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Efficacy of *Tithonia diversifolia* and NPK fertilizers on papaya seedling growth in marginal soils

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Eficacia de fertilizantes de *Tithonia diversifolia* y NPK en plántulas de papaya en suelos marginales

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ABSTRACT

The utilization of marginal soils, particularly peat (Histosol) and Ultisol, presents challenges due to low fertility and unfavorable physical and chemical characteristics. This study evaluates the efficacy of liquid organic fertilizer derived from *Tithonia diversifolia* (wild sunflower) and compound NPK fertilizer (with a ratio 16:16:16) in stimulating the growth of papaya (*Carica papaya* L.) seedlings in tropical marginal soils. The soil samples were collected from agricultural lands in Riau Province, Indonesia, where both peat and Ultisol soils are dominant and commonly used for farming. A factorial experiment was conducted using a split-split plot design with two factors: *T. diversifolia* liquid fertilizer (0, 100, and 200 mL L^{-1}) and NPK fertilizer (0, 1.5, and 3 g per polybag), applied to both peat and Ultisol soils. Each treatment combination was replicated three times in an open-field setting, with three seedlings grown in individual polybags per replicate. Significant interaction effects between *T. diversifolia* liquid fertilizer and NPK were observed on growth parameters, including plant height, stem diameter, leaf number, and leaf length. The combination of 200 mL L^{-1} *T. diversifolia* liquid fertilizer and 3 g per polybag of NPK resulted in the highest growth across both soil types. Peat soil showed comparatively better growth performance, attributed to higher water retention and organic matter content. These findings provide empirical evidence supporting the use of integrated organic and chemical fertilizers to enhance papaya seedling growth in low-fertility tropical soils.

Keywords:
Carica papaya seedlings
Low fertility soils
Organic fertilizers
Soil nutrient availability
Sustainable agriculture

RESUMEN

El uso de suelos marginales, particularmente turba (Histosol) y Ultisol, presenta desafíos debido a su baja fertilidad y características físicas y químicas desfavorables. Este estudio evaluó la eficacia de un fertilizante orgánico líquido derivado de *Tithonia diversifolia* (girasol silvestre) y un fertilizante NPK compuesto (con proporción 16:16:16) en la estimulación del crecimiento de plántulas de papaya (*Carica papaya* L.) en suelos marginales tropicales. Las muestras de suelo se recolectaron en tierras agrícolas de la provincia de Riau, Indonesia, donde los suelos de turba y Ultisol son dominantes y se utilizan comúnmente para la agricultura. Se realizó un experimento factorial utilizando un diseño de parcelas divididas y subdivididas con dos factores: fertilizante líquido de *T. diversifolia* (0, 100 y 200 mL L^{-1}) y fertilizante NPK (0, 1,5 y 3 g por bolsa), aplicados tanto en suelos de turba como en Ultisol. Cada combinación de tratamiento se replicó tres veces en condiciones de campo abierto, con tres plántulas cultivadas en bolsas individuales por repetición. Se observaron efectos de interacción significativos entre el fertilizante líquido de *T. diversifolia* y el NPK sobre los parámetros de crecimiento, incluidos la altura de planta, el diámetro del tallo, el número de hojas y la longitud de las hojas. La combinación de 200 mL L^{-1} de fertilizante líquido de *T. diversifolia* y 3 g de NPK por bolsa resultó en el mayor crecimiento en ambos tipos de suelo. El suelo de turba mostró un rendimiento de crecimiento comparativamente mejor, atribuido a su mayor retención de agua y contenido de materia orgánica. Estos hallazgos proporcionan evidencia empírica que respalda el uso de fertilizantes orgánicos y químicos integrados para mejorar el crecimiento de plántulas de papaya en suelos tropicales de baja fertilidad.

Palabras clave:
Plántulas de *Carica papaya*
Suelos de baja fertilidad
Fertilizantes orgánicos
Disponibilidad de nutrientes del suelo
Agricultura sostenible

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Marginal soils, including peat (Histosols) and Ultisols, differ fundamentally in their parent materials—organic and mineral, respectively—and are characterized by low fertility, high acidity, and poor structural stability, which pose significant challenges to agricultural productivity (Csikós and Tóth 2023). However, these soils represent a vast reserve for agricultural expansion, particularly in tropical regions where arable land is becoming increasingly scarce (Purnama et al. 2023). Mitigating the limitations of these soils is essential for sustainable agricultural intensification, particularly in high-value crops such as papaya (*Carica papaya* L.), a species of recognized nutritional and economic significance (Schut et al. 2016).

Organic amendments have been extensively investigated for their potential to enhance soil quality and nutrient availability (Purnama et al. 2023). Liquid organic fertilizers derived from *Tithonia diversifolia* (wild sunflower) have attracted considerable attention due to their favorable nutrient composition—particularly 2.7–3.59% nitrogen, 0.14–0.47% phosphorus, and 0.25–4.10% potassium—which are critical for early seedling development (Wang et al. 2021). In several tropical farming systems, *T. diversifolia* has been applied either alone or in combination with mineral inputs to improve soil health and crop performance. Nevertheless, the integration of *T. diversifolia*-based liquid fertilizers with chemical fertilizers such as NPK remains insufficiently studied, particularly in the context of marginal soils.

Research on the synergistic effects of organic and inorganic fertilizers has shown promising results. Khairi et al. (2023) demonstrated that integrating organic amendments with NPK fertilizer enhances nutrient availability, microbial activity, and plant growth. Annisa and Gustia (2017) reported that the application of *T. diversifolia*-based liquid organic fertilizer, which was poured directly onto the soil and plant base, in combination with reduced NPK doses, influenced flowering traits and maintained fruit yield and quality in melon (*Cucumis melo* L.), demonstrating its potential as a complementary nutrient source in horticultural production. However, most studies have focused on mineral soils, leaving a knowledge gap regarding their application in marginal soils such as peat and Ultisol.

Peat soils, while rich in organic matter, suffer from nutrient imbalances, high acidity, and poor drainage, which can limit crop growth. Conversely, Ultisol soils are highly weathered and nutrient-deficient but have better drainage and structure compared to peat (Hewitt et al. 2021). The contrasting characteristics of these soils suggest that fertilization strategies must be tailored to optimize nutrient use efficiency and crop performance. Although several studies, including Watini et al. (2023), have evaluated the individual effects of *T. diversifolia* and NPK on crop performance, limited attention has been given to their combined application on fruit crops grown in marginal soils. Papaya (*Carica papaya* L.) is a high-value tropical fruit that is moderately sensitive to soil fertility constraints, making it a suitable indicator for assessing soil amendment strategies. However, research examining the interaction effects of *T. diversifolia*-based liquid organic fertilizer and NPK on papaya seedling performance, particularly in contrasting soil types such as Ultisols and peat, remains scarce. To address this gap, plant growth responses and changes in soil properties were evaluated under integrated fertilization strategies combining *T. diversifolia* liquid fertilizer with NPK.

This study aimed to evaluate the synergistic effects of organic liquid fertilizer from *Tithonia diversifolia* and NPK fertilizer on the growth of *C. papaya* seedlings in two types of marginal soils: peat and Ultisol. It was hypothesized that the integrated application would enhance seedling performance more effectively than sole inputs, particularly in nutrient-depleted Ultisols. By analyzing growth responses across treatments and soil types, this study contributes to the development of effective fertilization strategies for the sustainable management of low-fertility tropical soils.

MATERIALS AND METHODS

Study site and experimental design

The study was conducted at the Experimental Farm of the Faculty of Agriculture, Universitas Lancang Kuning, Pekanbaru, Indonesia (0°32'N, 101°27'E). The site is characterized by a tropical climate with an average temperature of 31 °C and a relative humidity of 80%. The soils used in the study were peat and Ultisol, collected from agricultural lands in Riau, Indonesia. Peat and Ultisol soils were selected based on their dominance in Riau

Province, Indonesia, where both soil types are widely used for agricultural production, including papaya cultivation. These soils represent contrasting fertility conditions that are commonly encountered in tropical farming systems. A split-split plot design was used to evaluate the effects of soil type (peat and Ultisol), *T. diversifolia* liquid fertilizer (P0: 0 mL L^{-1}, P1: 100 mL L^{-1}, P2: 200 mL L^{-1}), and NPK fertilizer (16:16:16 formulation), applied at rates of 0 g (N0), 1.5 g (N1), and 3 g (N2) per polybag. The P0N0 combination (no *T. diversifolia* liquid fertilizer and no NPK) was used as the control treatment. Soil type was assigned to the main plot, liquid organic fertilizer to the subplot, and NPK fertilizer to the sub-subplot. All treatments were applied in an open-field setting at the same location and time, with three replications per treatment combination. Each replicate consisted of three seedlings grown individually in polybags.

Preparation of liquid organic fertilizer

The liquid organic fertilizer was prepared using fresh biomass of *T. diversifolia* collected from local fields in Pekanbaru. The biomass was chopped and mixed with a solution of molasses and water at a 1:10 (w/v) ratio, where 1 part molasses was diluted in 10 parts water. The mixture was then added to the biomass at a ratio of 1:1 (w/w) and fermented anaerobically for 14 days. During the anaerobic fermentation process, pH was monitored and stabilized between 5.2 and 5.5 by day 14. While the microbial composition and C/N ratio were not characterized in this study, the preparation followed standardized protocols as outlined by Annisa and Gustia (2017), which have demonstrated efficacy and consistency in extracting nutrients from Tithonia biomass. The fermented solution was filtered and stored in plastic containers at room temperature for seven days before application.

Planting materials and soil preparation

Seeds of papaya (*Carica papaya* L., var. California) were procured from a certified supplier in Pekanbaru, Indonesia. The seeds were first germinated in small polybags containing a mixture of sterilized sand to support uniform seedling development. The seedlings were maintained in these small polybags for one month to ensure proper root development before being transplanted into 30×25 cm polybags filled with a soil mixture. The planting medium was prepared by mixing peat or Ultisol soils with cow manure compost and rice husk biochar in a 2:1:1 ratio (v/v/v), respectively representing peat or Ultisol, cow manure, and rice husk biochar. These organic amendments were applied uniformly across all treatments to standardize the base growing medium and ensure comparability of fertilizer effects. This mixture was designed to improve soil aeration, water retention, and nutrient availability, facilitating optimal root growth. Before planting, the soils were analyzed for pH, organic carbon, total nitrogen, and cation exchange capacity (CEC) to assess baseline soil properties (Purnama et al. 2023).

Fertilizer application

The *Tithonia diversifolia*-based liquid fertilizer (TLF) was applied starting at 7 days after transplanting (DAT), then reapplied at two-week intervals for a total of three applications, and discontinued two weeks before the final observation. The TLF was prepared at 100- and 200-mL L^{-1} concentration according to the treatment levels. These concentrations were selected based on previous studies showing enhanced plant growth responses within this range (Annisa and Gustia 2017), as well as preliminary observations indicating no signs of phytotoxicity or nutrient imbalance at these dosages.

Applications were carried out in the early morning using a hand sprayer equipped with a fine-mist nozzle to ensure uniform foliar coverage while minimizing excessive run-off. Each plant received 50 mL of TLF solution per application. After a light foliar misting, any remaining volume from the 50 mL was applied directly to the soil surface around the plant base to enhance nutrient availability in the root zone. Prior to each application, plants were irrigated on the previous day to ensure adequate soil moisture and to minimize stress-related variability in nutrient uptake. The experimental NPK fertilizer (16:16:16; Petro Nitrat, PT Petrokimia Gresik, Indonesia) was applied in two split doses, with half of the total treatment applied at 15 DAT and the remaining half at 45 DAT.

Growth parameter measurements

Plant height, stem diameter, leaf number, and leaf length were recorded at 90 days after transplanting (DAT). Plant height was measured from the soil surface to the tip of the highest leaf using a measuring tape (Stanley Tools, United Kingdom). Stem diameter was measured at 2 cm above the soil surface using a digital caliper (Mitutoyo, Japan). Leaf number was counted manually by recording all fully expanded leaves per plant. Leaf length was measured from the base of the petiole to the tip of the leaf blade using a standard ruler (Faber-Castell, Germany), taken from the second fully expanded leaf from the apex to ensure consistency.

Soil and fertilizer analysis

The chemical composition of the *TLF* was analyzed for total nitrogen, phosphorus, and potassium content using standard procedures (AOAC 2019). Prior to planting, composite soil samples were collected from the top 0–20 cm layer of each soil type (Ultisol and peat), with three replicates per type to ensure representativeness. Soil pH was measured in a 1:2.5 soil-to-water suspension; organic carbon was determined using the Walkley–Black method; total nitrogen was analyzed using the Kjeldahl method; and cation exchange capacity (CEC) was measured via ammonium acetate extraction at pH=7.0. The peat soil used in this study was classified as sapric in decomposition stage, obtained from a shallow peatland (< 1 m depth) in Riau, Indonesia. The field moisture content was approximately 350%, and all analyses were corrected to an oven-dry basis at 105 °C prior to testing. At the end of the experiment, post-treatment soil samples were collected from each treatment pot. Available phosphorus was analyzed using the Bray I extraction method, while exchangeable potassium was measured using ammonium acetate extraction, following procedures described by Purnama et al. (2023).

Data analysis

All data were subjected to analysis of variance (ANOVA) using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA). Significant differences between treatment means were determined using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

RESULTS AND DISCUSSION

Soil Characteristics and the Role of Organic Amendments

The characteristics of Ultisol and peat soil significantly influence their suitability for crop growth, necessitating the use of fertilization strategies to enhance soil fertility and support plant development. Based on the soil analysis (Table 1), Ultisol is characterized by low organic carbon (1.2%), low total nitrogen (0.09%), and limited phosphorus availability (12.4 mg kg^{-1}). These factors make Ultisols highly weathered and nutrient-poor, which aligns with previous findings indicating that Ultisols are often strongly leached, acidic, and have low CEC, thus requiring appropriate fertilization strategies to support sustainable agricultural productivity (Lestari et al. 2022).

Table 1. Comparison of initial and post-treatment (P2N2) soil properties in Ultisol and peat soil.

Parameter	Ultisol (before)	Ultisol (after P2N2)	Peat soil (before)	Peat soil (after P2N2)
pH (H_2O)	4.80±0.10^b	5.30±0.08^a	3.90±0.05^b	4.40±0.06^a
Organic carbon (%)	1.20±0.12^b	2.80±0.15^a	47.50±1.10^b	50.20±1.25^a
Total nitrogen (%)	0.09±0.01^b	0.21±0.02^a	1.20±0.04^b	1.45±0.05^a
Available phosphorus (mg kg^{-1})	12.40±1.05^b	18.50±1.12^a	5.20±0.30^b	7.90±0.44^a
Exchangeable potassium (cmol kg^{-1})	0.15±0.01^b	0.28±0.02^a	0.10±0.01^b	0.16±0.01^a
Cation exchange capacity (cmol kg^{-1})	8.50±0.45^b	10.20±0.52^a	34.70±0.90^b	36.50±0.88^a

Note. Values are presented as mean ± SD (n=3). Different letters within rows indicate significant differences at $P<0.05$ based on Duncan's Multiple Range Test (DMRT). P2N2 = 200 mL L^{-1} TLF + 3 g NPK per polybag.

Conversely, peat soil exhibits a significantly higher organic carbon content (47.5%) and total nitrogen (1.20%), which contribute to greater nutrient retention and microbial activity. However, its low pH (3.9) and limited phosphorus availability (5.2 mg kg^{-1}) can inhibit nutrient uptake and root development (Gillespie et al. 2020). The CEC of peat soil (34.7 cmol kg^{-1}) is substantially higher than that of Ultisol (8.5 cmol kg^{-1}), suggesting that peat can retain more nutrients but may also lead to nutrient imbalances, particularly potassium deficiency (Woittiez et al. 2019). This justifies the need for external nutrient supplementation to optimize plant growth.

To address the fertility constraints of both soil types, organic amendments such as TLF play a crucial role in enhancing nutrient availability and improving soil structure. As shown in Table 2, the TLF contains essential macronutrients—total nitrogen (2.1%), phosphorus (0.45%), and potassium

(2.9%)—which help address the nutrient deficiencies in both Ultisol and peat soils. These values are consistent with previous studies reporting high nutrient concentrations in both the biomass and liquid extracts of *T. diversifolia* (Olabode et al. 2007), confirming its potential as a nutrient-rich organic input for marginal soils.

Table 2. Composition of TLF after 14 days of fermentation.

Parameter	*T. diversifolia* fertilizer
pH	5.5
Total nitrogen (%)	2.1
Total phosphorus (%)	0.45
Total potassium (%)	2.9
C/N ratio	15.4

The C/N ratio of TLF (15.4) indicates a moderate decomposition rate, ensuring a steady release of nitrogen into the soil, supporting prolonged plant growth without rapid nutrient depletion (Kagan et al. 2024). Moreover, the pH of TLF (5.5) suggests that its application can help neutralize the acidity of peat soil and moderately improve the pH of Ultisol, making essential nutrients more bioavailable (Johan et al. 2021). Several studies have shown that *T. diversifolia*-based fertilizers can enhance soil organic matter, microbial activity, and nutrient cycling, contributing to increased crop yields and soil sustainability in degraded lands (Ewané et al. 2020).

Following the application of TLF and NPK (P2N2 treatment), improvements in soil chemical properties—such as increased pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium—were recorded (Table 1). The pH of Ultisol increased from 4.8 to 5.3, indicating that the treatment contributed to reducing soil acidity, which is often associated with improved nutrient availability. In peat soil, pH increased from 3.9 to 4.4, suggesting that while the treatment helped buffer acidity, additional amendments may still be necessary for long-term pH stabilization. The organic carbon content of Ultisol increased from 1.2 to 2.8%, highlighting the role of TLF in enhancing soil structure, microbial activity, and organic matter accumulation. In peat soil, organic carbon remained high at 50.2%, ensuring adequate carbon availability for microbial processes.

In terms of macronutrient availability, total nitrogen content increased significantly in both soil types (Ultisol: 0.09 to 0.21%; Peat: 1.20 to 1.45%), reinforcing the role of TLF in supplying plant-available nitrogen. The application of TLF and NPK also improved phosphorus availability (Ultisol: 12.4 to 18.5 mg kg^{-1}; Peat: 5.2 to 7.9 mg kg^{-1}), demonstrating that organic amendments help reduce phosphorus fixation and enhance plant uptake in acidic soils. Exchangeable potassium also increased (Ultisol: 0.15 to 0.28 cmol kg^{-1}; Peat: 0.10 to 0.16 cmol kg^{-1}), reflecting the contribution of TLF in maintaining potassium availability. Additionally, the CEC of Ultisol improved from 8.5 to 10.2 cmol kg^{-1}, while peat soil increased from 34.7 to 36.5 cmol kg^{-1}, confirming that TLF enhances nutrient retention capacity.

These results demonstrated that the combined application of TLF and NPK not only supports plant growth but also significantly improves soil fertility. The improvements in organic matter content, pH, and nutrient availability under the P2N2 treatment highlight the potential of TLF as an effective organic fertilizer for sustaining soil health and optimizing plant productivity in marginal soils. Although TLF was primarily applied as a foliar spray, excess solution was also applied to the soil surface, allowing for partial absorption through the root zone. This dual application contributed to enhanced soil chemical properties. The findings further support the integration of organic and inorganic fertilizers as a sustainable strategy to improve soil fertility and enhance agricultural productivity in degraded land areas.

Effects of TLF and NPK on plant growth

The application of TLF and NPK significantly enhanced the growth of papaya seedlings, as demonstrated by improvements in plant height, leaf number, stem diameter, and leaf length (Figure 1, Table 3). The combination of 200 mL L^{-1} TLF and 3 g per polybag NPK (P2N2) consistently produced the highest growth performance in both Ultisol and peat soil, reinforcing the effectiveness of integrated organic and inorganic fertilization in improving nutrient uptake and plant vigor.

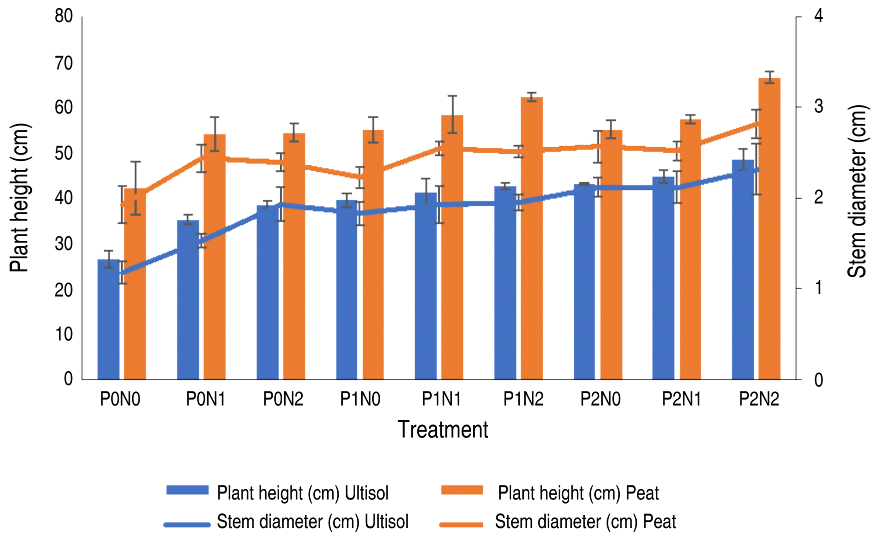

Figure 1. Effect of integrated TLF and NPK treatments on plant height and stem diameter of papaya seedlings grown in Ultisol and peat soils. Bars represent mean values (n=3) ± SD.

Table 3. Leaf number and leaf length of papaya seedlings in Ultisol and peat soils under TLF and NPK treatments.

Treatment	Leaf number		Leaf length (cm)	
	Ultisol	Peat	Ultisol	Peat
P0N0	8.00±2.01[a]	8.53±1.80[a]	12.52±0.50[a]	17.50±0.29[a]
P0N1	9.33±0.63[ab]	11.00±2.62[ab]	17.92±1.89[b]	23.40±1.80[b]
P0N2	9.50±1.21[ab]	10.17±1.44[ab]	18.02±2.50[b]	24.17±1.61[b]
P1N0	8.33±1.96[ab]	10.50±1.44[ab]	17.77±0.58[b]	23.83±0.87[b]
P1N1	11.00±0.60[bc]	11.17±0.50[ab]	19.93±0.50[c]	24.00±0.29[b]
P1N2	11.00±2.52[bc]	12.17±1.32[bc]	20.08±1.00[c]	24.50±1.26[bc]
P2N0	10.17±0.76[bc]	12.67±1.33[bc]	18.08±1.26[b]	24.87±1.26[bc]
P2N1	11.00±1.08[bc]	19.67±1.89[d]	20.73±0.50[cd]	25.33±0.76[bc]
P2N2	12.17±1.73[c]	23.33±1.96[e]	20.87±1.04[d]	29.13±0.50[c]

Note. Values are presented as mean ± SD (n=3). Different letters within the same column indicate significant differences at P<0.05 based on Duncan's Multiple Range Test (DMRT). P0: 0 mL L^{-1} TLF; P1: 100 mL L^{-1} TLF; P2: 200 mL L^{-1} TLF and N0: 0 g NPK per polybag; N1: 1.5 g NPK per polybag; N2: 3 g NPK per polybag.

The increase in plant height was particularly evident, with the P2N2 treatment yielding 48.50 cm in Ultisol and 66.58 cm in peat soil, significantly higher than the control (P0N0) at 26.50 and 42.17 cm, respectively — representing an 83.02% increase in Ultisol and 57.84% increase in peat. These results highlight the role of nitrogen and potassium in stimulating vegetative growth, as both nutrients are essential for cell division, elongation, and photosynthesis efficiency (Jasim et al. 2016). The improved response in peat soil compared to Ultisol is likely due to its higher organic matter content and superior water retention capacity, which enhance nutrient availability. However, the significant improvements observed in Ultisol following fertilization demonstrate the ability of TLF and NPK to replenish soil nutrients and mitigate fertility constraints, making nutrient-poor soils more suitable for cultivation. The post-treatment soil analysis (Table 1) further supports this finding, showing increased nitrogen, phosphorus, and exchangeable potassium levels in both soil types, which contributed to improved plant height.

Leaf number, an essential indicator of plant health and photosynthetic capacity, also exhibited a strong response to fertilization. The highest leaf production was observed in the P2N2 treatment, reaching 12.17 leaves per plant in Ultisol and 23.33 leaves per plant in peat soil, significantly higher than the control (P0N0) with 8.00 and 8.53 leaves, respectively — equivalent to an increase of 52.13% in Ultisol and 173.52% in peat. The increased leaf number is likely attributed to the steady supply of nitrogen and phosphorus, which are essential for leaf expansion, chlorophyll biosynthesis, and photosynthetic activity (Malhotra et al. 2018). This aligns with previous research indicating that *T. diversifolia*-based fertilizers enhance foliage development in tropical crops by improving soil nutrient availability and microbial activity (Ewané et al. 2024).

A similar trend was observed in stem diameter, where P2N2 produced the thickest stems (2.32 cm in Ultisol and 2.82 cm in peat soil), significantly greater than the control (P0N0) at 1.18 and 1.93 cm, respectively — an increase of 96.61% in Ultisol and 46.11% in peat. The increase in stem diameter suggests stronger plant structural integrity, which is essential for nutrient transport, water conduction, and overall plant stability. Organic fertilizers such as *T. diversifolia* have been reported to improve stem robustness and increase seedling drought resistance, likely due to their slow nutrient release and ability to enhance soil physical properties (Setyowati et al. 2022). The enhanced structural growth in Ultisol demonstrates the potential of TLF to improve nutrient retention and soil fertility, reducing the constraints associated with highly weathered tropical soils.

Leaf length, another key growth parameter, also significantly increased following fertilization. The longest leaves were recorded in the P2N2 treatment (20.87 cm in Ultisol and 29.13 cm in peat soil), compared to the control (P0N0), which only reached 12.52 and 17.50 cm, respectively — corresponding to an increase of 66.70% in Ultisol and 66.46% in peat. The elongation of leaves is strongly associated with higher nitrogen and potassium availability, as these nutrients facilitate cell expansion, metabolic activity, and photosynthetic efficiency (Shah et al. 2024). The positive effects of *T. diversifolia* on leaf growth are consistent with previous studies, where organic amendments contributed to increased leaf surface area, chlorophyll content, and overall plant productivity (Gao et al. 2020).

The differences in growth responses between Ultisol and peat soil highlight the distinct soil characteristics and their interactions with fertilization. While peat soil supported higher overall growth, particularly in plant height and leaf number, due to its higher organic carbon (50.2%) and total nitrogen content (1.45%) after P2N2 application (Table 1), Ultisol showed greater relative improvements in nutrient availability, particularly in total nitrogen (0.21%), available phosphorus (18.5 mg kg^{-1}), and exchangeable potassium (0.28 cmol kg^{-1}), which helped mitigate its initial fertility limitations. The increase in CEC observed in both soil types under the P2N2 treatment further supports the contribution of organic amendments to improved soil nutrient retention, which is critical for long-term soil fertility.

The results indicate that the combination of TLF and NPK fertilization significantly outperformed single fertilizer applications, reinforcing the importance of balanced nutrient management in optimizing seedling growth. The application of *T. diversifolia*-based liquid fertilizer (TLF) led to improved soil nutrient indicators (e.g., total N, available P, and exchangeable K) in Ultisol, where baseline fertility was limited. However, as nutrient uptake by plant tissues was not directly measured in this study, conclusions regarding actual nutrient use efficiency remain tentative and warrant further investigation. These findings support the integration of organic and inorganic fertilizers as a sustainable strategy for improving plant growth in marginal soils, providing both short-term nutrient availability and long-term soil health benefits.

Comparison of ultisol and peat soil in supporting growth

The results of this study demonstrated that peat soil supported better overall growth performance than Ultisol, as evidenced by higher plant height, greater leaf number, thicker stem diameter, and longer leaves. This disparity is largely explained by the inherent differences in soil properties. Compared to Ultisol, peat soil had substantially higher organic carbon (50.2 vs. 2.8%), total nitrogen (1.45 vs. 0.21%), and cation exchange capacity (36.5 vs. 10.2 cmol kg^{-1}) (Table 1). These properties are known to enhance nutrient retention and availability in the rhizosphere, thereby supporting more robust plant growth (Ali et al. 2025). Despite these initial differences, the application of TLF and NPK significantly improved growth performance in both soil types, as confirmed by ANOVA and DMRT analyses, suggesting that organic and inorganic fertilization can enhance the productivity of even nutrient-poor soils like Ultisol.

Figure 2 shows the visual comparison of papaya seedling growth in Ultisol and peat soil following the application of TLF and NPK. The image on the left represents the peat soil experiment, where seedlings exhibit denser foliage, greater stem robustness, and enhanced vigor compared to those grown in Ultisol (right image). The improved growth in peat soil aligns with its higher organic carbon and nitrogen content, which facilitates better nutrient retention and water availability, thereby supporting enhanced physiological development. Conversely, while the Ultisol-grown seedlings initially exhibited slower growth, the integration of TLF and NPK significantly improved plant height, stem diameter, leaf number, and leaf length, demonstrating the potential of combined organic and inorganic amendments in mitigating the fertility limitations of highly weathered soils.

Figure 2. Growth performance of papaya (*Carica papaya* L.) seedlings in peat soil (A) and Ultisol (B) under *Tithonia diversifolia* liquid fertilizer and NPK application.

The superior performance of papaya seedlings in peat soil is primarily linked to its high organic carbon content (47.5%) and total nitrogen (1.20%), which create a nutrient-rich growing environment that supports root development and vegetative growth. Organic matter plays a crucial role in improving soil structure, enhancing microbial activity, and increasing nutrient retention, making peat soil inherently more fertile than Ultisol (Liu et al. 2019). Additionally, peat soil's high CEC (34.7 cmol kg^{-1}) allows it to retain nutrients more effectively, reducing leaching losses and ensuring a more consistent supply of essential macronutrients like nitrogen and potassium. However, its low pH (3.9) and phosphorus availability (5.2 mg kg^{-1}) present challenges for long-term crop production, as extreme soil acidity can reduce nutrient solubility and inhibit root nutrient uptake (Gillespie et al. 2020).

In contrast, Ultisol exhibited significantly lower growth performance under unfertilized conditions, as reflected in shorter plants, fewer leaves, smaller stem diameters, and shorter leaf lengths. Ultisol is highly weathered and characterized by low organic carbon (1.2%), limited total nitrogen (0.09%), and poor phosphorus availability (12.4 mg kg^{-1}), which restricts its ability to support vigorous plant growth without external fertilization (Malhotra et al. 2018). The low CEC of Ultisol (8.5 cmol kg^{-1}) suggests that it has poor nutrient retention, making it more prone to leaching, particularly under high rainfall conditions. Without intervention, these limitations lead to low nutrient availability and suboptimal plant development. However, the significant improvements observed after fertilization indicate that Ultisol can be managed effectively through the integration of organic and inorganic amendments.

The ANOVA results confirmed that both soil type and fertilization significantly affected all measured growth parameters (*P*<0.05), with a notable interaction effect between TLF and NPK. The DMRT analysis further revealed that P2N2 (200 mL L^{-1} TLF + 3 g per polybag NPK) produced the best results, significantly increasing plant height, leaf number, stem diameter, and leaf length compared to other treatments. These findings highlight the importance of balanced nutrient management, particularly in marginal soils, to optimize seedling growth.

For plant height, seedlings grown in peat soil consistently outperformed those in Ultisol, particularly in the P2N2 treatment, where plant height reached 66.58 cm in peat soil and 48.50 cm in Ultisol. The statistical difference between these values (*P*<0.05) suggests that peat soil's higher nitrogen and organic matter content contributed to more robust shoot elongation, whereas Ultisol's lower fertility limited plant growth unless supplemented with fertilization. The increase in plant height with fertilization aligns with previous studies that demonstrated *T. diversifolia'*s ability to enhance nitrogen availability and stimulate vegetative growth in degraded soils (Suyanto and Astar 2024).

Similarly, leaf number increased significantly with higher doses of TLF and NPK, particularly in peat soil, where P2N2 resulted in 23.33 leaves per plant, compared to 12.17 leaves per plant in Ultisol. This difference was statistically significant (*P*<0.05), reinforcing the role of TLF as a nitrogen source that enhances leaf expansion and chlorophyll biosynthesis. The integration of organic and inorganic fertilizers allowed for both immediate and sustained nitrogen availability, promoting healthier leaf development and higher photosynthetic efficiency, which are essential for strong seedling establishment (Moe et al. 2019).

A similar pattern was observed in stem diameter, where P2N2 produced significantly thicker stems (2.82 cm in peat soil and 2.32 cm in Ultisol) compared to unfertilized treatments. Stem diameter is a key parameter indicating plant strength and structural stability, with thicker stems facilitating better water and nutrient transport. The improvement in stem diameter following fertilization is consistent with previous findings that organic amendments enhance root activity, increase biomass allocation, and promote drought resistance (Benaffari et al. 2022). The fact that Ultisol, despite its lower initial fertility, showed significant improvement in stem thickness after TLF and NPK application, suggests that integrated fertilization can strengthen plant architecture even in nutrient-poor soils.

The same trend was evident in leaf length, where P2N2-treated plants in peat soil recorded 29.13 cm, while those in Ultisol reached 20.87 cm. The ANOVA and DMRT results confirmed that both soil type and fertilization had a statistically significant impact on leaf elongation (*P*<0.05), with TLF and NPK enhancing cell expansion and leaf development. Longer leaves contribute to greater light interception and higher photosynthetic efficiency, further promoting seedling growth and vigour (Anthony et al. 2020).

Collectively, these findings demonstrate that while peat soil provides a more favorable growing environment for papaya seedlings due to its higher organic matter content and nutrient retention capacity, its low pH and phosphorus deficiency require external supplementation to sustain long-term plant productivity. Meanwhile, Ultisol, despite its lower initial fertility, responded well to fertilization, showing significant improvements in all growth parameters after TLF and NPK application. These results support the use of *T. diversifolia* as an effective organic amendment for enhancing soil fertility and optimizing plant growth in marginal soils, offering both immediate nutrient benefits and long-term improvements in soil health. The statistical validation through ANOVA and DMRT confirms that P2N2 (200 mL L^{-1} TLF + 3 g per polybag NPK) was the most effective treatment, reinforcing the importance of integrated organic and inorganic fertilizer strategies for sustainable agricultural development.

Potential of *Tithonia diversifolia* as an organic fertilizer

The findings of this study confirm that TLF significantly enhances papaya seedling growth in marginal soils, particularly Ultisol and peat soil, which exhibit inherent fertility constraints. The observed improvements in plant height, leaf number, stem diameter, and leaf length following TLF application highlight its nutrient-rich composition, particularly its high nitrogen (2.1%) and potassium (2.9%) content, which support vegetative growth, root development, and overall plant health. The role of *T. diversifolia* in improving soil nutrient availability aligns with previous studies demonstrating that it enhances CEC, soil organic matter, and microbial activity, thereby mitigating the nutrient deficiencies commonly associated with highly weathered tropical soils (Ewané et al. 2020).

The application of TLF has a profound impact on soil properties post-treatment, as shown in Table 1. In Ultisol, TLF application increased organic carbon, nitrogen, and phosphorus levels while slightly improving soil pH, making nutrients more bioavailable for plant uptake. Similarly, in peat soil, TLF contributed to reducing extreme acidity and enhancing phosphorus availability, which are crucial factors in improving plant nutrient absorption. These effects suggest that TLF not only acts as a direct nutrient source but also serves as a soil conditioner, facilitating improved nutrient retention and microbial processes.

Compared to other organic fertilizers, such as compost tea and cow manure extract, TLF offers a more concentrated source of readily available nutrients. Compost tea has been shown to improve microbial biomass and nutrient uptake, but often contains lower levels of macronutrients (Raza et al. 2023). Similarly, cow manure extract enhances soil fertility through microbial activity and organic matter content, yet its nutrient release tends to be slower and less consistent (Ikeh et al. 2023). In contrast, TLF, with its high nitrogen and potassium content and rapid nutrient release due to fermentation, provides faster stimulation of vegetative growth in nutrient-poor soils. Additionally, its liquid form facilitates integration with fertigation systems, providing an advantage over solid compost or manure applications, as summarized in Table 4.

Table 4. Comparative characteristics of *Tithonia diversifolia* liquid fertiliser (TLF) and other organic fertilizers commonly used in marginal soils.

Parameter	*Tithonia diversifolia* Liquid Fertilizer	Compost tea*	Cow manure extract**
Form	Liquid	Liquid	Liquid
N content (%)	2.10	0.007–0.036	0.20
K content (%)	2.90	0.003–0.005	0.29
Mode of action	Fast nutrient release, microbial boost	Microbial biomass enhancer	Organic matter enrichment
Effect on seedling growth	High	Moderate	Moderate
Ease of application	High (e.g., fertigation)	Moderate	Moderate
Additional benefit	Biopesticidal potential	Enhances microbial activity	Improves soil structure

*(Raza et al. 2023); **(Ikeh et al. 2023).

While this study specifically assessed the organic fertilizer potential of *T. diversifolia*, previous studies have reported its antimicrobial and pesticidal properties, owing to bioactive compounds such as flavonoids, tannins, and alkaloids (Purnama et al. 2024). These attributes warrant further investigation, particularly in the context of integrated pest and nutrient management (Anggrayni et al. 2025). Future studies should explore its biopesticidal efficacy under field conditions, alongside its long-term impacts on soil microbiota and crop protection.

CONCLUSION

This study demonstrated that *Tithonia diversifolia* liquid fertiliser (TLF) significantly improved the early growth of *Carica papaya* L. seedlings in both peat and Ultisol soils, with the P2N2 treatment (200 mL L^{-1} TLF + 3 g NPK per polybag) resulting in the highest performance in terms of plant height, stem diameter, and leaf development. Peat soil supported better seedling growth, likely due to its higher organic matter content and favorable moisture retention characteristics, whereas Ultisol—despite its low initial fertility—showed notable responsiveness to integrated fertilization. These findings support the potential of combining organic and inorganic fertilizers to enhance seedling establishment in degraded tropical soils. However, the results are based on a short-term, container-based experiment conducted under controlled conditions without biotic stressors. Therefore, extrapolation to other crops, soil types, or field-scale conditions should be approached with caution. Future studies should incorporate longer-term trials under field conditions, assess microbial and root dynamics, and evaluate pest interactions to more comprehensively understand TLF's multifunctional roles. Additionally, cost-effectiveness analysis and elucidation of the phytochemical contributions of *T. diversifolia* will further inform its potential in sustainable nutrient management systems. To better understand soil organic carbon turnover and its link with fertilizer-induced changes, future research should also employ more detailed carbon fractionation methods or stable isotope tracing techniques.

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CONFLICT OF INTERESTS

The authors declare no competing interests.

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