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Growth and Fiber Yield of Red Spanish Pineapple (*Ananas comosus* L.) through Fertilizer Management and Planting Density in Aklan, Philippines

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Abstract: The Red Spanish Pineapple (*Ananas comosus* L.) is a natural fiber-producing crop primarily cultivated for its *piña* fiber and is deemed the "Queen of Philippine Fabrics" and "Mother of all Phillippine Textiles". The Aklan province is the center and top producing *piña* fiber in the country and holds historical significance for *piña* weaving using traditional handlooms. However, proper fertilization of this crop has not yet been explored to optimize its potential to directly influence fiber leaves and fruits. This study analyzed the growth dynamics of RSP using planting density and fertilizer treatments. The study experimented to analyze the growth dynamics of the RSP using three planting densities (80 × 50 × 30 cm, 60 × 30 cm, and 30 × 30 cm) and five fertilizer treatments (control, STK recommendation 55-40-50, ASU recommendation 56-56-56, 20 t/ha vermicompost, and 40 t/ha vermicompost). The study showed that 20 tons per hectare of vermicompost consistently exhibited a significant influence on the growth performance of the RSP, while STK recommendations (55-40-50) also showed a significant effect on growth performance. In contrast, the ASU recommendation (56-56-56) exhibited moderate influence but had a lesser impact compared to other treatments. Meanwhile, planting distance demonstrated minimal influence; therefore, the growth performance of RSP was not as effective as that of fertilizer management. The results of this study provide relevant information and address the scarcity of data, sustain tradition, and optimize RSP to meet the demand for high-quality fiber locally and internationally.

Keywords: Agronomic practices; crop spacing; fertilizer application, growth enhancement, *Piña*

1. Introduction

The Red Spanish Pineapple (*Ananas comosus* L.) is a tropical plant from *Bromeliaceae* and is widely cultivated in the Philippines, particularly in the Province of Aklan. This natural fiber-producing crop is valued in the country not only for its sweet edible fruit for consumption but also primarily due to the fiber known as *Piña* silk, which contributes to the textile industry. Red Spanish Pineapple Silk is deemed the "Queen of Philippine Fabrics", "Mother of all Phillippine Textiles", and the finest Philippine fabric primarily due to its delicate silk and cream color. Aklan province is the center of *piña* weaving in the country. Likewise, this province holds historical significance for *piña* weaving using traditional handlooms, which were passed down to family and community generations [1]. In fact, Aklan's *piña* handloom was recognized by UNESCO as an intangible cultural heritage of humanity in the country [2]. These fibers are known for their fine texture, dye-holding capacity, creamy white color, sat tolerant resistance, and high tensile strength. It is very popular in the local and international scenes due to its distinct, unique, and texture qualities, making it an export product of the country. However, the supply of planting materials and fibers cannot sustain the increasing demand for *piña* fibers and requires immediate attention for the sustainable production of RSP fibers in the country [3].

One of the key challenges in addressing this concern is the lack of standardized nutrient management practices for fiber production. Most of the varieties for pineapple fruit production have recommended planting distances, fertilizer rates (such as in the Soil Test Kit), and local formulations (ASU recommendation 56-56-56). Furthermore, vermicomposting has been shown to significantly improve plant growth and yield performance [4]. However, these protocols are rarely applied in RSP to determine and evaluate its fiber traits. Additionally, comprehensive studies determining the fiber yield of RSP using these protocols are lacking. Fertilization is one of the factors responsible for the quality of the fruit, especially in relation to the weight achieved. Furthermore, the macronutrients required by pineapple for growth and development are N, P, K, and Ca [5]. Several factors, such as nutrient availability, cultural practices, and fertilization, influence the quality and quantity of RSP leaf fiber. These practices enhance overall quality and quantity of the fiber, such as tensile strength, color, number of fibers extracted, and length. RSP is cultivated primarily for its fiber rather than fruit, and limited studies were conducted to determine the relationship between fertilizer application, planting density, and fiber yield in RSP [6-7]. The government recognizes and research initiatives have been conducted to support RSP production. In 2004, Aklan researchers created a tissue culture method for RSP to mass-produce planting materials for future plantation growth to satisfy the market for *piňa* fibers [8]. The growth performance of the RSP is influenced by the nutrients in the soil, which ensure optimal pineapple productivity. Pineapples require a proper supply of nutrients to sustain their growth, development, yield, and quality of fruit and fiber. Nitrogen and other macronutrients play an important role in the growth performance of pineapple, particularly in photosynthetic activity and overall fertility [9-12]. Moreover, it is vital to ensure optimum pineapple growth and productivity through the balanced use of fertilizers [13]. Proper fertilization enhances leaf quality and directly influences fiber and fruit quality, thereby increasing the income of growers and farmers [6].

The Red Spanish Pineapple has significant economic value not only in the Province of Aklan but throughout the entire country. Unlike other varieties (Queen Formosa and MD2) that are sweeter, this is the only pineapple variety mainly cultivated for its high-quality fibers for luxury fabrics, such as barong tagalog and filipinana. Moreover, news reported that pineapple (all varieties) produced an average of 580-600 US dollars per metric ton in recent years, and exported roughly 787.12 million U.S. dollars in 2024, with fresh/dried pineapple $428.74 million. But there were challenges, and many issues/concerns regarding RSP in relation to RSP's low production [15]. Despite its economic significance, there has been a significant decrease in production due to several challenges, leading to an inadequate fiber supply [16]. Hence, there is a need to address the problem of the decline of *piña* fibers and optimize the potential of the RS pineapples [3]. Furthermore, RSP is still understudied, and there is limited information on the growth dynamics of this crop, specifically on cultural management, which is crucial for optimizing the fiber yield and fruit production of RSP. Hence, this research seeks to establish optimal planting density, implement an effective fertilizer program, and other cultural practices to enhance the production of quality fibers from tissue-cultured RSP. The conducted research fills a crucial gap in the industry by focusing on sustaining the tradition and livelihoods linked to the Red Spanish Pineapple and meeting the demand for high-quality fiber locally and internationally [17-18].

2. Materials and Methods

2.1 Research design

This research employed an experimental design and was laid out in Split Plot Design to accommodate two variables: planting density (main plot) and fertilizer management (sub-plot). The main plot was composed off three types of plant spacing and was divided into subplots composed of five fertilizer treatments with three replications. The treatments included the following:

MAIN PLOT: Planting Density
- Treatment 1 (A_1) – 80 x 50 x 30 cm
- Treatment 2 (A_2) – 60 x 30 cm
- Treatment 3 (A_3) – 30 x 30 cm

SUB-PLOT: Fertilizer Management
- Treatment 1 (B_1) – 0 fertilizer (control)
- Treatment 2 (B_2) – STK Recommendation (55-40-50)
- Treatment 3 (B_3) – ASU Recommendation (56-56-56)
- Treatment 4 (B_4) – Vermicompost (20 t/ha)
- Treatment 5 (B_5) – Vermicompost (40 t/ha)

2.2 Location of the study

The study was conducted at the Diversified Field Crops Production Project at the Aklan State University—Main Campus in Banga, Aklan. Banga, Aklan, is situated in the central plain of Aklan, at approximately 11° 38' North, 122° 20' East, on the island of Panay. It is 21.3 meters (69.9 feet) above sea level with a level to nearly level (0-8%) and categorized as a hot and humid tropical climate, with an average temperature of 27.68 ºC, 243.85 (mm) monthly rainfall, and 78.77 relative humidity as of 2024, according to the Philippine Atmospheric, Geophysical and Astronomical Services Administration.

2.3 Selection and collection of planting materials

Quality tissue-cultured planting materials (slips) were sourced from a laboratory greenhouse. Disease-free and uniform-in-size planting materials were collected from the source to contribute to the high probability of survival when planted in the field.

2.4 Clearing of the area

Before land preparation, the area was cleared of previous crop debris and other foreign objects that might hinder land preparation. Weeds of various kinds were removed/cut using a grass cutter. Cut grasses were then piled in a specific area of the field to allow decomposition or compost to be returned later to the soil.

2.5 Land preparation

A land area of 700 sq m was prepared by plowing and harrowing. Each main plot measured 5 m × 10 m (50 m²) and was divided into five subplots, each measuring 1 m × 10 m (10 m²). Plowing was performed using animal-drawn implements to aerate the soil, reduce weeds and other pests, and incorporate crop residues into the soil. This was accomplished to ensure that the soil was in good tilth for better establishment of tissue-cultured RS pineapple to be planted in the area as experimental crops.

A week after plowing, the area was harrowed twice to reduce the potential weed population by preventing them from germinating, and plots and pathways were constructed after plowing and harrowing. After the land had been thoroughly prepared, plots were laid out, and staking followed using bamboo sticks to mark each designated hill where the plantlets were planted. Staking ensured the proper distance between plants, as this was one of the treatment variables of the study.

2.6 Planting Distance and Selection of Sample Plants

RSP plants were planted at different planting distances. For treatment 1 (A1 – 80 × 50 × 30 cm), plants were planted at a spacing of 80 cm between rows, 50 cm between plants within a row, and 30 cm between successive planting points or diagonal spacing. Meanwhile, treatment 2 (A2 – 60 × 30 cm) was planted at a planting distance of 60 cm between rows and 30 cm within the row. Lastly, for treatment 3 (A3 – 30 × 30 cm), the plants were properly distance at at 30 cm between rows and 30 cm between plants within the row.

In selecting the sample plants, ten representative plant samples were randomly assigned for data gathering by staking or marking the plants. Missing hills were immediately replanted as soon as the mortality of tissue-cultured plantlets was observed.

2.7 Fertilizer application

Fertilizer management was one of the treatment variables of the study, hence the fertilizers applied were: no fertilizer (B1, control), STK recommendation (B2, 55-40-50 at 3.5 g/plant), ASU recommendation (B3, 56-56-56 at 5 g/plant), vermicompost at 20 t/ha (B4, 180 g/plant), and vermicompost at 40 t/ha (B5, 360 g/plant). This was done only once, four months after transplanting, and the fertilizer materials were applied as bands around the base of the plant. This was then covered with fine soil to minimize the volatilization of dissolved nutrients, especially during intense sunlight.

2.8 Leaf harvesting and processing

Leaf harvesting (manual) commenced 18 months after planting (MAP). Harvested leaves were processed following the manner of leaf processing for RSP, such as hand scraping, washing, beating, combing, and drying. This was done to gather the necessary data on the yield parameters of the fibers processed from the experimental plants. Two kinds of fiber were extracted from the leaf—the *liniuan* and *bastos* fiber.

2.9 Data gathering

Data were obtained from 10 randomly identified sample plants, preferably growing at the center of the plot. The uniformity of sample plants was considered to avoid bias in data gathering. These sample plants were identified and marked, and the desired data on growth and fiber yield were measured. Appropriate equipment and instruments were used to gather or obtain the needed data that would contribute to the attainment of the specified objectives. It is worth noting that the RSP fiber is split into two classifications: *bastos* (which is strong and coarse), and *liniuan* (which is very fine and is suitable for weaving cloth). The following data were gathered at specified times throughout the study duration:

The height (cm) of the Red Spanish Pineapple (RSP) was obtained by measuring the plants from the base to the tip of the growing point using a meter stick in centimeters (cm). The mean difference between the final and initial data was used for analysis. The total number of fully developed leaves was manually counted and subtracted from the number of initially developed leaves. The length of the leaves was measured from the base of the leaf up to the highest tip using a meter stick in centimeters (cm). The leaf width (cm) was measured in the widest part of the leaf, particularly in the middle using a meter stick in centimeters (cm). Meanwhile, the fiber length of *linuan* and *bastos* was measured from both ends using a meter stick in centimeters (cm). The number of *liniuan* and *bastos* fibers extracted was manually counted, while the number of *liniuan* and *bastos* fibers strands was measured using a weighing scale in grams (g).

2.10 Statistical analysis

Data gathered were subjected to Analysis of Variance following Split Plot Design using STAR software. A pairwise comparison of treatment means was performed using the Least Significant Difference. Significant differences were declared at P-value <0.05.

3. Results and Discussion

3.1 Plant height

Table 1 depicts the mean plant height (in centimeters) of tissue-cultured Red Spanish Pineapple (RSP) as influenced by different fertilizer management at different planting distances. Results revealed that notable differences were observed in the plant height of the tissue cultured RSP by both fertilizer management and distance of planting. Moreover, statistics show that treatments with 20 tons vermicompost per hectare and STK Recommendation (55-40-50) showed comparable results of 101.63 and 101.59 cm, respectively, and yielded the tallest plants among all treatments applied. Moreover, the ASU recommendations (56-56-56) and treatments with vermicompost (40 tons per hectare) were comparable to each other, with values of 100.52 and 98.96 cm, respectively. In contrast, the lowest plant height was observed in the control group (without treatment), at 96.60 cm (Figure 1a).

STK recommendations may have provided well-balanced essential nutrients enhancing the growth performance of the RSP particularly on its plant height. A specific percentage of macronutrients, such as NPK, might have met the RSP nutrition needs, resulting in good plant height performance. Vermicompost enhances the growth, yield, and intake of some basic plant nutrients (NPK) and increases plant height by about 50% [19].

Additionally, vermicompost treatment likely enriched the soil organic content, positively impacting plant growth. Studies, like Rekha *et al.* [20], affirm that vermicompost-treated plants experienced substantial growth. Vermicompost aids nutrient uptake by providing readily available nutrients, as supported by Mahmud *et al.* (2020), who noted reduced soil acidity and increased macro and micronutrient levels in both soil and plants [21]. Nonetheless, excessive application of vermicompost, especially at 40 tons per hectare, may hinder plant growth and cause nutrient imbalance, as cautioned by Chamani *et al.* [22].

Numerous studies have been conducted on balanced nutrient management. For instance, ASU's recommendations focus on using well-balanced amounts to optimize plant growth and development. Fertilizer application increased the amount of NPK available in the root zone, which increased the plant's ability to absorb nutrients. Numerous studies have shown that the increased leaf photosynthetic capability resulting from this nutrient increase contributes to the buildup of plant biomass [23-24]. However, excessive fertilizer application can cause plant stunting due to insufficient water availability caused by high osmotic conditions in the soil [25].

Therefore, in terms of encouraging optimal growth, the ASU Recommendation (56-56-56), while balanced, may not have been as successful as the STK Recommendation. In contrast, the shorter plants in the control group demonstrated the importance of additional nutrients and proper fertilizer administration for RSP growth and development. Fertilizer recommendations contain several important factors, including fertilizer form, source, application timing, placement, and irrigation management. Another important aspect of fertilizer recommendation is the amount of a particular nutrient to be applied. The optimum fertilizer amount is determined from extensive field experimentation conducted for several years, at multiple locations, with several varieties, etc. [26]. It is essential to emphasize that the fertilizer rate aims to ascertain the precise quantity of fertilizer required to attain a commercially viable crop yield of satisfactory quality, which is economically viable for Red Spanish Pineapple growers.

Spacing between pineapple plants during cultivation can significantly impact their growth, fruit development, and overall performance due to competition for nutrients, water, and sunlight [27]. Certain studies have indicated that increasing planting density, such as up to 78,000 plants per hectare, can lead to increased plant height and reduced width of the D-leaf (the longest leaf in a pineapple plant), as well as a decrease in the percentage of plants responding to flowering induction after artificial flowering induction [28-29]. However, findings regarding the specific planting distances show variations in mean plant height, ranging from 98.71 cm to 100.66 cm. It was concluded that the planting distance did not have a significant impact on plant height during this experiment involving Red Spanish Pineapple cultivation.

The specific alterations made in fertilizer application and distance of planting might not have exerted a considerable impact on the growth conditions of the plants. The variation in the combined ranges probably did not lead to significant differences in height. It seems that the fertilizer might have influenced the height independently rather than in conjunction with distance. Each factor may have individually influenced plant growth to a certain degree, but their combined effects during simultaneous investigation may not have been notably impactful.

3.2 Number of leaves

The leaf count serves as a critical measure reflecting the Red Spanish pineapple's vegetative growth and leaf development. Pineapple leaf fiber (PALF) is a natural fiber with specific strength, rigidity, flexural resistance, and torsional resistance similar to jute fibers [30]. The analysis of mean leaf count demonstrated no substantial interaction effect between fertilizer management and planting distance (refer to Table 1). This suggests that the combined influence of these factors did not notably affect the leaf count. Notably, only the fertilizer management factor had a significant effect across all planting distance variations.

The findings revealed that plants treated with 40 tons of vermicompost per hectare exhibited the highest leaf count (104 pcs), as shown in Figure 2b. This indicates superior leaf development under this specific fertilizer management for RSP. Conversely, the 55-40-50 STK Recommendation resulted in a comparable leaf count (103 pcs), highlighting its efficacy in supporting leaf production at varying planting distances. However, lower levels of organic fertilizer, such as 20 tons/ha of vermicompost and the ASU Recommendation (56-56-56), yielded slightly fewer leaves (102 pcs), suggesting a limited impact on RSP leaf development. The control treatment recorded the lowest leaf count (97 pcs), aligning with previous studies emphasizing vermicompost's role in bolstering leaf productivity. These results corroborated with Balan, *et al.*, 2019 and Joshi *et al.* (2010), who revealed that the application of vermicompost increased the productivity of leaves in the plants [31-32]. Regarding planting distance, mean leaf count ranged from 101 pcs (for 60 x 30 cm spacing) to 102 pieces (both for 80 x 50 x 30 cm and 30 x 30 cm spacing). However, planting distance did not significantly affect the plant height during this experiment.

The study underscores the significance of specific nutrient management, particularly the application of 40 tons/ha of vermicompost, in enhancing leaf growth in RSP. It also emphasizes the role of fertilizer composition in supporting leaf productivity, elucidating the intricate link between fertilizer application, planting distance, and leaf count per square meter in the Red Spanish pineapple variety grown in the region. While each factor individually contributed to higher leaf counts, their combined influences might not have been notable due to diverse influences or differing experimental conditions.

3.3 Length of the leaves

As depicted in Table 1, the mean leaf length of tissue-cultured RSP was affected by fertilizer management. The findings indicated that employing vermicompost at 20 tons per hectare resulted in the most extended leaf length at 74.19 cm across varied planting distances, surpassing other applied treatments. Following closely were the STK (55-40-50) and ASU (56-56-56) recommendations, achieving 73.15 cm and 72.37 cm, respectively, slightly trailing the 20 t/ha vermicompost. In contrast, vermicompost at 40 t/ha and the control group exhibited the shortest leaf lengths at 71.25 cm and 69.48 cm, respectively.

Vermicompost is widely used because it contains high nutrient content, specifically macro and micronutrients, to enhance the growth performance of crops. According to Mahmud et al. (2018), fertilization plays an important role in crop management to increase growth potential and crop yield [33]. Pineapple plants have a large nutrient uptake demand, especially for potassium, followed by nitrogen, calcium, magnesium, sulfur, and phosphorus [34].

Pineapple plants have a large nutrient uptake demand, especially for potassium (K), followed by nitrogen (N), sulfur (S), calcium (Ca), magnesium (Mg), and phosphorus (P) [35]. Macro- and micronutrients can be obtained by supplementing inorganic or organic fertilizers, such as vermicompost. Vermicompost is a slow-release fertilizer and is rich with essential plant nutrients produced by the joint action of certain species of earthworms (especially *Eisenia fetida* or *Eudriculus eugeniae*) and microorganisms in the decomposition of organic waste such as agro-wastes, sewage sludge and food wastes [36-38]. Several studies have shown that vermicompost amendment can directly increase plant production by increasing available plant nutrients and indirectly promote soil quality by improving soil structure and stimulating microbial activities, relative to conventional chemical fertilization [39,40].

The results showed that the interaction of planting distance and fertilizer management had a considerable effect on leaf length, most noticeably for 60 × 30 cm and 30 × 30 cm spacings with STK fertilizer, and the application of 20 t/ha of vermicompost, which produced the longest leaves (74–75 cm). Meanwhile, the shortest leaves were observed on the control treatments (68–70 cm) among all planting densities as shown in Figure 2c. This highlights the narrow distance of planting supplied with balanced fertilizer results and longer leaves due to the competition for light [41].

3.4 Width of the leaves

The examination of leaf width averages in tissue cultured RSP, detailed in Table 1, suggests the absence of a substantial interaction between fertilizer management and planting distance. However, a notable impact was evident in terms of fertilizer management across all planting distance variations. The widest leaves were observed in plants subjected to the 55-40-50 STK Recommendation, measuring 2.80 cm. The study emphasized that the STK recommendation provided a well balance nutrient blend with specific rations of nitrogen, phosphorus, and potassium resulting in significantly wider lead of RSP. According to Chen *et al.*, 2021, balanced fertilization could provide benefits starting from increasing productivity and quality of crop yields and can increase yield by 3–7% with less fertilizer input [42]. Balanced use of nutrients has been proven to improve crop yield and organic matter in soil [43].

The widest leaves were observed in plants subjected to the 55-40-50 STK Recommendation, measuring 2.80 cm. Slightly narrower widths were recorded in plants treated with the 56-56-56 ASU Recommendation, measuring 2.67 cm. The control group displayed a width of 2.44 cm, akin to the leaf widths observed in plants treated with 40 tons (2.38 cm) and 20 tons (2.37 cm) per hectare of vermicompost (Figure 2d). Plant spacing influences the leaf width of pineapple plants. According to Kaamoga, 2018, in his study, there were significant differences between plants in plant height and width, leaf length, and leaf width at different spacing in pineapple plants as affected by plant spacing and nutrient source on growth and yield of pineapple [44].

These variations were influenced by both plant spacing and nutrient sources, highlighting their impact on pineapple growth and yield. In contrast, no significant influence was detected on RSP, with mean values ranging from 2.41 cm for the 30 × 30 cm spacing to 2.63 cm for the 60 × 30 cm spacing. The results revealed that well-balanced fertilizer management can significantly influence the width of leaves in tissue-cultured RSP. The STK Recommendation notably contributed to the widest leaves, indicating its substantial effect. While planting distance accounted for some differences in leaf width, its influence was comparatively modest when contrasted with the use of fertilizers. These findings signify the noteworthy impact of the chosen fertilizer management on leaf width, while the studied planting distances did not exhibit a substantial effect on this aspect.

3.5 Number of liniuan fibers

The findings indicated that there was an interaction effect between the management of fertilizer and *liniuan* fiber strands. Statistical analysis demonstrated that all treatments applied with a planting distance of 80 x 50 x 30 cm yielded comparable results, with Treatment 5 (Vermicompost at 40 t/ha) exhibiting the highest average count of 31 pieces. Hence, the study shows that specific planting distance and the amount of vermicompost at 40 t/ha significantly influenced the *linuan* fiber strand, as shown in Table 1 and Figure 2e.

There was also an interaction effect between fertilizer management and *the liniuan* fiber strand at a planting distance of 60 × 30, but it was slightly different compared to an 80 × 50 × 30 planting distance. However, similar results show that all treatments are comparable. Treatment 3 (ASU recommendations) exhibited the highest number of *liniuan* fiber strands with 30 pcs, followed by T2 (STK Recommendation) and T4 (Vermicompost at 40 t/ha). The study suggests that vermicomposting using ASU recommendations is suitable for *liniuan* fiber strand production at planting of 60 x 30 cm.

Furthermore, there were interactions between fertilizer management and *the effects of the liniuan* fiber strands at a 30 × 30 cm planting distance. However, this time treatment 4 (vermicompost at 20 t/ha) shows the highest mean of *liniuan* fiber strands (31 pieces) followed by STK recommendation (30 pcs), treatment 5 (vermicompost at 40/ha), and treatment 3 (ASU recommendations). Results exhibited that using the 30 x 30 planting distance, lower rate application of vermicompost may produce good number *liniuan* fiber strands compared to other fertilizer management approaches. Moreover, the study revealed that there is an interaction effect between fertilizer management and distance of planting in RSP resulting in higher *liniuan* fiber strands. Vermicompost with higher rates significantly influences the *liniuan* fiber strands and specific fertilizer management can yield a better number of *liniuan* fiber strands depending on the planting distance.

Production of *liniuan* fiber strands would be affected to an extent by planting distance and fertilizer management, given the variety of connected factors like soil nutrition or spacing's influence on growth patterning in plants. Each element could also have a different effect due to differences among nutrients that are taken up differently into roots at varying rates.

Soil conditions vary with planting distances, affecting the availability of nutrients and root distribution. Several studies have demonstrated that planting distance influences crop performance [45-46]. The purpose of changing the planting distance is to provide each individual with sufficient room for growth. This has a great impact on the efficiency of light use, plant density, and interplant competition for water and nutrients (and hence overall crop productivity) [47].

Proper planting distance enhances growth performance by minimizing nutrient competition, thus reaching optimal growth [48-49]. On the other hand, a shorter distance of planting may cause stunted growth and a decrease in yield, thus hindering the optimal growth performance and reducing production. The planting density intertwines with plant population per area and, hence, significantly influences the essential factors in the growth performance of the plant such as sunlight, nutrients, plants, and space [50]. Moreover, nutrients in the soil are crucial for enhancing the growth and fiber development of RSP; thus, it relies largely on the approach of fertilizer management and distance of planting. Improper application of synthetic fertilizers may affect the pH in soils, causing them to be vulnerable to acidification, pests, diseases, and crusting of soils. These significant changes can result in a decrease in organic matter in the soil and a reduction in beneficial organisms. However, it will negatively affect growth performance, reduce yield, and potentially release greenhouse gas emissions, resulting in climate change [51,52]. Moreover, the management of combining planting distance and proper fertilization can significantly increase root expansion thus absorbing more nutrients and may produce more fiber yield.

According to Omotoso and Akirinde in 2013 [53], pineapple growth and yield performance increased due to the proper use of fertilizers. Fiber production, planting distance, and fertilizer management may be related because they affect the distribution of nutrients in the soil. Similarly, researchers proved that fertilization influenced high-quality fibers in plants. The fiber properties suggested that fertilization was an essential attribute of fiber growth. Moreover, the notable interaction may have resulted from the interplay between the factors affecting nutrients in the soil, plant growth, and fiber production, which were influenced by both planting interval and fertilizer application strategies.

3.6 Number of bastos fibers

Results showed that a significant interaction between planting distance and fertilizer management was absent in the number of *bastos* fibers produced by RSP (Table 1). Individually, the fertilizer management factor significantly affected the number of *bastos* fiber strands, with the highest mean from plants that received the 56-56-56 ASU Recommendation (33 pcs), followed by those with the 55-40-50 STK Recommendation and application of 40 tons and 20 tons of vermicompost per hectare (32 pcs). The least number (31 pcs) of *bastos* fiber strands was observed in the control treatment, where no fertilizer was applied. The different planting distances also had no significant effect on this parameter across all the fertilizer management treatments, with the same mean value of 32 pieces recorded (Figure 2f).

Certain types of pineapples, particularly the Red Spanish variety, possess a natural ability to adapt to various planting distances. The pineapple plant employs a unique photosynthetic process known as Crassulacean Acid Metabolism (CAM). This adaptation is particularly beneficial because it enables the plant to efficiently preserve moisture. Pineapples exhibit the capacity to thrive in diverse soil types provided there is proper drainage and aeration. Different pineapple varieties possess inherent strengths in terms of resistance and adaptability to varied environments; however, this broad adaptability might lead to a decline in quality [54]. Their response to different spacing suggests that within this range, the plant adjusts its growth rate and fiber production instead of reacting distinctly to varied space patterns.

Pineapples excel at efficiently utilizing resources such as nutrients, water, and light. In this scenario, the plants might have equalized spacing differences by optimizing resource utilization, resulting in similar fiber quantities across the tested distances. The utilization of vermicompost, rich in organic matter and beneficial microorganisms, influenced *the production of bastos fiber* by enhancing soil structure, increasing water retentionn, and improving the delivery of minerals to the plants. This implies that employing specific nutrient ratios from recommended fertilizers (56-56-56 and 55-40-50) might have precisely met the pineapple's nutritional requirements during fiber development.

The interaction effect showed that the ASU fertilizer recommendation (56-56-56) exhibited the largest number of bastos fiber strands counted (33) regardless of the planting distance, whereas the control showed the least number of bastos fiber strands counted (31). This highlights that balanced fertilizer produces more fiber strands. Further, it's notable that wider planting distance (80 × 50 × 30 cm) produced significantly more fibers as the pineapple plants had more room and less competition [55]

3.7 Weight if liniuan fibers

The interaction of planting distance and fertilizer management did not greatly affect the weight of *liniuan* fiber strands. The data in Table 1 also showed that the main effects of both factors did not influence the weight of *liniuan* fiber strands, where the mean weight ranged from 0.23 g to 0.25 g at 80 x 50 x 30 cm planting distance, 0.23 g to 0.26 g at 60 x 30 cm planting distance, and 0.22 g to 0.26 g at 30 x 30 cm planting distance.

Although the mean weight differences between the treatments were minimal, there were noticeable variations within individual treatments and specific spacing intervals within certain planting distances. For instance, the mean weights of plants subjected to the STK Recommendation and Vermicompost (20 t/ha) treatments were higher than those at other planting distances.

The study showed that RSP responded differently to different fertilizers. At a certain distance, the nutrient ratio or specific components of STK Recommendation or Vermicompost (20 t/ha) were more aligned with the plants' nutritional needs, which resulted in slightly lighter fiber weights than for other treatments. Thus, despite some of the treatments not statistically differing in mean weights, these cellular weights from plants grown at the same planting distance are indicative of the dynamics of the soil and nutrients, the environment, and the responses of the plants. These significant differences in the weight of fiber per treatment with distance indicate the sensitivity of pineapple growth to various management practices and the environmental effects generated through management practices. These differences in the fiber weight of the treatments were significantly lower relative to environmental variations such as fertilization or spacing [56]. However, vermicomposting in organic amendments promotes soil fertility and structure, and thus performs better than spacing [57].

Minimal differences in the weight of the fibers from all treatments were observed. According to studies and analyses, these differences depend more on the weight and length of the leaves than on external factors such as fertilization and spacing [44]. On the other hand, vermicomposting as organic amendments outperforms spacing, as it improves fertility as well as the structure of soil [57]. *Liniuan* fiber weight had no significant effect because it had less effect on the distance of planting and fertilizer management. The impact of genetics, leaf morphology, and time of harvest are key contributing factors that need to be examined further to elucidate the effect on the fiber development of RSP [56,57].

3.8 Weight of bastos fibers

The results showed that there is no significant interaction between planting distance and fertilizer management in the weight of *bastos* fibers produced by RSP. The data presented in Table 1 also show that of these two factors, only fertilizer management had a significant effect on this parameter across all planting distance settings. The heaviest fiber strands were recorded in plants treated with the 55-40-50 STK Recommendation (0.32 g). Comparable to this value were those applied with vermicompost at rates of 20 tons (0.31 g) and 40 tons (0.30 g) per hectare, and the control (0.30 g). The lightest fiber strands were those with the 56-56-56 ASU Recommendation (0.28 g). The different planting distances also had no significant effect on this parameter across all the fertilizer management treatments, with the mean values ranging from 0.30 g at 60 x 30 cm and 30 x 30 cm planting distances to 0.31 g at 80 x 50 x 30 planting distance. When it comes to planting distance's impact on fiber weight, while it does play a role, its influence is notably weaker compared to the significant effects resulting from diverse fertilizer management practices. Factors such as nutrient distribution in the soil or root development might be influenced by planting distance, but these effects pale in comparison to the direct impact of fertilizer on available nutrients and plant growth.

Fertilizers have different nutrient compositions and proportions, which are essential for plant fiber growth and quality. For example, the ASU Recommendation (56-56-5) lacks specific element necessary for strong fiber formation, which can result in low weight in *bastos* fibers. On the other hand, the STK recommendation with heavy fibers showed a more balanced nutrient fertilization ratio (N, P, K), hence contributing to creating an ambiance for a strong formation of fiber. This fertilization enhances lignin deposition and secondary fiber cell walls [38]. Potassium (K) is among the most critical nutrients for metabolic function and strong fiber. This nutrient is involved in regulating stomatal opening and translocation of carbohydrates [58]. Compared an organic amendment of vermicompost (20–40 tons/ha) and STK (20 tons/ha), results were similar with improved fertility, mineralization, and root development affecting the water weight of fiber *bastos* [59]. Planting distance affected fiber weight to some degree, but the actual differences between treatments (planting distance) were not as pronounced as the differences occurring due to the different effects of the fertilizer. However, specific ratios have slight variations. Nutrient-specific formulations of macroelements (N, P, K) have been demonstrated to significantly influence the yield of fiber as well as its characteristics through regulation of photosynthesis, elongation, and wall strengthening of fiber cells and lignin biosynthesis [59-60].

Results revealed a significant interaction in the weight of bastos fiber strands, indicating that fiber weight varies depending on both fertilizer type and planting distance. Plants spaced at 80 × 50 × 30 cm and applied with 20 t/ha or 40 t/ha vermicompost, as well as those planted at closer spacing (30 × 30 cm) with STK fertilizer, produced the heaviest fibers (0.32–0.34 g). In contrast, the control treatment consistently resulted in lighter fibers (0.29 g), as shown in Figure 2g. These findings confirm that both organic (vermicompost) and inorganic (STK) fertilizers are effective in enhancing fiber weight, but their effectiveness depends on planting distance [61].

3.9 Length of liniuan fibers

The data in Table 1 showed that planting distance and fertilizer management did not influence the length of *liniuan* fiber strands. The interaction effect was also absent. The mean values ranged from 48.36 cm to 50.60 cm at an 80 x 50 x 30 cm planting distance, 49.18 cm to 50.27 cm at a 60 x 30 cm planting distance, and 46.91 cm to 51.89 cm at a 30 x 30 cm planting distance. Changes in planting distance and the nutrient composition provided by fertilizers might not significantly affect fiber length during this growth phase. These external factors seem to have a limited impact on the genetic mechanisms governing fiber elongation at this stage.

Environmental factors have played a significant role in fiber elongation, such as optimized and stable climate (e.g., temperature, humidity, and lighting) supported fiber elongation [56]. When these environmental variables remain optimal across treatments, they could overshadow the effects of planting distance or fertilizer management on fiber length. It is unlikely that substantial changes in the length of *liniuan* fiber strands occur within the observed growth period. Perhaps the most significant variations due to planting distance or fertilizer management occur at stages of development not captured in this study. In this specific case, the genetic stability or growth characteristics of tissue-cultured Red Spanish Pineapple seem to override any potential impact of planting distance and specific fertilizer management on fiber length. The fiber length of *liniuan* was not affected by planting distance and fertilizer management, and this was probably due to internal (gene) and external (environmental) factors. It has been reported in studies that genetically regulating cellulose and lignin in pineapple fibers is the main determinant of RSP fiber elongation and tensile strength [62].

3.10 Length of bastos fibers

The interaction of planting distance and fertilizer management did not greatly affect the weight of *bastos* fiber strands. The data in Table 1 also showed that these factors did not influence the length of *bastos* fiber strands, where the length ranged from 52.02 cm to 55.93 cm at an 80 x 50 x 30 cm planting distance, 53.80 cm to 54.64 cm at a 60 x 30 cm planting distance, and 52.06 cm to 56.04 cm at a 30 x 30 cm planting distance. Factors suggest that changes in the planting distances or fertilizer management did not have a large effect on the fiber length. Across different planting distances, the mean strand length remained relatively steady, ranging from 52.02 to 56.04 cm. The mean fiber strand length remained relatively consistent across different planting distances. Lengths ranged from 52.02 to 56.04 cm, suggesting that a standard fiber length prevails not only regardless of the fertilizer management strategy adopted but also irrespective of its planting distance. However, the study found no effect of the placement distance nor specific fertilizer management on bastos fiber strand length for tissue-cultured Red Spanish Pineapple. Hence, similar fiber lengths were found in all treatments and distances, both factors had little effect on *bastos* fibers.

The data exhibited similar fiber strands in *bastos* RSP but with minimal influence by a distance of planting and fertilizer management. Studies have shown that external factors (e.g., temperature and planting density) did not significantly influence fiber length in cotton. Similarly, the length of fiber also showed stable results regardless of agricultural practices applied [60]. Therefore, these factors such as planting distance and types of fertilizers did not make a direct contribution to influence *bastos* fiber length in RSP but may attributed to genetic traits such as high cellulose content and crystallinity.

Table 1. Growth and fiber yield performance of tissue-cultured Red Spanish Pineapple (RSP) as influenced by different fertilizer management planted at different planting distance.

Fertilizer Management	**Planting Distance**	**Plant Height (cm) ***	**No. of Leaves ***	**Leaf Length (cm) ***	**Leaf Width (cm) ***	**No. of *Liniuan* Fiber Strands ***	**No. of Bastos Fiber Strands ***	**Weight of *Liniuan* Fiber Strands (g) ns**	**Weight of *Bastos* Fiber Strands (g) ***	**Length of *Liniuan* Fiber Strands (cm) ^{ns}**	**Length of *Bastos* Fiber Strands (cm) ^{ns}**
T1 – Control (No Fertilizer)	80 × 50 × 30	94.78	97	68.24	2.34	29^{ab}	31^{b}	0.24	0.30^{a}	48.36	52.71
	60 × 30	97.94	96	70.52	2.30	28^{b}	31^{b}	0.23	0.30^{a}	49.18	53.80
	30 × 30	96.78	97	69.68	2.69	27^{b}	31^{b}	0.22	0.29^{a}	46.91	52.06
Mean		**96.50^{c}**	**97^{c}**	**69.48^{d}**	**2.44^{b}**	**28.00^{b}**	**31^{c}**	**0.23**	**0.30^{a}**	**48.15**	**52.86**
T2 – STK Rec. (55-40-50)	80 × 50 × 30	101.22	103	72.88	2.99	30^{a}	32^{b}	0.23	0.33^{a}	48.47	52.02
	60 × 30	103.56	104	74.56	2.88	29^{ab}	32^{b}	0.26	0.29^{a}	49.96	54.07
	30 × 30	100.00	103	72.00	2.55	30^{a}	33^{b}	0.26	0.34^{a}	51.89	56.04
Mean		**101.59^{a}**	**103^{ab}**	**73.15^{ab}**	**2.80^{a}**	**29.67^{a}**	**32^{b}**	**0.25**	**0.32^{a}**	**50.10**	**54.04**
T3 – ASU Rec. (56-56-56)	80 × 50 × 30	100.11	103	72.08	2.50	29^{ab}	33^{a}	0.24	0.29^{b}	50.35	53.47
	60 × 30	99.89	102	71.92	3.08	30^{a}	33^{a}	0.23	0.29^{b}	49.98	54.51
	30 × 30	101.56	102	73.12	2.43	28^{b}	33^{a}	0.22	0.24^{b}	49.89	53.71
Mean		**100.52^{ab}**	**102^{b}**	**72.37^{bc}**	**2.67^{ab}**	**29.00^{ab}**	**33^{a}**	**0.23**	**0.28^{b}**	**50.07**	**53.90**
T4 – Vermicompost (20 t/ha)	80 × 50 × 30	100.44	102	73.32	2.56	29^{ab}	32^{b}	0.25	0.31^{a}	49.93	55.93
	60 × 30	102.89	101	75.11	2.45	28^{b}	32^{b}	0.24	0.31^{a}	50.27	54.64
	30 × 30	101.56	103	74.14	2.10	31^{a}	31^{b}	0.26	0.32^{a}	50.89	54.11
Mean		**101.63^{a}**	**102^{b}**	**74.19^{a}**	**2.37^{b}**	**29.33^{a}**	**32^{b}**	**0.25**	**0.31^{a}**	**50.36**	**54.89**

Table 1. Growth and fiber yield performance of tissue-cultured Red Spanish Pineapple (RSP) as influenced by different fertilizer management planted at different planting distance. (Continue)

Fertilizer Management	Planting Distance	Plant Height (cm) *	No. of Leaves *	Leaf Length (cm) *	Leaf Width (cm) *	No. of *Liniuan* Fiber Strands *	No. of Bastos Fiber Strands *	Weight of *Liniuan* Fiber Strands (g) ns	Weight of *Bastos* Fiber Strands (g) *	Length of *Liniuan* Fiber Strands (cm) ns	Length of *Bastos* Fiber Strands (cm) ns
Mean		**101.63[a]**	**102[b]**	**74.19[a]**	**2.37[b]**	**29.33[a]**	**32[b]**	**0.25**	**0.31[a]**	**50.36**	**54.89**
T5 – Vermicompost (40 t/ha)	80 × 50 × 30	97.00	105	69.84	2.24	31[a]	32[b]	0.23	0.32[a]	50.60	54.51
	60 × 30	99.00	103	71.28	2.45	29[ab]	32[b]	0.24	0.29[a]	49.65	54.31
	30 × 30	100.89	104	72.64	2.28	28[b]	32[b]	0.24	0.30[a]	49.98	53.80
Mean		**98.96[b]**	**104[a]**	**71.25[c]**	**2.38[b]**	**29.33[ab]**	**32[b]**	**0.24**	**0.30[a]**	**50.08**	**54.21**
Planting Distance Mean	**80 × 50 × 30**	**98.71[b]**	**102**	**71.67**	**2.53**	**29.6**	**32.0**	**0.24**	**0.31**	**49.95**	**53.73**
	60 × 30	**100.85[a]**	**101**	**72.68**	**2.63**	**28.8**	**32.0**	**0.24**	**0.30**	**49.81**	**54.67**
	30 × 30	**100.16[a]**	**102**	**72.72**	**2.39**	**28.8**	**32.0**	**0.24**	**0.30**	**49.91**	**53.94**
Grand Mean		99.80	101.2	71.76	2.52	29.07	32.0	0.24	0.30	49.89	54.11
CV (Planting Distance)		*3.72%*	*3.83%*	*3.83%*	*10.84%*	*7.70%*	*5.36%*	*8.41%*	*5.68%*	*2.29%*	*4.75%*
CV (Fertilizer Management)		*2.33%*	*1.85%*	*1.85%*	*14.66%*	*4.27%*	*2.87%*	*7.88%*	*8.82%*	*4.82%*	*4.19%*
Interaction (A × B)		ns	ns	*	ns	ns	*	ns	*	ns	ns

CV (Coefficient of Variation) = values indicate variability across planting distances and fertilizer management; * - significant; ns - not significant; Mean values with different letter superscript indicate significant difference (p<.05) using Least Significant Difference (LSD) Test

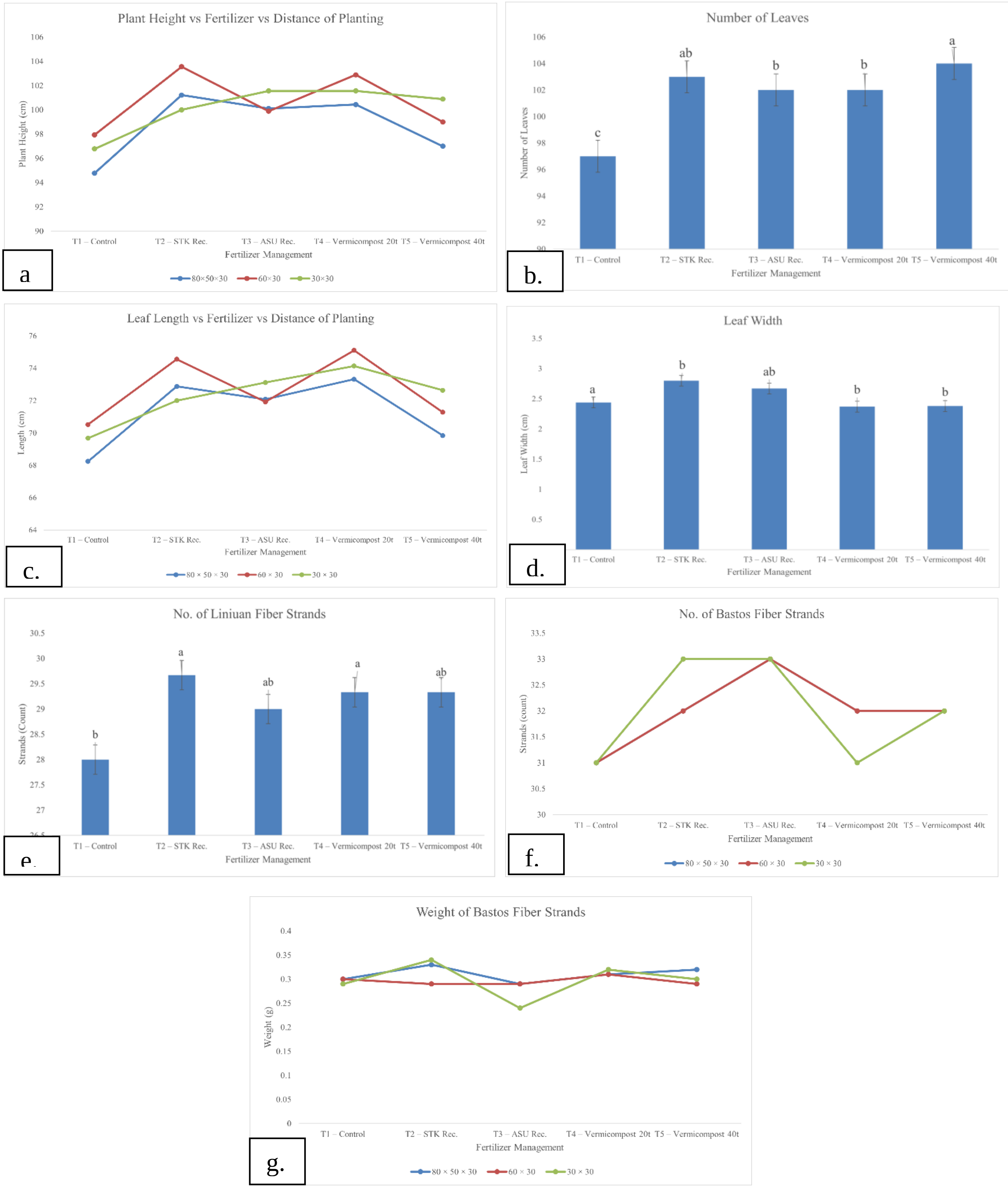

Figure 1. Significant growth and fiber yield responses of tissue-cultured Red Spanish Pineapple to fertilizer management and planting distance: (a) Plant height, (b) Number of leaves, (c) Leaf length, (d) Leaf width, (e) Number of *liniuan* fiber strands, (f) Number of *bastos* fiber strands, and (g) Weight of *bastos* fiber strands. Differences in planting distances or cultural management had little effect on the length of the *bastos* fiber strands in the tissue-cultured Red Spanish Pineapple. The relative absence of significant effects from these

4. Conclusions

Results revealed that among the fertilizers, vermicompost at 20 t/ha and the STK Recommendation (55-40-50) had consistently exhibited positive effects and promoted optimal plant height, leaf length and leaf width, *liniuan* and *bastos* fiber weight. On the other hand, vermicompost application at 40 t/ha had resulted in higher leaves number and *liniuan* fiber. Additionally, the incorporation of vermicompost at specific rates enhanced leaf growth and fiber strand production. Wider leaves were associated with the broadest STK recommendation (55-40-50) and more *bastos fibers* with the ASU recommendation (56-56-56). Wider planting distance influenced the number of *bastos* fiber strands; however, planting distance did not significantly influence most growth parameters. Interaction between fertilizer management and spacing positively affected the number of *liniuan* fibers in most treatments, suggesting site-specific agronomic practices. The study highlights the importance of site-specific fertilization approaches, including the application of vermicompost, for the improved growth and performance of tissue-cultured Red Spanish Pineapple. The outcome of the study is a very critical contribution to the pina fiber industry, as it is aimed at helping preserve the tradition and the livelihoods associated with the Red Spanish Pineapple, as well as fulfill the domestic and international demand for quality fiber.

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