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Effects of Fertilization and Planting Distance on Growth Parameters of *Musa AAB Simmonds*

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Abstract: In Colombia, technology has been developed for plantain cultivation management; however, knowledge regarding the response of this species to various agronomic practices remains limited. This study aimed to assess the impact of fertilization and planting distance on seven growth variables of the Dominico-Hartón plantain (*Musa AAB Simmonds*). Our hypothesis suggests a differential response to fertilization based on the planting distance. The study was conducted using 1200 corm cuttings planted at La Bella Nubia farm, La Bella village, Calarcá Quindío, Colombia. A randomized complete block design with five replications and two treatments was employed: 1) nutrients at four levels: compost (CO), agrochemicals (AG), necromass (NE), and control (T), and 2) two planting distances: 1.7 m (D1) and 2.5 m (D2). Every 60 days, five plants were sampled to quantify the leaf area and dry weight of the root, pseudostem, and leaf growth parameters. Plantain plant growth was influenced by both the fertilization type and planting distance. Plants fertilized with agrochemicals and compost exhibited positive responses in relative growth rate, net assimilation rate, and stem weight ratio when planted closely but showed negative effects on specific leaf area, leaf area ratio, leaf weight ratio, and root weight ratio at greater distances. Conversely, plants treated with necromass and control plants showed opposite trends. We concluded that nutrient availability favors growth when plants are closely spaced; however, under low nutrient availability, separate planting is beneficial for growth. At the same time, it can be concluded that it is necessary to add balanced mixtures of chemical fertilizers and biofertilizers to guarantee the adequate development of the Dominico-Hartón plants.

Keywords: growth parameters; biomass distribution; nutrition; planting distance; *Musa AAB Simmonds*

施肥和栽植距离对香蕉生长参数的影响

摘要：哥伦比亚已开发出车前草种植管理技术，但关于该物种对各种农艺实践的反应的知识仍然有限。本研究旨在评估施肥和种植距离对多米尼科-哈顿车前草(穆萨·AAB·西蒙兹)七个生长变量的影响。我们的假设表明，施肥对种植距离的反应不同。这项研究使用种植在哥伦比亚卡拉卡金迪奥省拉贝拉村拉贝拉努比亚农场的1200个球茎插穗进行。采用完全随机区组设计，重复五次，处理两种：1)四个水平的营养物质：堆肥(CO)、农用化学品(AG)、腐殖质(NE)和对照(T)，以及2)两种种植距离：1.7米(D1)和2.5米(D2)。每60天，对五株植物进行取样，以量化根、假茎和叶片生长参数的叶面积和干重。车前草植物的生长受施肥类型和种植距离的影响。施用农用化学品和堆肥的植物在密植时对相对生长率、净吸收率和茎重比表现出正反应，但在较远距离时对比叶面积、叶面积比、叶重比和根重比表现出负反应。相反，用死灵团处理的植物和对照植物表现出相反的趋势。我们得出结论，当植物间距较小时，养分供应有利于生长；然而，在养分供应低的情况下，分开种植有利于生长。同时，可以得出结论，有必要添加平衡的化学肥料和生物肥料混合物，以保证多米尼克-哈顿植物的充分发育。

关键词：生长参数；生物量分布；营养；种植距离；香蕉

1. Introduction

Plantain (*Musa paradisiaca, AAB*) is a cornerstone of tropical food resources, playing a significant socio-economic role in developing countries in tropical and subtropical regions. Indeed, plantains ensure food security and provide income for small-scale farmers, who constitute the majority of producers in the tropics [1, 2]. It serves as a major income source for producing countries and as a staple food for over 400 million people residing in many developing nations, particularly in Africa, Latin America, and the Caribbean. In 2020, plantains were cultivated in 54 countries, yielding over 43 million tons globally, with Latin America and the Caribbean contributing 18% of the global plantain production [3]. Therefore, sustainable plantain production in this region is crucial to ensure food security and income for millions of people [2, 4, 5].

In Colombia, plantain-producing families amount to approximately 213.950 Agricultural Production Units (UPAs), with an average area of 3.5 hectares cultivated across all 32 departments and 786 municipalities in the country. This subsector generates 960.000 direct and indirect employment opportunities [6]. Despite this, plantain cultivation faces numerous challenges, including phytosanitary issues, agronomic management, inappropriate cultural practices, and irrational use of agrochemicals, all of which affect its sustainability [4, 7].

Owing to these challenges, organic farming is gaining importance globally because of its beneficial effects: it reduces the use of chemical fertilizers, improves soil physicochemical properties, and enhances beneficial microflora [8, 9]. One alternative is to incorporate easily decomposable organic matter into the soil, enriching it with fauna and flora, particularly bacteria. This activates the decomposition of native and added organic matter, benefiting crop nutrition [9, 10]. Additionally, Bolaños et al. [11] suggested that the combined application of organic matter and mineral fertilizer has a positive effect on soil, contributing to root growth and the absorption capacity of mineral nutrients by plantain plants [12].

The process of plant growth is key to understanding the potential and limitations of cultivated plants under any management scenario [8, 13]. Therefore, plant growth analysis is widely used in plant physiology and ecology because it helps establish plant quality, which is determined by photosynthetic efficiency and plant production, that is, efficiency expressed as the conversion of solar radiation into biomass such as leaves, stems, shoots, roots, flowers, and fruits [1, 14]. The biomass of these organs and leaf dimensions are readily quantifiable for evaluating the growth parameters [1, 15].

The assessment of crop growth parameters is fundamental for monitoring agricultural productivity. Relative growth rate (RGR), net assimilation rate (NAR), leaf area ratio (LAR), specific leaf area (SLA), leaf weight ratio (LWR), stem weight ratio (SWR), and root weight ratio (RWR) are important plantain production parameters. These variables allow for the evaluation of the nutritional and physiological status of plantains and thus their performance.

Although technology for plantain cultivation management has been developed in Colombia, published studies on the growth and development of the plant are scarce in the Quindío region, which likely limits the efficiency and effectiveness of the technology generated for cultivation. Therefore, the purpose of this study was to determine the effects of fertilization and planting distance of the Dominico-Hartón plantain (*Musa AAB Simmonds*) on seven growth variables, with the aim of contributing greater knowledge about the response of this species to different agronomic management strategies. The formulated hypothesis suggests the existence of a differential response to fertilization based on the planting distance.

2. Materials and Methods

The study was conducted at the La Bella Nubia farm, located in La Bella village, municipality of Calarcá, Quindío Department (4°29'48″ N, 75°40'20″ W; elevation 1497 m), Colombia. The soil taxonomic classification is Typic Humudepts, characterized as coarse, mixed, active, and isothermal, with volcanic torrential deposits influenced by volcanic ash [16]. Soil analysis conducted in September 2020 for the top 10-cm layer revealed the following values: pH 5.64, electrical conductivity of saturation extract 0.95 dS m^{-1}, oxidizable organic carbon (Walkey-Black method) 63.13 g kg^{-1}, nitrogen: $N\text{-}NH_4$ (ammonium) 41.57 mg kg^{-1}, $N\text{-}NO_3$ (nitrate) 50.0 mg kg^{-1}, and extractable phosphorus (P) (Bray II method) 115.55 ppm. For the composite sample from 0- to 30-cm depth: cation exchange capacity 18.4 cmol kg^{-1}, calcium (Ca^{2+}) 7.39 cmol kg^{-1}, magnesium (Mg^{2+}) 1.26 cmol kg^{-1}, sodium (Na^{+}) 0.07 cmol kg^{-1}, and potassium (K^{+}) 1.15 cmol kg^{-1}. Throughout the experimental period, a meteorological station was available in the same area, recording an average temperature of 20°C, annual average precipitation of 2000 mm, and relative humidity of 85%. The plantain monoculture occupies 3 ha of the farm.

For crop establishment, 1200 corm cuttings (each weighing 500 g) of Dominico-Hartón plantain (*Musa AAB Simmonds*) were used. These cuttings were sourced from the La Bodega nursery (Buenavista municipality, Quindío) and registered with the Colombian Institute of Agriculture (ICA). They were planted at two distances: Distance 1 (D1) of 1.7 m between rows and 1.7 m between plants and Distance 2 (D2) of 2.5 m between rows and 2.5 m between plants, all in holes measuring 40 cm in diameter and 40 cm in depth. Desuckering, leaf pruning, and weed and disease management were performed following technical recommendations established for plantain cultivation [17].

2.1. Fertilization

For this study, a factorial arrangement of treatments was designed, comprising two factors: fertilization (four levels) and planting distance (two levels), with five repetitions. The treatments consisted of the following steps:

- Control (T): plants without fertilizer application
- Agrochemical (AG): plants treated with the commercial product Platanero® (N 14, P 4, K 23, Mg 4, Ca, and minors 4) at a rate of 120 g per plant
- Necromass (NE): plantain leaf and pseudostem chopped and buried at a depth of 5 cm at a rate of 1.5 kg per plant
- Compost (CO): vermicompost applied at a rate of 1.5 kg per plant

Fertilization was carried out at the beginning of the experiment, at two months of age when the plant had five leaves (25% of the first-year dose), at five months after planting (50% of the first-year dose), and at ten months after planting (25% of the first-year dose). The fertilization treatments were applied to plants located at two planting distances: D1 of 1.7 m and D2 of 2.5 m (Table 1 and Figure 1).

Table 1. Assigned treatments and nomenclature used (The authors' elaboration)

Nomenclature	Treatment description
AGD1	Agrochemical fertilization, D1
AGD2	Agrochemical fertilization, D2
NED1	Necromass fertilization, D1
NED2	Necromass fertilization, D2
COD1	Compost fertilization, D1
COD2	Compost fertilization, D2
TD1	No fertilization, D1
TD2	No fertilization, D2

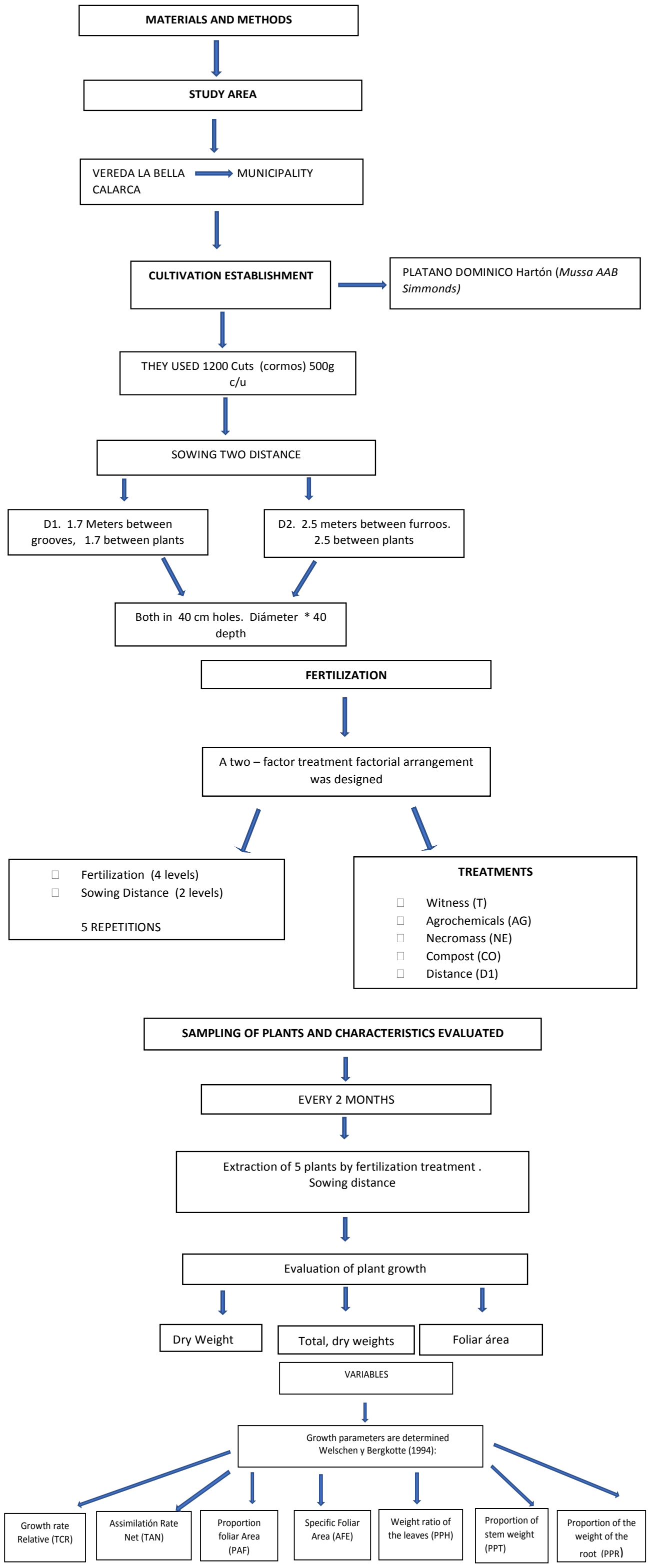

Figure 1. Flowchart to evaluate the effect of fertilization type and planting distance on growth parameters in *Musa AAB Simmonds* plants (The authors' elaboration)

2.2. Plant Sampling and Evaluated Characteristics

Every two months, over a year (October 2020–October 2021), five plants per fertilization treatment and planting distance were sampled. The leaf area was measured using the formula established by Martínez [18], which involves multiplying: leaf length × leaf width × 0.80 [1].

Subsequently, the plants were separated into roots, pseudostems, and leaves, then dried in a forced air oven at 60-70°C until reaching a constant weight (approximately 72 h), and the dry weight was obtained using a digital balance (Lexus Electronic, Model Mix-A 3000 g, China).

To assess plant growth, the dry weight of each section, total dry weight, and leaf area were measured. Using these variables, the following growth parameters were determined following Welschen and Bergkotte [19]:

2.2.1. RGR

$$RGR = (\ln psf - \ln psi)/t \qquad (1)$$

where ln is the natural logarithm, psf is the final dry weight, psi is the initial dry weight at the beginning of the experiment, and t is the time elapsed between harvest (plant cutting) and the start of the experiment (days).

2.2.2. NAR

$$NAR = RGR/af \qquad (2)$$

where af - leaf area.

2.2.3. LAR

$$LAR = af/P \qquad (3)$$

where P - total dry weight of the plant.

2.2.4. SLA

$$SLA = af/psh \qquad (4)$$

where psh - dry weight of the leaves.

2.2.5. LWR

$$LWR = psh/P \qquad (5)$$

2.2.6. SWR

$$SWR = pst/P \qquad (6)$$

where pst - dry weight of the stem.

2.2.7. RWR

$$RWR = psr/P \qquad (7)$$

where psr - dry weight of the root.

2.2.8. Statistical Analysis of Data

The growth variables RGR, NAR, LAR, SLA, LWR, SWR, and RWR were analyzed using two-way ANOVA to evaluate the effect of fertilization on the growth of plants planted at two distances (D1 and D2). In cases with significant differences ($p \leq 0.05$) in the fertilization treatment or planting distance, Tukey's test was performed.

3. Results and Discussion

3.1. RGR

The RGR of the plantain plants showed a tendency to decrease over time, with a high RGR observed during the first 60 days of the experiment (Figure 2). This rapid initial growth is explained by the plant's meristems exhibiting very high cell division for vegetative growth, with a large investment in leaf production to allow for photosynthesis and the production of assimilates to reinvest in new vegetative growth. Additionally, the rapid development of the plants allows them to quickly reach a size that is less vulnerable to herbivore attacks. The decrease in RGR over time is partly due to the gradual increase in non-assimilatory tissues, as the number of cells differentiating into tissues and organs is higher than the number of meristematic cells [20].

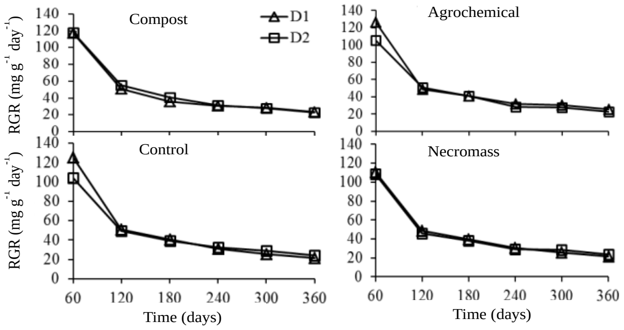

Figure 2. Mean RGR of plantain plants subjected to four fertilization treatments and two planting distances (The authors' elaboration)

Furthermore, during plant senescence, respiration rates typically increase, whereas photosynthesis decreases, consequently reducing RGR.

RGR was affected by planting distance and fertilization, with interactions observed between the two factors (F = 8795.00, p = 0.001) (Figure 6A). For the CO and AG treatments, RGR values were higher in D1 than in D2, whereas T and NE showed higher RGR in D2 than in D1. Planting density affects plant biomass production; when plants have appropriate nutrient availability, they optimize them by being closer together, achieving a larger size (biomass) in less time, allowing them to capture more resources (light, water, and nutrients), and ultimately conferring greater competitive capacity.

According to Poorter and De Jong [21], plants growing in nutrient-rich environments have a high RGR. Conversely, those limited by nutrients, when closer together, compete for space and nutrients, implying an energy cost that results in slower growth than when they are spaced apart. The similar behavior of plants treated with NE compared to that of T plants can be explained by nutrients not being immediately available, as they must wait for decomposition to release them.

3.2. SLA

The quantification of this variable expressed the relationship between leaf area and leaf dry weight. In all treatments, SLA decreased (Figure 3). According to Pérez et al. [22], SLA decreases as leaf dry weight increases and the plants reach maturity.

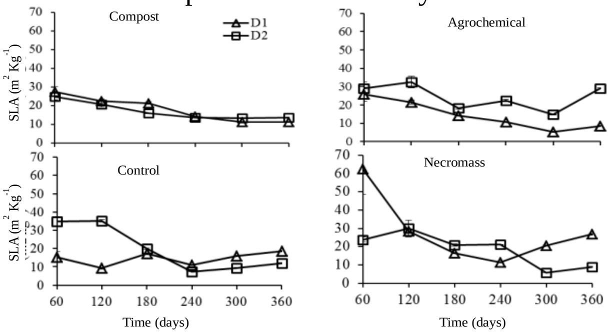

Figure 3. Average SLA of plantain plants subjected to four fertilization treatments and two planting distances (The authors' elaboration)

SLA was affected by both distance and fertilization, with interactions between the two factors (F = 2365.43, p = 0.001) (Figure 6B). For the CO and AG treatments, the values were higher in D2 than in D1, while T and NE showed higher SLA in D1 than in D2. This suggests that both fertilization and plant spacing affect leaf surface development, such that when plants have adequate nutrient availability, they maximize it to expand foliage when spaced apart. Conversely, when nutrient availability is limited, an increase in leaf surface area occurs in plants growing in close proximity. High SLA increases leaf fragility [23], posing a risk of premature tissue loss due to environmental factors, such as precipitation and strong winds, and biotic factors, such as herbivore attacks.

3.3. LAR

The proportion of leaf area relative to total plant biomass in all treatments exhibited an initial increase followed by a subsequent decrease (Figure 4). This phenomenon can be attributed to the necessity for seedlings to establish rapidly and allocate resources to leaf surface area for the efficient capture and processing of solar energy. The decreasing trend was associated with an increase in the non-photosynthetic biomass of the plant during the growth cycle. According to Gaytan-Mascorro et al. [24], plants, during their initial stages of growth, allocate the majority of assimilates to the development of their photosynthetic apparatus.

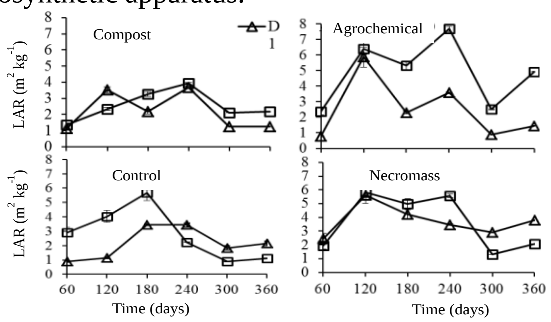

Figure 4. Average LAR of plantain plants subjected

to four fertilization treatments and two planting distances (The authors' elaboration)

The proportion of leaf area was affected by distance and fertilization, exhibiting an interaction between the two factors (F = 3912.07, p = 0.001) (Figure 6C). For the CO and AG treatments, the values were higher at D2 than at D1, while T and NE showed higher PAF at D1 than at D2. This indicates that fertilization with AG and CO influences the production of photosynthetic tissue biomass when plants are spatially dispersed, a phenomenon not observed in T plants and those treated with NE. The latter invest more resources in photosynthetic tissue when in close proximity, potentially as a competitive strategy in response to limited nutrient availability.

3.4. NAR

The observed trend was a decrease in NAR (rate of increase in plant weight per unit leaf area) (Figure 5). The initially high value of NAR implies photosynthetic activity in the plants, and its decrease, according to Milthorpe and Moorby [25], is related to the shading of the upper leaves over the lower ones and the reduction in the photosynthetic capacity of the latter due to their low chlorophyll and soluble protein levels. The decrease in the rate of net assimilation of photoassimilates indicates that as more leaves are produced, the lower leaves become shaded, and their photosynthetic rates decrease directly with the availability of solar radiation [26]. According to Medina [27], the NAR tends to zero when plants reach maturity. In general, NAR is more related to plant ontogeny than to the environment because it also decreases, and at the end of the biological cycle, it may be insufficient to contribute to growth [28].

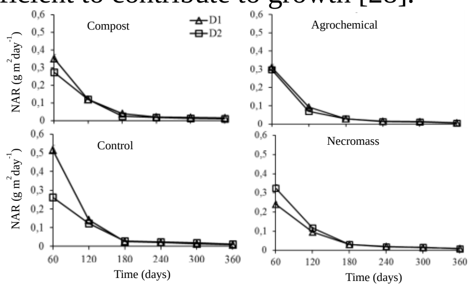

Figure 5. Average NAR of plantain plants subjected to four fertilization treatments and two planting distances (The authors' elaboration)

The plants in D1 treated with CO showed significantly higher mean NAR values than those in the other treatments, while those treated with AG exhibited the lowest values. This implies that the plants treated with CO had a higher percentage of intercepted radiation and better efficiency in utilizing this resource, making them more effective in producing photoassimilates with high productivity efficiency. CO probably provides adequate initial availability of nutrients, leading to high dry matter production per unit leaf area and per unit time, resulting in higher photosynthetic efficiency. In plants treated with AG, low NAR can be explained by plant size and leaf expansion, which increased self-shading, thereby decreasing the photosynthetic activity of the lower leaves. According to Cayón-Salinas [29], NAR mainly depends on solar radiation and decreases with an increase in leaf area during the growth process due to shading effects.

The NAR was affected by both distance and fertilization, with interactions observed between the two factors (F = 649.00, p = 0.001) (Figure 6D). For CO, AG, and NE treatments, values were higher in D1 than in D2, whereas T showed higher NAR in D2 than in D1. This response is associated with low AFE and PAF values, representing an increase in NAR because the plant responds with higher photosynthetic activity when the leaf area is reduced and self-shading is minimized. According to Gardner et al. [30], high planting densities and appropriate spatial arrangement of plants (e.g., narrow rows) are used to accelerate soil coverage and increase light interception.

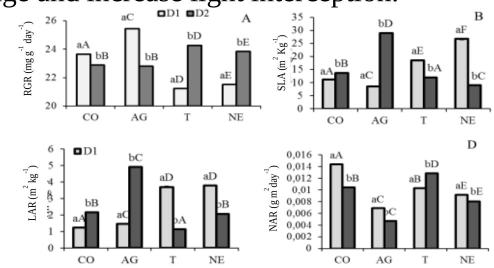

Figure 6. Mean RGR, AFE, PAF, and NAR of plantain plants subjected to two planting distances and four fertilization treatments. Different letters indicate differences ($p \leq 0.05$); lowercase letters correspond to the comparison between the two distances, and uppercase letters compare the different fertilization treatments: compost (CO), agrochemicals (AG), control (T), and necromass (NE) (The authors' elaboration)

3.5. Leaf Weight Proportion (LWP)

In all treatments, the LWP (ratio of leaf dry weight or biomass to the total plant weight) increased until 240 days and then progressively decreased (Figure 7). This can be explained by the high proportion of leaf weight relative to the plant biomass, which tends to decrease as the biomass of non-photosynthetic tissue increases.

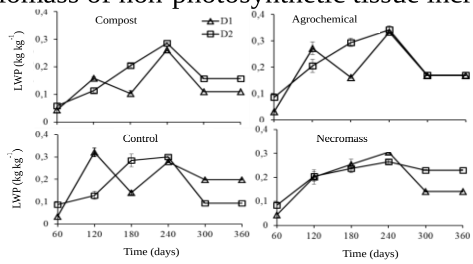

Figure 7. Mean LWP of plantain plants subjected to

four fertilization treatments and two planting distances (The authors' elaboration)

LWP was affected by both distance and fertilization, with interactions observed between the two factors ($F = 977.66$, $p = 0.001$) (Figure 10A). For the CO and NE treatments, the values were higher in D2 than in D1, while AG showed no differences between distances, and T exhibited higher LWP in D1 than in D2. When plants were fertilized with AG, the biomass allocation pattern to leaves was independent of distance, whereas in those treated with CO and NE, the investment in leaf biomass depended on distance; the biomass allocation pattern to leaves was higher when plants were spaced apart.

3.6. Stem Weight Proportion (SWP)

In all treatments, the SWP (ratio of stem dry weight or biomass to the total plant weight) increased (Figure 8). This pattern of biomass allocation to the pseudostem during the plant life cycle is explained by the role of the stem, primarily as a supporting and conducting organ for assimilates, which are necessary for the metabolic activity of demanding structures and overall plant health.

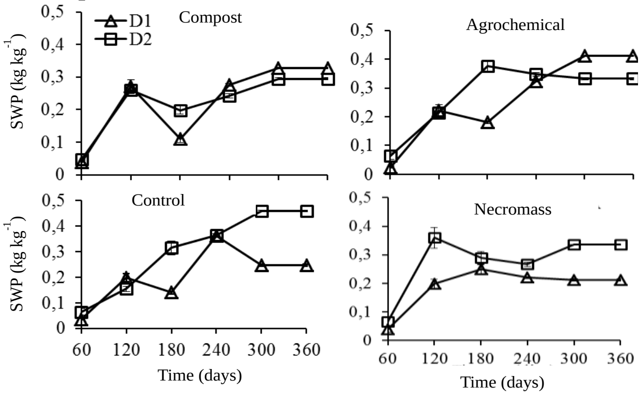

Figure 8. Average SWP of plantain plants subjected to four fertilization treatments and two planting distances (The authors' elaboration)

SWP was affected by both distance and fertilization, with interactions observed between the two factors ($F = 916.35$, $p = 0.001$) (Figure 10B). For the CO and AG treatments, the values were higher in D1 than in D2, while treatments T and NE showed higher SWP in D2 than in D1. This indicates that plants planted at closer distances maximize nutrient availability by investing more biomass in the pseudostem, whereas plants limited by nutrients develop more robust pseudostems when they have more available space.

3.7. Root Weight Proportion (RWP)

In all treatments, the RWP (ratio of root dry weight or biomass to total plant weight) was high at the start of the experiment and then decreased (Figure 9). This initial investment in root biomass ensures the uptake of nutrients and water for plant development and growth.

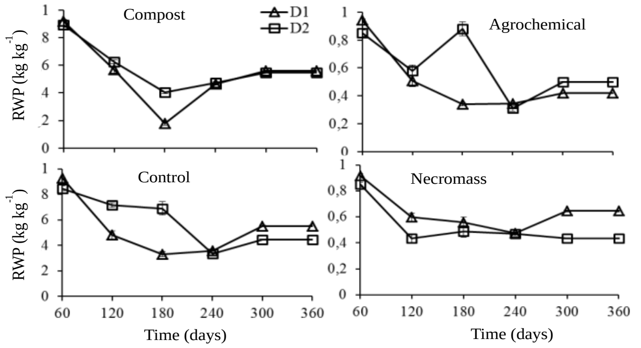

Figure 9. Average RWP of plantain plants subjected to four fertilization treatments and two planting distances (The authors' elaboration)

RWP was affected by both distance and fertilization, with an observed interaction between the two factors ($F = 390.70$, $p = 0.001$) (Figure 10C). For treatments T and NE, the values were higher at D1 than at D2, whereas CO showed no differences between distances, and AG exhibited higher RWP at D2 than at D1. Plant proximity and low soil nutrient availability result in greater biomass allocation to roots, enhancing water and mineral nutrient uptake from the soil but at the expense of reduced growth. Ecologically, a plant with a high investment in root biomass may exhibit slower growth but could benefit from increased absorption surface area and greater survival in habitats where soil resources (water and nutrients) are limiting [23]. According to Aerts and Chapin [31], plants growing in nutrient-poor substrates allocate more biomass to roots than to stems, representing a phenotypic response to nutrient scarcity. The response of AG-treated plants when spaced apart was to produce more root biomass, ensuring rapid establishment and enhanced resource use efficiency for photosynthetic organ production [32, 33].

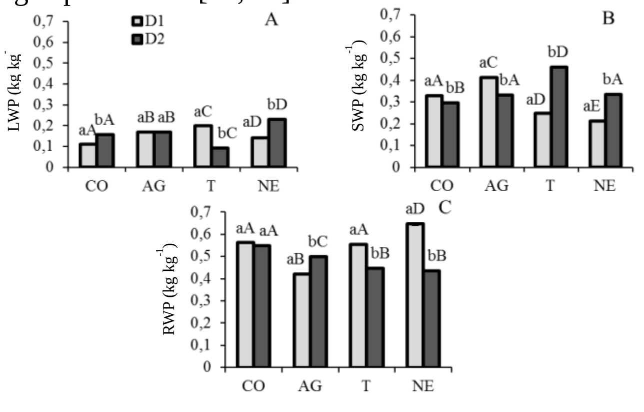

Figure 10. Average PPH (proportion of stem weight), PPT (proportion of root weight), and PPR (proportion of leaf weight) of plantain plants subjected to four fertilization treatments. Different letters indicate significant differences ($p \leq 0.05$); lowercase letters denote comparisons between the two planting distances, and uppercase letters compare different fertilization treatments: compost (CO), agrochemicals (AG), control (T), and

necromass (NE) (The authors' elaboration)

Research developed for this purpose indicates that when using planting distances that vary from 2.0 x 1.25 to 2.5 x 2.0 m and populations that fluctuate between 2000 and 4000 plants/ha, these do not affect plant height, pseudostem perimeter and the number of leaves emitted. Regarding the duration of the vegetative cycle, these findings demonstrate that its length increases progressively with an increase in population density. Specifically, the shortest cycle (16.6 months) is observed at a density of 2000 plants/ha, while the longest cycle (18.1 months) occurs at a population of 4000 plants/ha [34, 35].

4. Conclusion

Musa AAB plants subjected to fertilization with agrochemicals and compost demonstrated a positive response in RGR, NAR, and SWP when cultivated in close proximity. However, these plants exhibited a negative effect on SLA, leaf area proportion, LWP, and RWP. Conversely, under these conditions, necromass-treated plants and control plants showed a positive effect on the latter four variables, but the relative growth and assimilation rates were negatively affected. Therefore, when plants have sufficient nutrients, growth is favored when they are planted close together, whereas under low nutrient availability, they should be spaced apart to promote growth. In general, it can be concluded that optimal plant density and the optimization of nutritional inputs in Musaceae through the application of chemical and organic fertilizers may facilitate significant enhancements in plant growth.

Declarations

Author Contributions

Conceptualization, L.J.M.R. and L.M.A.A.; methodology, J.C.L.A.; software, L.J.M.R.; validation, L.J.M.R., L.M.A.A. and J.C.L.A.; formal analysis, L.J.M.R., L.M.A.A. and J.C.L.A.; investigation, L.J.M.R. and L.M.A.A.; writing—original draft preparation, all authors contributed equally; writing—review and editing, L.J.M.R., L.M.A.A. and J.C.L.A. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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Funding information is not available.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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