using the loss-on-ignition method (Cheftetz *et al.,* 1996). Air-dried soil samples were first oven-dried at 60 °C for 24 hours and then cooled in a desiccator. The empty porcelain crucible was weighed before adding 5 g of the dried soil sample. The crucibles containing the soil were placed in a muffle furnace and heated initially at 300 °C for 1 hour, followed by ignition at 550 °C for an additional 8 hours. After cooling, the crucibles were reweighed to determine the weight loss due to combustion. The percentages of OM and TOC were subsequently calculated using the following equations:

$$OM\ (\%) = ((Initial\ sample\ weight\ (g) - Final\ sample\ weight\ (g))/Initial\ sample\ weight) \times 100$$

$$TOC(\%) = ((Initial\ sample\ weight\ (g) - Final\ sample\ weight\ (g))/Initial\ sample\ weight) \times 100 \times 0.58$$

Cation exchange capacity (CEC) was determined using the leaching method (Cottenie, 1980) followed by steam distillation (Bremner, 1965). A leaching tube (20 cm in length and 2 cm in diameter) was prepared by placing Whatman ashless floc at the base and covering it with Whatman No. 2 filter paper. Then, 10 g of air-dried soil was added and covered again with filter paper to prevent disturbance during leaching. The soil was initially leached with 100 mL of 1 M ammonium acetate (NH_4OAc) over 5–6 hours. This was followed by rinsing with 25 mL of 95% ethanol, which was discarded after drainage. Subsequently, the soil was leached with 100 mL of 0.1 M potassium sulfate (K_2SO_4), and the leachate was collected in a 100 mL volumetric flask and adjusted to volume. A 10 mL aliquot of the extract was transferred into a distillation unit, followed by the addition of 10 mL of 40% NaOH. The mixture was then distilled, and the released ammonia was trapped in 10 mL of 2% boric acid indicator solution, with the final volume adjusted to 20 mL. The collected distillate was titrated against 0.01 M hydrochloric acid (HCl) until the solution changed colour from green to reddish-purple. CEC was then calculated using the standard equation provided below:

$$CEC\ (cmol_c\ kg^{-1}) = V \times M \times R \times (1000\ kg^{-1}/Wt)/10$$

where,

V = Volume of HCl used for titration
M = Molarity of HCL used for titration,
R = Ratio of volume of initial leachate to the volume of leachate used for distillation
Wt = Weight of air-dried sample

Measurement of soil ammonium-nitrogen and nitrate-nitrogen

Soil exchangeable NH_4^+ and available NO_3^- were determined using the method described by Keeney and Nelson (1982). A 5 g air-dried soil sample was extracted with 2 M potassium chloride (KCl) at a soil-to-solution ratio of 1:10 and shaken for 1 hour using a mechanical shaker. The suspension was then filtered through Whatman No. 2 filter paper, and the filtrate was collected for further analysis. For NH_4^+ determination, a 20 mL aliquot of the extract was transferred into a distillation tube, followed by the addition of approximately 0.2 g of magnesium oxide (MgO). The mixture was steam-distilled for 5 minutes, and the released

ammonia was absorbed in 10 mL of 2% boric acid indicator solution. For NO_3^- analysis, 0.2 g of Devarda's alloy was added to the same distillation setup, and the sample was subjected to an additional 5 minutes of steam distillation. The liberated ammonia was again trapped in 10 mL of 2% boric acid indicator solution. Both distillates were subsequently titrated with standardized 0.01 M hydrochloric acid (HCl). The concentrations of exchangeable NH_4^+ and available NO_3^- were then calculated using the equation provided below:

$$NH_4^+ / NO_3^-(mg\ kg^{-1}) = (V \times M \times 14.01/Vd) \times 100\% \times 10{,}000$$

where,
V = Volume of 0.01 M HCl used for titration (mL)
M = Molarity of HCl solution
14.01 = Atomic mass of N
Vd = Volume of filtrate used for distillation (mL)

Measurement of soil total nitrogen

Total N was determined using the Kjeldahl digestion method as described by Bremner (1965). A 0.5 g air-dried soil sample was placed into a 50 mL Kjeldahl digestion tube. A few drops of distilled water were added to moisten the sample, followed by 10 mL of concentrated sulfuric acid (H_2SO_4). A Kjeldahl catalyst tablet was then introduced, and the mixture was allowed to stand for 30 minutes to ensure initial digestion. The samples were subsequently heated in a digestion block at 180 °C for 1 hour, after which the temperature was increased to 320 °C and maintained for 4 to 5 hours until the digest became clear. After cooling, 30 mL of distilled water was added to each tube, and the mixture was homogenized using a vortex mixer. The digest was filtered to remove the remaining residue (sand fraction), and the filtrate volume was adjusted accordingly. For distillation, a 10 mL aliquot was transferred to a distillation flask, followed by the addition of 10 mL of 40% NaOH. The liberated ammonia was steam-distilled and trapped in 10 mL of 2% boric acid indicator solution until the collected volume reached twice the original amount. The distillate was then titrated against 0.01 M HCl. Total nitrogen content in the soil was calculated using the following equation:

$$Percentage\ of\ total\ N = ((V - B) \times M \times R \times 14.01/Wt \times 1000) \times 100$$

where,
V = Volume of 0.01 M HCl titrated for the sample (mL)
B = Digested blank titration volume (mL)
M = Molarity of HCl solution
14.01 = Atomic weight of nitrogen
R = Ratio of total volume of the digest and digest volume used for distillation
Wt = Weight of air-dry soil (g)

Measurement of soil available phosphorous and total phosphorus

Soil available P was determined using the Mehlich No. 1 double-acid extraction method followed by the molybdenum blue colorimetric procedure described by Murphy and Riley (1962). A 5 g air-dried soil sample was placed in a 250 mL Erlenmeyer flask, and 20 mL of double-acid extractant was added. The suspension was mechanically shaken at 180 rpm for 10 minutes to extract plant-available P effectively. The mixture was then filtered through Whatman No. 2 filter paper, and the clear filtrate was collected for analysis. Phosphorus concentration in the extract was measured using a UV–VIS spectrophotometer (PerkinElmer Lambda 25, USA) at 882 nm after colour development using the molybdenum blue method.

Soil total P was determined using the Aqua Regia digestion method (Gupta and Roget, 2004). A 2 g air-dried soil sample was weighed into a 250 mL conical flask, followed by the

Received: 3/4/2026; Revised: 3/10/2026; Accepted: 6/11/2026; Online: 8/11/2026

addition of 20 mL of aqua regia solution (a mixture of HCl and HNO_3 in a 3:1 ratio). The mixture was heated on a hot plate for 30 minutes until a clear digest was obtained. After cooling, the digest was filtered through Whatman No. 2 filter paper into a 50 mL volumetric flask, and the volume was adjusted with distilled water. Total P concentration was then measured using the molybdenum blue method (Murphy and Riley, 1962) with a UV–VIS spectrophotometer at 882 nm.

For colour development, acid molybdate (Reagent A) and ascorbic acid (Reagent B) stock solutions were prepared. Standard P solutions (0–0.6 ppm P) were prepared by pipetting 0, 1, 2, 3, 4, 5, and 6 mL of working standard into separate 50 mL volumetric flasks, followed by the addition of 8 mL of Reagent B. The solutions were then diluted to volume with distilled water and mixed thoroughly to develop the molybdenum blue colour. For soil samples, 4 mL of filtrate was transferred into a 50 mL volumetric flask, and 8 mL of Reagent B was added. The mixture was diluted to the mark with distilled water, shaken well, and left for complete colour development. Absorbance of standards and samples was measured using a UV–VIS spectrophotometer (PerkinElmer Lambda 25, USA). A calibration curve was constructed from the standard solutions, and concentrations of available and total P were calculated using the equation provided below:

$$P\ (mg\ kg^{-1})\ =\ (UV\ reading\ (ppm))\ x\ (50\ mL/A)\ x\ (B/Wt)$$

where,
A = Volume of extractant used for blue colour development
B = Initial volume of extractant
Wt = Weight of sample used for extraction

Preparation and characterization of black soldier fly larvae frass

Black soldier fly larvae (BSFL) frass used in this study was produced through the larval digestion and excretion of decanter cake and palm kernel expeller as feedstock. As reported in our previous study, the resulting frass contains considerable amounts of essential nutrients and is also rich in organic carbon (David *et al*., 2024).

Pot experiment

The pot experiment was carried out at the front yard of the Crop Science Department, Universiti Putra Malaysia Sarawak (UPMS), and arranged in a completely randomized design with three replications. Medium-sized plastic pots measuring 300 mm in diameter and 248 mm in height were filled with 7 kg of soil per pot, based on calculated soil bulk density. The maize test crop used was the Thai Super Sweet hybrid F1 variety (*Zea mays* L.). Fertilizer application rates were based on the recommended requirements for optimal maize growth, which are 60 kg N ha^{-1} (equivalent to 130 kg ha^{-1} urea) and 60 kg P_2O_5 ha^{-1} (equivalent to 214 kg ha^{-1} Egyptian rock phosphate), as reported by MARDI (1993). These field rates were converted to a per-plant basis, corresponding to 4.7 g urea per plant and 7.7 g Egyptian rock phosphate per plant. For BSFL frass, an application rate equivalent to 5 t ha^{-1} was used and similarly converted to a per-plant basis, resulting in 180 g of frass per plant. Prior to sowing, maize seeds were soaked in water for 24 hours to enhance germination. Urea, Egyptian rock phosphate (ERP), and BSFL frass were thoroughly incorporated into the soil one day before pot filling. Two seeds were sown in each pot, and thinning was carried out at 7 days after sowing (DAS), leaving one healthy plant per pot. Soil moisture was maintained at approximately 60% of water holding capacity throughout the experiment. Fertilizer applications were split into two equal doses and applied at 10 and 28 DAS, as described by Hasbullah (2016). Plants were harvested at the

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Received: 3/4/2026; Revised: 3/10/2026; Accepted: 6/11/2026; Online: 8/11/2026

tasseling stage, 52 DAS. The treatment structure used in the pot experiment is summarized in **Table 1**.

Table 1. Evaluation of fertilizer regimes on the growth and development of maize under pot conditions

Treatment	Property	Soil	Urea	ERP	BSFL frass
		(kg pot^{-1})	g plant^{-1}		
S0	Soil only	7	-	-	-
UP	Soil + 100% urea + 100% ERP	7	4.7	7.7	-
UP1F1	Soil + 100% urea + 100% ERP + 100% frass	7	4.7	7.7	180
UP2F1	Soil + 80% urea + 80% ERP + 100% frass	7	3.8	6.2	180
UP1F2	Soil + 100% urea + 100% ERP + 80% frass	7	4.7	7.7	144
UP2F2	Soil + 80% urea + 80% ERP + 80% frass	7	3.8	6.2	144
UP1F3	Soil + 100% urea + 100% ERP + 60% frass	7	4.7	7.7	108
UP2F3	Soil + 80% urea + 80% ERP + 60% frass	7	3.8	6.2	108

Notes: S0 represents soil without any fertilizer addition; UP is a conventional source of N (urea) and P (ERP); UP1 and UP2 are conventional sources of N and P at different rates; F1-F3 represents frass addition at different rates.

Plant samples preparation and analysis

Maize plants were harvested at the tasseling stage and separated into leaves, stems, and roots. Each plant component was oven-dried at 60 °C until a constant weight was achieved, after which dry biomass was recorded using a digital balance. Plant tissues were subsequently analysed for total nitrogen (N) and total phosphorus (P) to determine nutrient concentrations. Total P in plant samples was determined using the single dry-ashing method described by Cottenie (1980). Briefly, 1 g of oven-dried plant material was weighed into a porcelain crucible. The samples were ashed in a muffle furnace at 300 °C for 1 hour, followed by 520 °C for an additional 5 hours. After cooling in a desiccator, a few drops of distilled water were added, followed by 2 mL of concentrated hydrochloric acid (HCl). The samples were then evaporated to dryness on a hotplate inside a fume hood. Subsequently, 10 mL of 20% nitric acid (HNO_3) was added, and the mixture was reheated until the volume was reduced by half. The digest was then filtered through Whatman No. 2 filter paper into a 100 mL volumetric flask and made up to volume with distilled water. Phosphorus concentration was determined using a UV–VIS spectrophotometer (PerkinElmer Lambda 25, USA) at 882 nm following colour development using the molybdenum blue method. Nutrient uptake in maize was calculated by multiplying nutrient concentration by the corresponding plant dry weight. Nutrient recovery efficiency was then computed using the equation described by Dobermann (2005).

$$Nutrient\ uptake\ (g\ plant^{-1}) = nutrient\ concentration\ (\%) \times dry\ weight\ (g)$$
$$Nutrient\ recovery\ efficiency\ (\%) = \ (A - B/R) \times 100$$

where,
A = plant nutrient uptake from fertilized treatment (kg ha^{-1})
B = plant nutrient uptake from unfertilized treatment (kg ha^{-1})
R = rate of fertilizer nutrients applied

Statistical analysis

Data was analyzed using one-way analysis of variance (ANOVA) to assess the effects of different treatments (fertilizations). When significant differences were observed, means were separated using Tukey's honestly significant difference (HSD) test at a probability level of $p \leq 0.05$. All statistical analyses were carried out using Statistical Analysis System (SAS) software version 9.4 (SAS Institute, Cary, NC, USA).

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RESULTS AND DISCUSSION

Initial characterization of Bekenu Series soil and black soldier fly larvae frass

The soil used in this experiment categorized as the Bekenu Series, which is widely distributed in coastal regions of Sarawak, East Malaysia and is typically characterized by coarse texture and low inherent fertility. The texture of Bekenu Series consists of 47.4% sand, 26.6% silt, and 23 % clay (sandy loam). The soil pH values were 4.44 extracted with distilled water and 3.75 extracted with KCl, suggesting that the Bekenu Series soil is strongly acidic. The soil is low in bulk density with value of 1.14 g cm^{-3} (**Table 2**). The OM content was also low at 5.03%, corresponding to a TOC concentration of 2.91%. Total N was 0.18%, while exchangeable NH_4^+ and available NO_3^- were 4.20 mg kg^{-1} and 3.74 mg kg^{-1}, respectively. Soil total P was 6.07 mg kg^{-1} and available P was 5.41 mg kg^{-1}. The soil CEC was 4.67 $cmol_c$ kg^{-1}, which is common with the sandy loam texture (**Table 2).**

The BSFL frass pH values were alkaline with the values of 7.29 (H_2O) and 7.19 (KCl) and high in OM content (64.67%) and total carbon (37.51%) (**Table 2**). The CEC of frass was 22.90 $cmol_c$ kg^{-1}, considered as high and suitable to be used as a soil organic amendment (Hassan *et al.*, 2025). Total N in frass is high with the value of 3.91%, whereas exchangeable NH_4^+ (111.38 mg kg^{-1}) and available NO_3^- (123.98 mg kg^{-1}) were also high reflecting the readily potential mineralizable inorganic N forms (**Table 2**). Total P of 6222.50 mg kg^{-1} and available P of 1385.81 mg kg^{-1}, shows that frass have potential source of plant-available P (**Table 2**).

Table 2. Selected initial properties of Bekenu Series soil and black soldier fly larvae frass used in pot study

Properties	Soil	BSFL frass
Soil texture	Sandy loam	NA
pH (H_2O)	4.44 ± 0.22	7.29 ± 0.05
pH (KCl)	3.75 ± 0.01	7.19 ± 0.12
Bulk density (g cm^{-3})	1.14 ± 0.09	NA
Total carbon (%)	2.91 ± 0.60	37.51 ± 0.39
Total organic matter (%)	5.03 ± 1.04	64.67 ± 0.67
Total nitrogen (%)	0.18 ± 0.03	3.91 ± 0.16
Exchangeable ammonium (mg kg^{-1})	4.20 ± 0.40	111.38 ± 14.155
Available nitrate (mg kg^{-1})	3.74 ± 0.23	123.98 ± 12.24
Total phosphorus (mg kg^{-1})	6.07 ± 0.16	6222.50 ± 277.92
Available phosphorus (mg kg^{-1})	5.41 ± 0.33	1385.81 ± 231.72
Cation exchange capacity ($cmol_c$ kg^{-1})	4.67 ± 0.29	22.90 ± 2.32

Notes: The values given are on a dry-weight basis; Mean value followed by ± standard error; CEC: Cation exchange capacity; NA: not applicable.

Soil selected chemical properties following maize cultivation

Maize plants were harvested at 52 days after sowing (DAS) during the tasselling stage to evaluate the effects of fertilizer and BSFL frass applications on soil selected chemical properties. The combined application of chemical fertilizers and BSFL frass significantly increased soil pH measured in both distilled water and KCl compared with the untreated control soil (S_0) with the range of 4.5 to 5.8 (**Figure 1 and Figure 2**). Soil pH (H_2O) under the treatment receiving fertilizer alone (UP) and the treatment with 100% fertilizer combined with BSFL frass (UP_1F_1) did not differ significantly, and both remained within the slightly acidic range compared with other combined treatments (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) (**Figure 1**). A similar pattern was observed for soil pH measured in KCl, where the integrated fertilizer–frass treatments generally resulted in higher pH values relative to the control and fertilizer-only treatments (**Figure 2**). The soil pH measured in both water and KCl in the unfertilized soil (S_0) were low with pH of 4.44 extracted with H_2O and pH 3.75 extracted with KCl, reflecting the inherently acidic nature of the soil and its limited OM content as stated in **Table 2**. Soils with

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Received: 3/4/2026; Revised: 3/10/2026; Accepted: 6/11/2026; Online: 8/11/2026

low OM generally exhibit reduced buffering capacity and are therefore more susceptible to acidity. Similarly, the treatments receiving 100% chemical fertilizers (urea and ERP) (UP) and 100% chemical fertilizers combined with BSFL frass (UP_1F_1) exhibited comparable pH values within the slightly acidic range, which were lower than those observed in other combined fertilizers treatments (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) with the range of pH 4.5 to pH 5.8 (**Figure 1 and Figure 2**).

The low pH (pH 4.4 in water and pH 3.4 in KCl) in soil fertilized with urea and ERP only (UP) could be related to the urea hydrolysis in soil following application of urea. During urea hydrolysis, NH_4^+ is released in soil and further nitrified to NO_3^- through nitrification process. The process generates hydrogen ions (H^+) after which the concentration of this acidic cation dominated the soil and contribute to lowering soil pH (Hamidi *et al.,* 2021; Liu *et al*., 2023). The lack of OM content in the Bekenu Series soil as shown in **Table 2** (5.03%) affect soil capacity to hold nutrients, thus favour the N loss through NO_3^- leaching or *via* ammonia volatilization (Omar *et al.*, 2021). Whereas, the lower of soil pH (4.55 and 3.58) in UP_1F_1 than in other combined applications of urea, ERP, and frass (pH 5.54 -5.83) could be partly related to mineralization of P from 100% ERP applications and 100% BSFL frass which occurred greater when excessive of P sources added in the soil (Johan *et al*., 2022). Soils fertilized with urea, ERP and BSFL at moderated rates exhibited comparatively higher pH values, although no significant differences were observed among these treatments suggested that fertilizers could be applied at optimize rates to neutralize soil acidity.

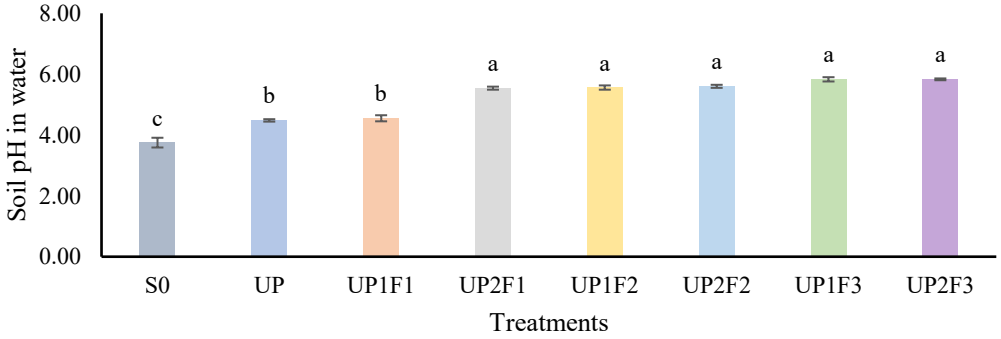


Figure 1. Effect of treatments on soil pH in water at tasselling stage (52 DAS). Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

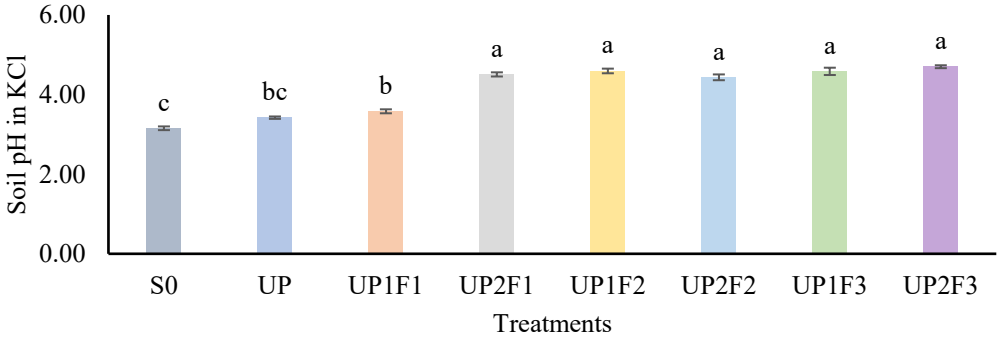


Figure 2. Effect of treatments on soil pH in KCl at tasselling stage (52 DAS). Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

The inclusion of frass with urea and ERP improved soil CEC as reflected in all fertilizers added with frass (12 $cmol_c\ kg^{-1}$) compared with fertilizer without addition of frass (UP) (6 $cmol_c\ kg^{-1}$) (**Figure 3**). The use of BSFL frass with urea and ERP significantly enhanced soil OM (5%) and total OC (3%) contents in all treatments compared with urea and

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ERP alone (UP) (**Figure 4 and Figure 5**). However, 100% fertilizer combined with BSFL frass (UP_1F_1) was low in OM (4%) and total OC (2.5%) contents compared with those treatments with higher amount of frass addition (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 - 5% OM and 3% OC). Seemingly, the higher amount of frass affects the improvement in soil OM build up and storage (**Figure 4 and Figure 5**). The low CEC values in soil fertilized with 100% urea and ERP (UP) compared with soil fertilized with combined application of urea, ERP, and BSFL frass (UP_1F_1, UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) seemingly related to the absence of additional organic materials presence in BSFL frass that have effects on increasing soil exchange sites. Without addition of BSFL frass, plant nutrients such as NH_4^+ released from urea hydrolysis could be more susceptible to leaching losses in the form of NO_3^- or volatilized as ammonia gas especially in sandy loam soil with lack of nutrient retention capacity (Omar *et al*., 2021). Consequently, the soil exchange complex is weakly developed, contributing to low CEC values (6.07 $cmol_c\ kg^{-1}$) as observed in application of 100% urea and ERP without addition of BSFL frass (**Figure 3**).

For soils fertilized with urea, ERP and BSFL frass in treatments UP_1F_1, UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3, the values of soil CEC (average of 12 $cmol_c\ kg^{-1}$) were improved significantly compared to UP suggests that the incorporation of BSFL frass contributed to the presence of additional negatively charged which related to the functional groups in the soil matrix (David *et al*., 2024). Organic amendments such as composts and including BSFL frass have been reported to consist abundant humified organic compounds and functional groups for example carboxyl and phenolic groups that contribute to the formation of negatively charged surfaces. These negative charged surfaces capable of attracting and retaining nutrient cations including Na^+, Ca^{2+}, Mg^{2+}, and K^+ (Hassan *et al*., 2025). Owing to the addition of BSFL frass regardless of their rates, the addition of frass able to enhance soil exchange capacity as observed in the higher values of soil CEC in soil added with frass compared with urea and ERP application (**Figure 3**).

Although with less impact in soil pH after maize harvested, soil applied with 100% fertilizers combined with 100% BSFL frass (UP_1F_1) have high CEC value (12 $cmol_c\ kg^{-1}$) The reason for the high value of soil CEC in UP_1F_1 could be associated with the decomposition of OM and N converted to NH_4^+ in soil. As mentioned in the previous section, the mineralization of organic N and the subsequent nitrification of NH_4^+ to NO_3^-, protons (H^+) are released, which led to soil acidification (Liu *et al*., 2023). With the presence of OM in BSFL frass in soil, the soil pH maintained and remained in preferrable values for most crop (pH 5.5 – 6.5). Total soil OM and total OC in urea and ERP without BSFL frass (UP) did not show significant differences compared with the control soil (S_0), suggesting that the organic amendment such as frass is important as a source of organic matter (**Figure 4 and Figure 5**). However, soil fertilized with 100% urea, ERP and 100% BSFL frass (UP_1F_1) showed slightly lower total OM, lower total OC, and lower soil pH among all soil added with BSFL regardless of their rates. The high rates of fertilizers application sis not necessarily effective or improved soil pH, total OM and total OC. Higher fertilizers application did not only result in high input cost, but it is also could contaminate soil from leaching process and volatilization. Balance application of inorganic and organic fertilization is important as reported by Mokhtar *et al.* (2025), whereby the organic amendments able to enhance soil CEC, improve OC accumulation, and improve nutrient retention in soils.

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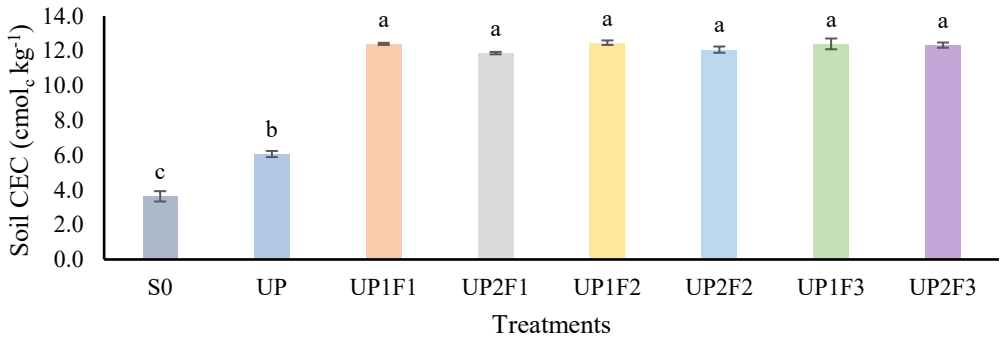


Figure 3. Effect of treatments on soil cation exchange capacity at tasselling stage (52 DAS). Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

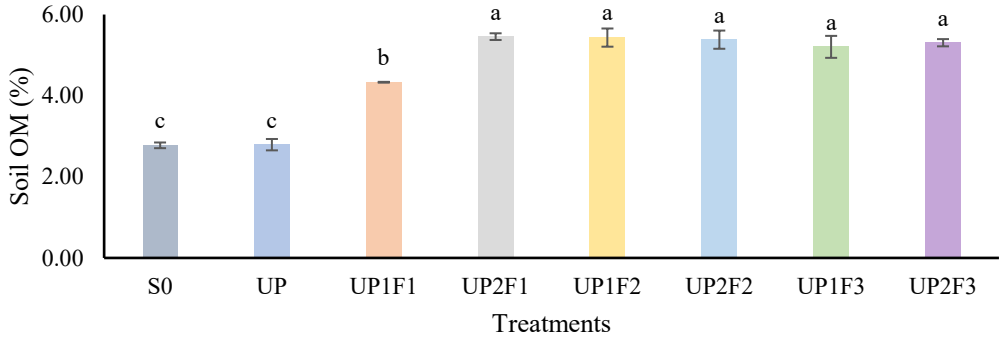


Figure 4. Effect of treatments on soil organic matter content at tasselling stage (52 DAS). Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

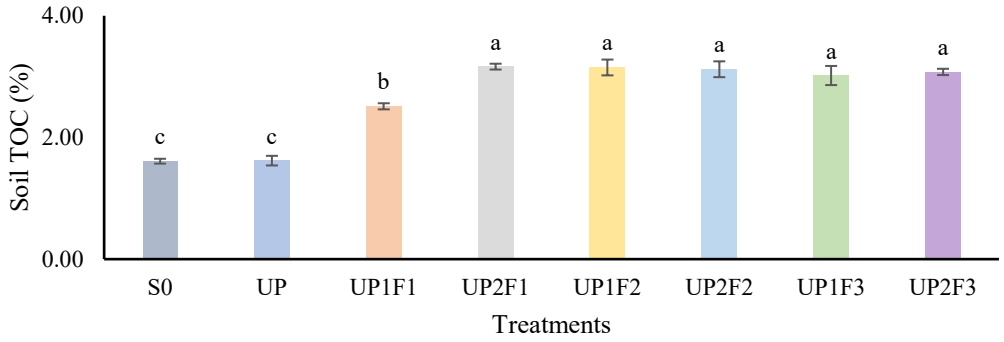


Figure 5. Effect of treatments on soil organic carbon content at tasselling stage (52 DAS). Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

Soil nitrogen and phosphorus following maize cultivation

The results obtained 52 days after maize planting indicated that the unfertilized soil (S_0) and the fertilizer only treatment (UP) exhibited significantly lower concentrations of soil exchangeable NH_4^+ (40.16 mg kg^{-1}), available NO_3^- (10.04 mg kg^{-1}), and total N (0.43%) compared with all treatments receiving the combined application of chemical fertilizers and BSFL frass (**Figures 6 – 8**). The higher N in all combined BSFL frass with chemical fertilizers

suggesting that the incorporation of BSFL frass combined with chemical fertilizers enhanced soil N availability. This improvement may be attributed to the additional organic N supplied by the frass and its potential to enhance nutrient retention and mineralization processes within the soil. Soil exchangeable NH_4^+ content was low with 4 mg kg^{-1} in the control (S_0) than in all other treatments, showing the importance of fertilization to provide N in soil (**Figure 8**). Soils fertilized with 100% urea and ERP (UP) were also low in exchangeable NH_4^+ compared to urea and ERP amended with BSFL frass (UP_1F_1, UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) (**Figure 6)** suggests that the total OM in BSFL frass have effects on the higher total exchangeable NH_4^+ in all soil added with BSFL frass. The absence of BSFL frass in urea and ERP alone (UP) could be partly due to the amount of total N loss in the soil because without addition of BSFL frass that serves as NH_4^+ absorbent, the cation subject to loss via ammonia volatilization or loss by leaching of NO_3^-. This is possible as reported in a study of Omar *et al*. (2021), half of the fertilizer N were loss in field cultivated with maize via volatilization and leaching without amendment such as compost. Furthermore, the addition of organic amendment such as BSFL frass, could contribute to the release of N from organic matter that present in the organic amendment or organic fertilizers. According to study done on using rice composts for N retention, the organic material in composts help to provide additional N and encourage microbial activity in soil, thus affect higher amounts of soil NH_4^+ (Omar *et al*., 2015). The use of inorganic fertilizers without adding organic material sources lead to low N in soil as observed in UP (urea and ERP only). The use of inorganic fertilizers only (UP) led to low soil pH and soil acidity supressed organic matter mineralisation, thereby limiting NH_4^+ accumulation (Wang and Kuzyakov, 2024).

Consistently, soil fertilized with urea and ERP only (UP) was significantly lower in soil NO_3^- and total N (**Figure 7 and Figure 8),** partly related to loss of N through leaching process because NO_3^- is anion which is easily mobile in soil with water movement (Omar *et al*., 2025). In addition, low soil pH in UP retarded the readily available of soil total N such as NO_3^- and soil exchangeable NH_4^+. Maintaining permissible soil pH in the range of 5.5. to 6.5 is very important in soil fertility and soil N management as stated by Dijkstra *et al.* (2008), the decomposition of organic N from organic matter occurred slowly under acidic condition which limited the supply of N in soil as observed in soil without BSFL frass addition (UP) (**Figure 8**). The advantage of applying inorganic fertilizer such as urea is related to the rapid release of N in soil to meet the immediate requirement of plant. However, not all N will be taken up by plant, the excess of N will be either evaporated or leached and lost from soil system. The advantage of applying the organic amendment such as BSFL frass could sustain the supply of N in soil through the slow decomposition of organic matter (Phillips *et al*., 2022).

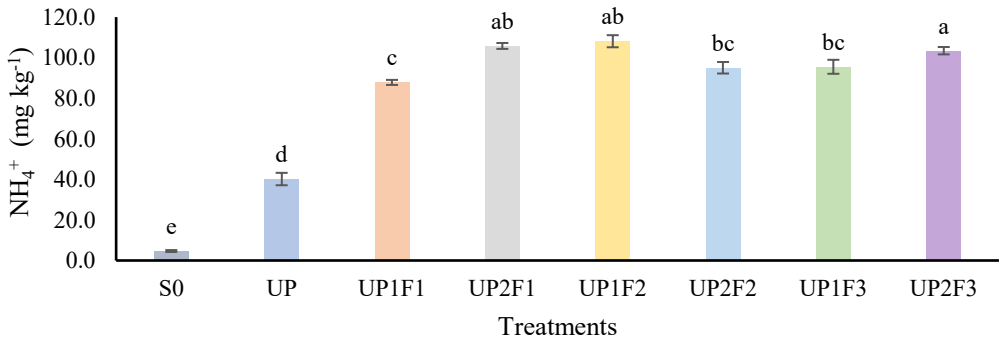


Figure 6. Soil exchangeable ammonium at tasselling stage (52 DAS) following different rates of fertilizations. Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

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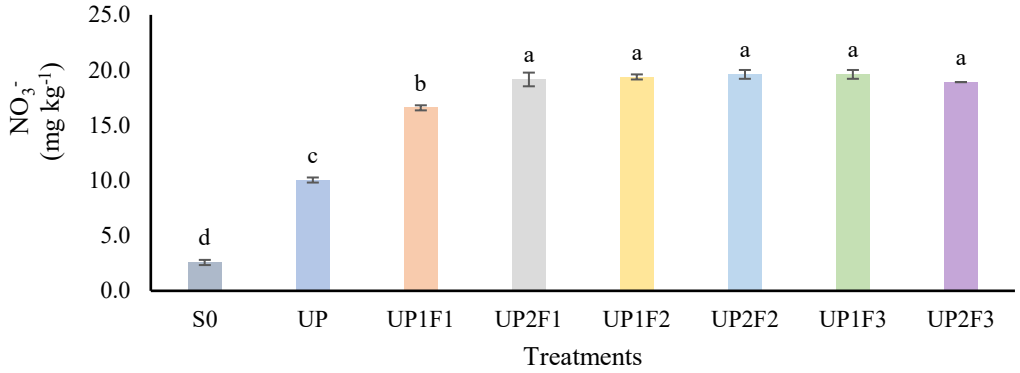


Figure 7. Soil available nitrate at tasselling stage (52 DAS) following different rates of fertilizations. Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

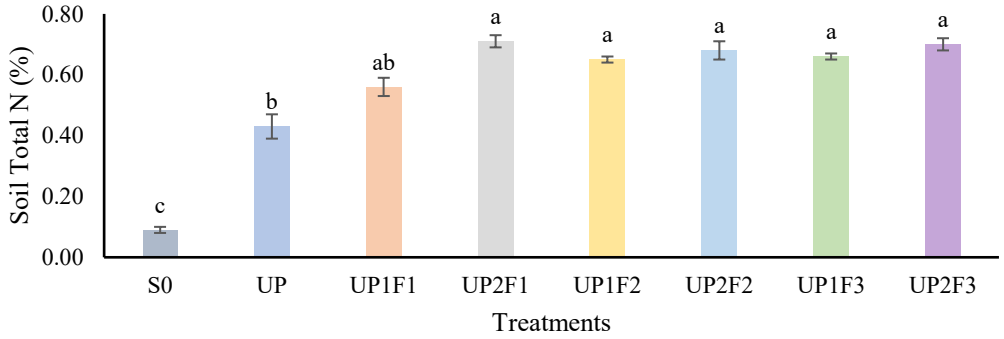


Figure 8. Soil total nitrogen at tasselling stage (52 DAS) following different rates of fertilizations. Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

Both total P (587.9 mg kg^{-1}) and available P (90.89 mg kg^{-1}) concentrations in the fertilizer only treatment (UP) were considerably lower than those observed in soils amended with the combined application of fertilizers and BSFL frass (**Figure 9 and Figure 10**). The application of urea and ERP fertilizer only (UP) and the treatment receiving 100% fertilizer combined with BSFL frass (UP_1F_1) were lower in P concentrations (1842.3 mg kg^{-1}) compared with P in the other urea, ERP, and frass application (2086.7 mg kg^{-1} – 2110 mg kg^{-1}) (**Figure 9**) and available P (359.63 mg kg^{-1} -362.32 mg kg^{-1}) (**Figure 10**). Soil treated with 100% fertilisers (UP) and soil with 100% fertiliser and BSFL frass (UP_1F_1,) were low in total P and available P in the soil despite fertilisers application (**Figure 10** and **Figure 11**). Similar to total N in soil, the availability of P is limited due to low soil pH (**Figure 2** and **3**) because P availability in soil is optimal within a pH range of 6.5 to 7.0 (Johan *et al*., 2021), thus acidic soil caused the soil P fixed by the active forms of Al and Fe oxides and hydroxides. Besides, excessive fertilization in soil with 100% fertiliser and BSFL frass (UP_1F_1,) could suppress organic P mineralization, thereby limiting the conversion of organic P into available forms (Dai *et al*., 2020). The absence of BSFL frass in soil with 100% urea and ERP (UP) might suggest that P could be potentially loss in soil through leaching due to lower binding sites of OM to hold P in the soil (Riddle *et al*., 2018). The availability of P in the soil within the treatment with ERP and BSFL frass (UP_1F_1, UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) is associated with the high inherent contents of P in the BSFL frass (**Table 2**). Besides, BSFL frass can serve as a chelating agent due to the presence of humic substances with functional groups such as

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carboxyl, hydroxyl and carbonyl and react with Fe and Al ions to form stable complexes to prevent iron react with P, thus supplying more P available in the soil (Johan *et al*., 2021).

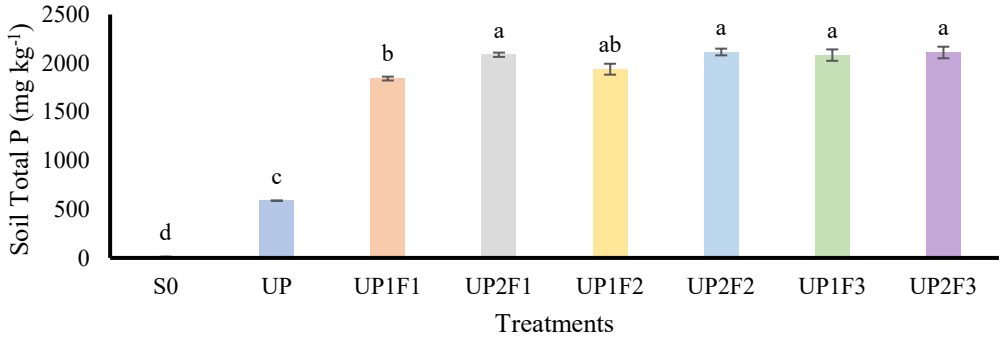


Figure 9. Soil total phosphorus at tasselling stage (52 DAS) following different rates of fertilizations Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

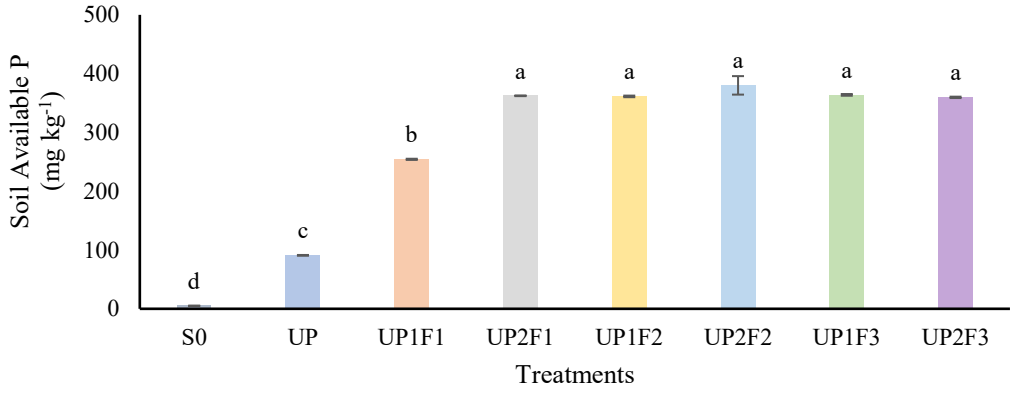


Figure 10. Soil available phosphorus at tasselling stage (52 DAS) following different rates of fertilizations Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

Dry matter production and growth performance of maize

The dry matter weight and growth performance of maize at 52 days after sowing (DAS) are presented in Table 3 and Fig. 12. Treatments combining mineral fertilizers with BSFL frass (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) exhibited significantly higher dry matter accumulation with the range of 56.9 g plant^{-1} – 63.2 g plant^{-1} compared with fertilizer-only treatment (UP) with 11.5 g plant^{-1} (**Table 3**). These results demonstrate that the combined application of BSFL frass with conventional fertilizers can effectively enhance maize biomass production, seemingly through improved nutrient availability, enhanced soil organic matter, and increased N and P supply. Although all integrated treatments enhanced biomass accumulation relative to the control and fertilizer only treatments, the treatment receiving 100% fertilizer combined with BSFL frass (UP_1F_1) produced slightly lower dry matter (33.4 g plant^{-1}) than other combined treatments (**Table 3**). The significant increase of dry matter production of maize leaves, stems and roots in the pots with urea, ERP and BSFL frass (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) suggested that the combined application of urea, ERP and BSFL improved N and P for plant uptake than use of either alone (**Table 2, Figure 11**). These results confirm the previous findings that the combined application of inorganic fertilisers and organic fertilisers in the soil significantly improved dry matter productions of sorghum plants and

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maize (Hamidi *et al.,* 2021; Debele and Abera, 2023). However, the dry matter production in soil with 100% urea, ERP and BSFL frass (UP_1F_1) were lower among all combined treatments which reflects a stunted growth of maize although with higher rates of urea, ERP and BSFL frass (**Figure 11**).

Table 3. Dry matter weight of leaves, stems and roots of maize after harvested

Treatment	Leaves	Stems	Roots	Total
	Weight (g plant^{-1}) Mean value followed by ± standard error			
S0	1.8 ± 0.13c	1.5 ± 0.15c	1.6 ± 0.15c	4.9 ± 0.2e
UP	3.7 ± 0.55c	4.0 ± 0.12c	3.8 ± 0.27c	11.5 ± 0.8d
UP1F1	11.6 ± 2.62b	9.7 ± 1.95b	12.1 ± 0.38b	33.4 ± 1.9c
UP2F1	21.7 ± 0.38a	18.7 ± 0.33a	17.4 ± 0.64a	57.7 ± 0.9ab
UP1F2	20.0 ± 0.52a	23.2 ± 0.40a	17.6 ± 0.70a	60.7 ± 0.8ab
UP2F2	20.7 ± 0.32a	19.0 ± 0.80a	17.4 ± 0.62a	57.1 ± 1.0b
UP1F3	18.2 ± 0.99a	20.5 ± 1.85a	18.2 ± 0.61a	56.9 ± 2.0b
UP2F3	20.9 ± 0.74a	22.0 ± 0.57a	20.3 ± 1.24a	63.2 ± 0.9a

Notes: Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$.

The growth of maize plants at 52 days after sowing (DAS) shows better performance in all pot added with urea, ERP and BSFL frass compared with urea and ERP only (**Figure 11**). The better growth performance of maize fertilized with urea, ERP and BSFL frass shows larger leaf area, deeper green foliage, and more robust stem development compared with low leaf area, yellowish leaf and shorter plant in urea and ERP only (**Figure 11**). Similar observation consistent with the development of maize root, whereby those of maize plants have better root development compared with urea and ERP only (**Figure 11**).

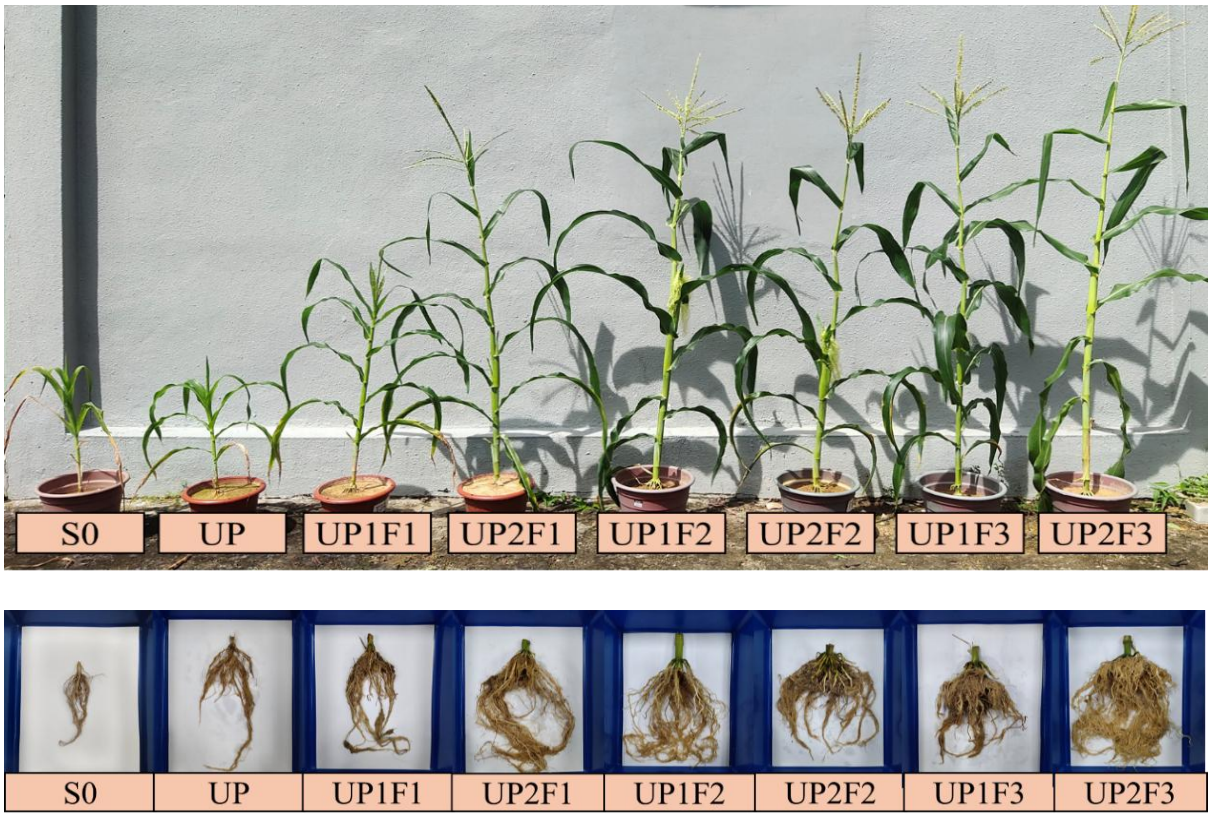


Figure 11. Plant height and root development of maize after harvested

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Nitrogen and phosphorus uptake and recovery in maize

The addition of BSFL frass in urea and ERP in UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 show greater N uptake in maize ranging from 0.76 to 0.88 g plant^{-1}, compared with uptake of 0.17 g plant^{-1} in maize fertilized with urea and ERP only (**Figure 12**). However, urea and ERP applied 100% fertilizer combined with BSFL frass (UP_1F_1) exhibited a comparatively lower N uptake (0.47 g plant^{-1}) than the other integrated treatments, despite the presence of both nutrient sources. Total P uptake were higher in maize plants grown under the combined application of urea and ERP (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) ranging from 0.41 to 0.45 g plant^{-1}, compared with the fertilizer only treatment (UP) (0.09 g plant^{-1}) and the treatment receiving 100% fertilizers combined with BSFL frass (UP_1F_1) (0.23 g plant^{-1}) (**Figure 13**). These findings are consistent with a previous study demonstrating that the application of BSFL frass significantly improved maize N uptake compared to conventional fertilizers which indicates that BSFL frass is a sustainable alternative fertilizer for maize cultivation (Beesigamukama *et al.*, 2020). However, the N uptake in treatment with 100% fertilisers and 100% BSFL frass (UP_1F_1) was lower compared with UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 despite the combination fertilisers application was higher in UP (Fig. 13). This could result from low soil total N, low soil exchangeable NH_4^+ and low available NO_3^- in soil due to slow mineralisation and nitrification processes under low pH conditions (**Figure 1** and **Figure 2**), which inhibit soil OM decomposition to release sufficient amount of N for plant uptake (**Figure 12**). The higher P uptake in maize plant fertilized with UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 compared with S0, UP and UP_1F_1 (**Figure 13**) is attributed to the high availability of P in the soil following the application of combined urea and ERP with BSFL frass that directly supplies more P for plant uptake (**Figure 13**).

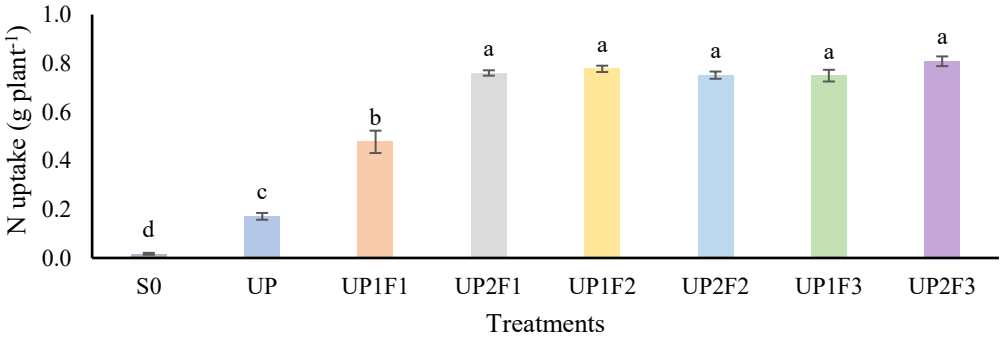


Figure 12. Amount of total nitrogen uptake in maize at fifty-two days after sowing. Means with different letters show significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

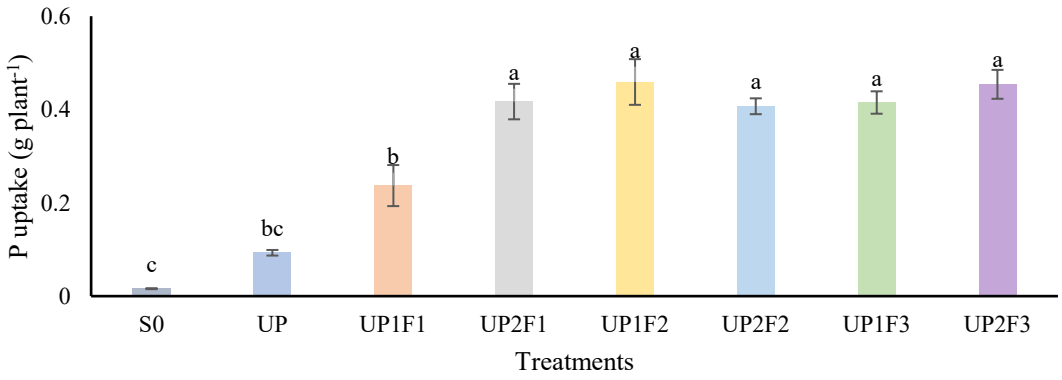


Figure 13. Total phosphorus uptake in maize at fifty-two days after sowing. Means with different letters show significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

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The fertilizer only treatment (UP) shows significantly lower N recovery (9.79%) compared with N recovery in combined application of urea, ERP, and BSFL frass (15% - 20%). All combined application of urea and ERP with BSFL frass (UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3) recorded higher N recovery, ranging from 15% to 20% (**Figure 14**). Soils fertilized with 80% rate of urea and ERP combined with 100% BSFL frass (UP_2F_1), UP_2F_2 (80% fertilizers + 80% frass), and UP_2F_3 (80% fertilizers + 60% frass) have higher N recoveries (19% and 20%) among all fertilizations (**Figure 14**). This indicates that any of these treatments could be selected for use of an organic amendment. Regarding P use efficiency, all soil applied with urea, ERP and BSFL frass recorded higher values of P use efficiency of maize plant ranging from 5% to 7%, which were higher than P use efficiency in maize fertilized with urea and ERP only (2%) (**Figure 15**). The higher P recovery of maize in UP_2F_1, UP_1F_2, UP_2F_2, UP_1F_3, and UP_2F_3 compared with UP and UP_1F_1 (Fig. 16) was associated with higher soil available P and greater P uptake by plant. In addition, BSFL frass act as a slow-release fertiliser (Manan *et al.*, 2024), which reduces N and P losses through soil runoff and leaching, thus maintaining N and P availability in soil for longer duration, thereby improving N and P recovery.

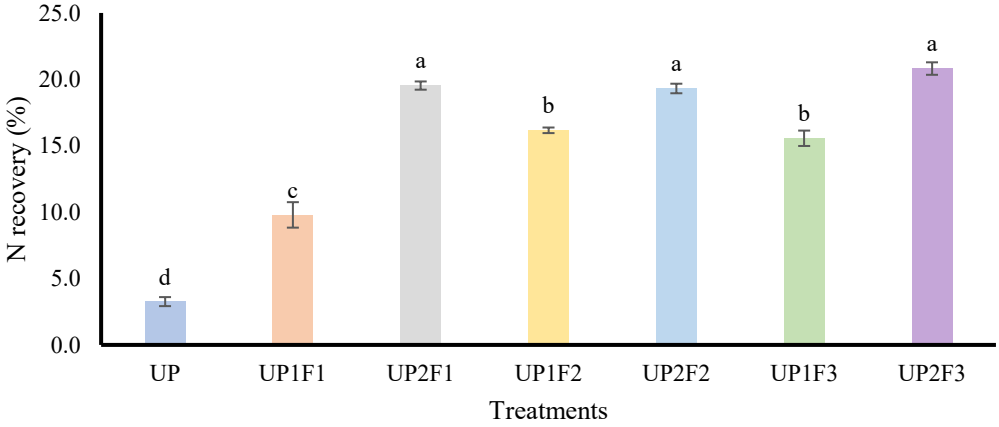


Figure 14. Nitrogen recovery of maize at fifty-two days after sowing. Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

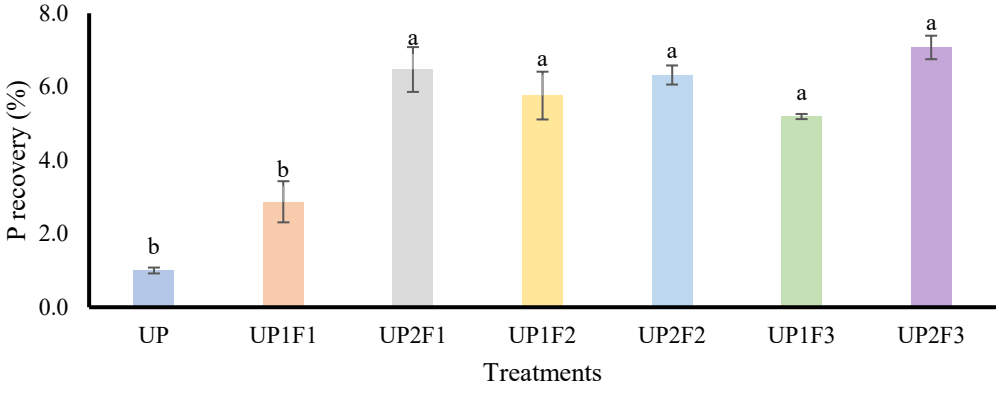


Figure 15. Phosphorus recovery of maize at fifty-two days after sowing. Means with different letters indicate a significant difference between treatments by Tukey's HSD test at $\rho \leq 0.05$. Bars represent the mean values ± SE.

CONCLUSION

The combined application of urea, ERP and BSFL frass significantly improved maize growth, dry matter production, N and P uptake, and nutrient recovery. The application of urea and ERP at 80% with different rates of BSFL frass in UP_2F_1 (80% fertilizers + 100% frass), UP_2F_2 (80%

fertilizers + 80% frass), and UP_2F_3 (80% fertilizers + 60% frass) provides selection for the use of combined application of inorganic fertilizers and BSFL frass in maize cultivation. In contrast, the higher fertilizer input under UP_1F_1 was associated with reduced maize growth, lower dry matter accumulation, and diminished N and P uptake and recovery, suggesting that excessive nutrient application may adversely affect crop performance. The poor growth of maize in excess of fertilizer applications as observed in UP_1F_1 is related to soil acidity from excessive fertilizer input. The improvement in maize growth performance, dry matter production, N and P uptake and N and P recovery through the co-application of BSFL frass with urea and ERP suggests that BSFL frass have a potential to be used as valuable organic amendment for improving soil N and P fertility in maize production systems.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Universiti Putra Malaysia Sarawak for providing the research facilities to this project from preparation to completion.

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