Row spacing and its impact on sugarcane yield across three consecutive harvests

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ABSTRACT

Row spacing directly influences sugarcane productivity and field longevity. This study aimed to identify, over three consecutive harvests, the row spacing that yields the highest and most stable production in sugarcane. The experiment was conducted over three consecutive seasons (2021/22, 2022/23, and 2023/24) at the Technology Development and Transfer Center (CDTT/UFLA), Minas Gerais, Brazil, covering the crop cycles of plant cane, first ratoon, and second ratoon. The experimental design was a randomized complete block (RCBD) with four treatments (row spacings) and three harvests, with four replications. The evaluated spacings were single 0.9 m, single 1.5 m, double (0.9 × 1.5 m), and triple (0.75 × 0.75 × 1.5 m). The analyzed traits included plant height (PH), stalk diameter (SD), number of stalks per meter (NSM), total soluble solids content (TSS, ºBrix), and stalk yield (t ha^{-1}). Mean plant height, averaged across the four row spacings, increased from 2.56 m in the plant cane to 3.23 m in the second ratoon, while stalk diameter, also expressed as the mean of the four spacings, peaked in the first ratoon (28.78 mm). The single 1.5 m spacing showed the highest stalk density (14–17 stalks m^{-1}), and TSS remained at an average of 18 °Brix. Yield was consistently high (>130 t ha^{-1}) at this spacing, whereas the single 0.9 m and double spacings ranged from 97 to 120 t ha^{-1}, and the triple spacing reached 142 t ha^{-1} in the second ratoon. The results indicate that the single 1.5 m spacing ensures greater stability in the number of stalks per meter and stalk yield.

Keywords: Plant arrangement, Planting longevity, Stand persistence; *Saccharum* spp.

Espaçamento entre linha e seu impacto no rendimento agrícola da Cana-de-açúcar em três safras consecutivas

RESUMO

O espaçamento entre linhas influencia diretamente a produtividade e a longevidade dos canaviais. O objetivo deste estudo foi identificar, em três safras consecutivas, o espaçamento de plantio que proporcione maior rendimento agrícola e maior estabilidade produtiva da cana-de-açúcar. O experimento foi conduzido ao longo de três safras consecutivas (2021/22, 2022/23 e 2023/24) no Centro de Desenvolvimento e Transferência de Tecnologia (CDTT/UFLA), Minas Gerais, Brasil, abrangendo os ciclos de cultivo de cana-planta, primeira cana-soca e segunda cana-soca. O delineamento experimental foi em blocos casualizados completos (DBC) com quatro tratamentos (espaçamento entre linhas) e três colheitas, com quatro repetições. Os espaçamentos avaliados foram: simples 0,9 m, simples 1,5 m, duplo (0,9 × 1,5 m) e triplo (0,75 × 0,75 × 1,5 m). As características analisadas incluíram altura da planta (AP), diâmetro do colmo (DP), número de colmos por metro (NSM), teor de sólidos solúveis totais (TSS, °Brix) e rendimento do colmo (t ha^{-1}). A altura média da planta, considerando a média dos quatro espaçamentos avaliados, aumentou de 2,56 m na cana-planta para 3,23 m na segunda soqueira, enquanto o diâmetro do colmo, também expresso como média dos quatro espaçamentos, atingiu o pico na primeira soqueira (28,78 mm). O espaçamento simples de 1,5 m apresentou a maior densidade de colmos (14–17 colmos m^{-1}), e o TSS manteve-se em média em 18 °Brix. A produtividade foi consistentemente alta (>130 t ha^{-1}) nesse espaçamento, enquanto os espaçamentos simples de 0,9 m e duplo variaram de 97 a 120 t ha^{-1}, e o triplo atingiu 142 t ha^{-1} na segunda soqueira. Os resultados indicam que o espaçamento simples de 1,5 m garante maior estabilidade do número de colmos por metro e rendimento de colmos.

Palavras-chave: Arranjo de plantas, Longevidade do plantio, Persistência do estande, *Saccharum* spp.

1. Introduction

Sugarcane (*Saccharum* spp.) is one of the most important crops for the Brazilian economy, playing a key role in the production of sugar, ethanol, and bioenergy (Vandenberghe et al., 2022). Beyond its industrial relevance, sugarcane cultivation drives employment and economic development across tropical and subtropical regions. Brazil (722 Mt), India (439 Mt), China (103 Mt), Thailand (92 Mt), and Pakistan (87 Mt) are the world's largest producers (FAO, 2025).

Among agronomic practices, row spacing has a decisive impact on the growth, longevity, and productivity of sugarcane fields, as it directly affects canopy architecture, light interception, and resource use efficiency, particularly water and nutrient use efficiency (Chiluwal et al., 2018; Saranraj et al., 2023). In Brazil, the most common row spacing ranges from 1.0 to 1.5 m, aiming to facilitate mechanized traffic or increase plant density within the cultivated area (Rossi Neto et al., 2018). Row spacing also influences tillering, weed suppression, and photosynthetic performance, ultimately affecting biomass accumulation and stalk yield (Saranraj et al., 2023; Abd-El-Kareem et al., 2024).

Narrower row spacing tends to increase plant population per hectare and promote early canopy closure; however, excessive competition for light, water, and nutrients may limit stalk development and reduce stand longevity. Conversely, wider row spacing can favor greater stalk diameter and root development due to reduced competition among plants (Munsif et al., 2015). Nevertheless, wider spacing may reduce land use efficiency, delay canopy closure, and prolong the critical period of weed interference for water and nutrients (Tomar and Singh, 2024). Studies conducted in various production environments suggest that intermediate spacings (1.2–1.5 m) often balance these effects, thereby optimizing stalk height and yield (Ellsworth and White, 2022; Khalid et al., 2015; Anjum et al., 2015).

Despite this evidence, information on how different row spacing arrangements affect sugarcane performance across multiple harvest cycles remains limited, particularly under edaphoclimatic conditions of the Brazilian Cerrado. Understanding the interaction between row spacing and ratoon longevity is crucial for defining agronomic practices that sustain productivity over successive harvests. Therefore, this study aimed to evaluate the effect of four row spacing configurations on the growth and yield stability of sugarcane over three consecutive harvests.

2. Material and Methods

The field experiment was conducted during the 2021/22 (plant cane), 2022/23 (first ratoon), and 2023/24 (second ratoon) growing seasons at the Technology Development and Transfer Center (CDTT/UFLA), located in Ijací, Minas Gerais, Brazil (21°14′43″ S; 44°59′59″ W). The local soil is classified as a Red-Yellow Latosol (Oxisol) with a clayey texture (Santos et al., 2018) and as a Typic Hapludox according to the U.S. Soil Taxonomy (Soil Survey Staff, 2014). The regional climate is classified as Cwa according to the Köppen classification, with a mean annual temperature of 20 °C and an average annual precipitation of 1,460 mm. Figure 1 presents the meteorological conditions during the experimental period.

The experimental design was a randomized complete block design (RCBD) with four treatments (row spacings) and three harvests, with four replications. The evaluated row spacings were single 0.9 m, single 1.5 m, double 0.9 × 1.5 m, and triple 0.75 × 0.75 × 1.5 m. Each plot consisted of four rows, 5 m in length, spaced according to the respective treatment. The two central rows were used for evaluations, with 2 m at both ends discarded as borders.

A composite soil sample from the 0–20 cm layer was collected before planting for chemical characterization. The chemical analysis results were as follows: pH ($CaCl_2$) 5.1; organic matter (OM) 2.6 dag kg^{-1}; P (Mehlich^{-1}) 14 mg dm^{-3}; K 2.3 mmolc/dm^{-3}; Ca 4.3 cmolc dm^{-3}; Mg 0.4 cmolc dm^{-3}; Al 0.1 cmolc dm^{-3}; H+Al 3.3 cmolc dm^{-3}; cation exchange capacity at pH 7 (CEC) 8.2 cmolc dm^{-3}; base saturation (V) 60%; and aluminum saturation (AS) 1%. For the 20–40 cm layer, the results were pH ($CaCl_2$) 4.6; organic matter 1.8 dag kg^{-1}; P (Mehlich^{-1}) 9.0 mg dm^{-3}; K 2.4 mmolc/dm^{-3}; Ca 1.6 cmolc dm^{-3}; Mg 0.4 cmolc dm^{-3}; Al 0.1 cmolc dm^{-3}; H+Al 4.2 cmolc dm^{-3}; CEC 6.4 cmolc dm^{-3}; base saturation 35%; and aluminum saturation 4%. Micronutrients were not evaluated. The average soil physical composition was: 24% sand, 25% silt, and 50% clay.

Based on soil analysis, fertilization at planting supplied 80 kg N ha^{-1}, 200 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1} using urea, monoammonium phosphate (MAP), and potassium chloride (KCl), respectively (Cantarella et al., 2022). The sugarcane cultivar RB966928 was planted on 2 March 2021.

Topdressing fertilization was applied at 90 days after emergence (DAE) in each harvest cycle, supplying 150 kg N ha^{-1} and 100 kg K_2O ha^{-1} using urea and KCl, respectively. Weed control was performed manually, and no phytosanitary interventions were required.

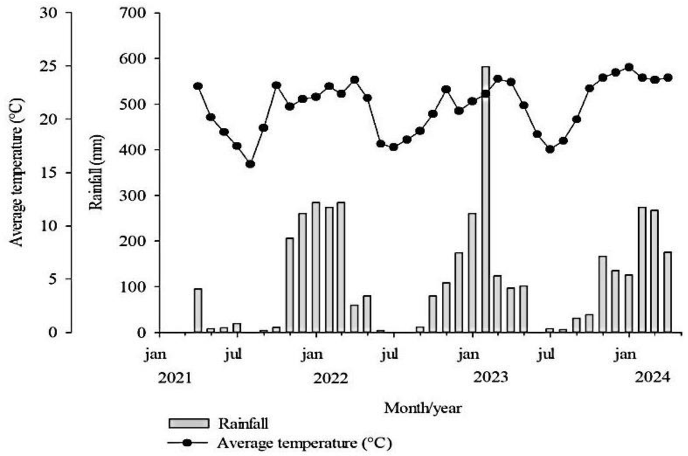

Figure 1. Meteorological conditions during the sugarcane growth cycles in the 2021/22, 2022/23, and 2023/24 growing seasons. Ijací, MG, Brazil. Source: INMET – National Institute of Meteorology.

The following biometric traits were evaluated: number of stalks per meter (NSM), obtained by counting stalks along 1 m in the two central rows; plant height (PH), measured from soil surface to the +1 fully expanded leaf using a measuring tape; and stalk diameter (SD), measured at the lower third of ten stalks per plot using a digital caliper (150 mm, model 6.0 POL). At harvest, total soluble solids content (TSS, °Brix) was determined by crushing stalks (model: B-721 Maqtron®) and homogenizing the juice, following Consecana (2006).

Stalk yield (TSH, tons of stalks per hectare) was estimated based on the number of stalks per meter, the mean fresh mass of ten representative stalks, and the row spacing, using the following equation:

$$TSH\ (t\ ha^{-1}) = (FM \times NSM)/RS$$

where: FM = fresh mass of ten stalks (kg); NSM = number of stalks per meter; RS = row spacing (m).

Data were tested for normality using the Shapiro–Wilk test and subsequently assessed using analysis of variance (ANOVA) using the F-test ($p < 0.05$). When significant effects were detected, means were compared using Tukey's test at the 5% probability level. All statistical analyses were performed using Sisvar® software (Ferreira, 2019).

3. Results and Discussion

Plant height (PH) and stalk diameter (SD) were influenced only by harvest cycles, with no significant effects of row spacing or interaction between factors (Table 1). Mean PH increased from 2.56 m in the plant cane to 3.23 m in the second ratoon, representing a 26% increase across cycles. In contrast, SD was highest in the first ratoon (28.78 mm), showing a 10% increase compared with plant cane, followed by a 9% reduction in the second ratoon. Across all treatments, PH ranged from 2.73 to 2.89 m, and SD ranged from 26.50 to 27.67 mm.

These findings indicate that seasonal conditions and ratoon age exerted stronger effects on plant morphology than spatial arrangement. Similar patterns were reported by Chiluwal et al. (2018), who observed significant differences in plant height between years, while the interaction between planting spacing and harvest year was not significant.

Furthermore, a larger stalk diameter in the first ratoon may be associated with reduced plant height, whereas the opposite trend was observed in the second ratoon. Maia Júnior et al. (2018), evaluating correlations among biometric parameters throughout the sugarcane growth cycle, reported a negative correlation between plant height and stalk diameter as plant density increased. Thus, the increase in stalk diameter in the first ratoon suggests a compensatory response to a lower number of stalks. Conversely, the increase in plant height in the second ratoon may reflect greater ratoon vigor, possibly due to a more developed root system occupying a larger soil volume (Rossi Neto et al., 2018).

A significant interaction between row spacing (RS) and harvest cycle was observed for the number of stalks per meter (NSM) (Figure 2). In plant cane, the single 1.5 m spacing showed the highest NSM (13.50 stalks m^{-1}), significantly exceeding the other arrangements (6.83–9.00 stalks m^{-1}).

This advantage was further amplified in the first ratoon, when the single 1.5 m spacing reached 17.00 stalks m^{-1}, while the other treatments ranged from 7.58 to 9.75 stalks m^{-1}. In the second ratoon, the single 1.5 m spacing again maintained the highest NSM (15.92 stalks m^{-1}), significantly exceeding the single 0.9 m (6.91 stalks m^{-1}) and double (9.00 stalks m^{-1}) spacing, whereas the triple spacing showed intermediate performance (9.83 stalks m^{-1}).

Across harvest cycles, the single 1.5 m spacing was the only treatment that sustained or increased stalk density, rising by 26% from plant cane to the first ratoon and maintaining similar levels in the second ratoon. In contrast, the single 0.9 m spacing showed marked reductions of 23% and 31% from plant cane to the first and second ratoons, respectively. The double and triple spacings maintained relatively stable NSM values across cycles (6.8–9.8 stalks m^{-1}), without significant gains.

This pattern highlights the role of row spacing in supporting ratoon establishment and stand longevity. The superior performance of the single 1.5 m spacing can be attributed to improved spatial distribution of plants, root systems, and canopy architecture, which enhances the efficient use of soil resources (Rossi Neto et al., 2018; Ellsworth and White, 2022). Similar positive effects of wider spacing on tillering have been reported by Khalid et al. (2015) and Anjum et al. (2015).

Table 1. Plant height (PH) and stalk diameter (SD) of sugarcane as affected by row spacing (RS) and harvest cycle.

Row spacing (RS)	**PH (m)**	**SD (mm)**
Single 0.9 m	2.88 a	27.05 a
Single 1.5 m	2.79 a	26.50 a
Double 0.9 × 1.5 m	2.89 a	27.67 a
Triple 0.75 × 0.75 × 1.5 m	2.73 a	27.06 a
Crop cycles		
Plant cane	2.56 b	26.19 b
First-ratoon	2.69 b	28.78 a
Second-ratoon	3.23 a	26.22 b

* Means followed by the same letter within each factor do not differ significantly according to Tukey's test ($p < 0.05$). C.V. (%): 8.62 (PH) and 6.34 (SD).

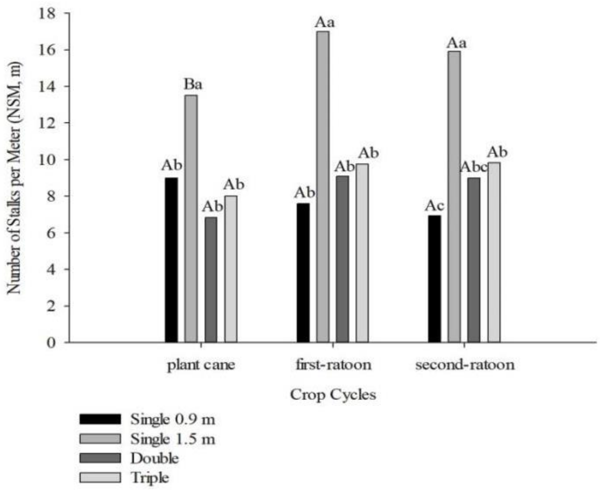

Figure 2. Number of stalks per meter (NSM) of sugarcane under different row spacings across three crop cycles. Ijací, MG, Brazil. Means followed by the same uppercase letter within each spacing across crop cycles and the same lowercase letter within each crop cycle across spacings do not differ significantly according to Tukey's test ($p < 0.05$).

Conversely, the pronounced reduction in NSM under the 0.9 m spacing suggests that high initial plant density promotes early canopy closure, basal bud shading, and intensified competition for water and nutrients, which reduces tillering and accelerates stand decline. This phenomenon has also been observed by Ellsworth and White (2022) under high-moisture conditions.

According to Manhães et al. (2015), excessive competition in dense stands restricts root system expansion and compromises ratoon survival, which explains the progressive NSM decline under narrow spacing found in this study.

A significant interaction between row spacing (RS) and harvest cycle was observed for total soluble solids content (TSS, °Brix) (Figure 3). In plant cane, TSS ranged from 17.05 to 18.95 °Brix, with the highest value observed in the double spacing (18.95 °Brix), followed by the single 1.5 m (18.50 °Brix) and single 0.9 m (18.40 °Brix) spacings, whereas the triple spacing showed the lowest value (17.05 °Brix).

In the first ratoon, TSS increased across most treatments, reaching 19.20 °Brix in the single 1.5 m spacing and 19.13 °Brix in the single 0.9 m spacing, both significantly higher than in the double spacing (18.40 °Brix). The triple spacing also increased to 19.00 °Brix.

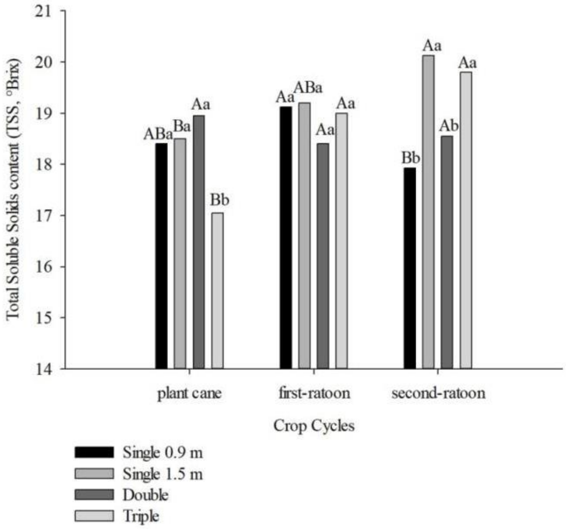

Figure 3. Total soluble solids content (TSS, °Brix) of sugarcane under different row spacings across three crop cycles. Ijací, MG, Brazil. Means followed by the same uppercase letter within each spacing across crop cycles and the same lowercase letter within each crop cycle across spacings do not differ significantly according to Tukey's test ($p < 0.05$).

In contrast, the single 0.9 m spacing showed a significant reduction to 17.93 °Brix, becoming the lowest among all treatments.

Across harvest cycles, the single 1.5 m and triple spacings exhibited progressive increases in TSS, whereas the single 0.9 m spacing declined after the first ratoon (−6.3%), and the double spacing remained relatively stable at approximately 18.5 °Brix. These results suggest that wider row spacings, particularly single 1.5 m, favor sugar accumulation over time, while narrow spacing may compromise sucrose concentration in later cycles. The reduction observed in the 0.9 m treatment during the second ratoon likely reflects stress caused by increased intraspecific competition, which limits assimilate partitioning to stalks and accelerates senescence, impairing sugar translocation (Manhães et al., 2015).

Additionally, part of the variation in TSS across cycles may be related to environmental conditions that favored flowering during the experimental period. The floral transition remobilizes stored sucrose from stalks to developing inflorescences, reducing juice sugar content while increasing fiber content and decreasing juice volume (Vasantha et al., 2022). Pavani et al. (2023) emphasized that flowering represents a strong sucrose sink and is undesirable for commercial sugarcane production.

Previous studies support the observation that TSS is more strongly influenced by environmental conditions and genotype × environment interactions than by planting arrangement alone. Khalid et al. (2015) and Kumar et al. (2023) reported no significant spacing effects on TSS when evaluating single harvest cycles. Thus, although row spacing can indirectly affect sugar content through its influence on plant vigor and canopy structure, it is not the primary determinant of sucrose accumulation in sugarcane stalks. A significant interaction between row spacing (RS) and harvest cycle was observed for stalk yield (TSH) (Figure 4).

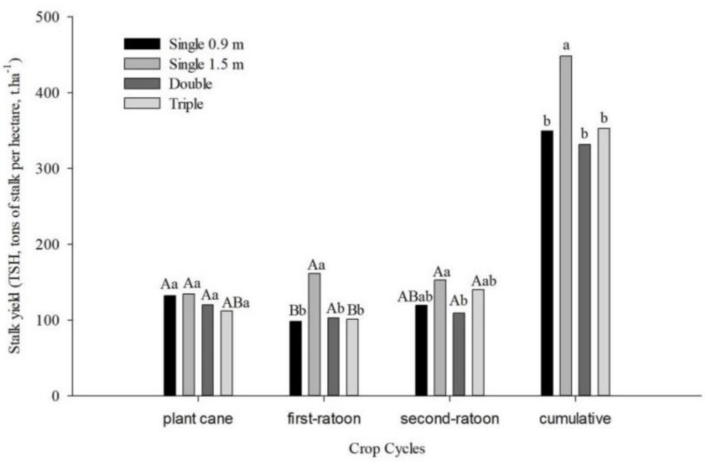

Figure 4. Stalk yield (TSH, t ha^{-1}) under different row spacings across three crop cycles and cumulative TSH over the production cycles. Ijací, MG, Brazil. Means followed by the same uppercase letter within each spacing across crop cycles and the same lowercase letter within each crop cycle across spacings do not differ significantly according to Tukey's test ($p < 0.05$).

In plant cane, TSH ranged from 111.81 to 134.48 t ha^{-1}, with no significant differences among treatments, although the single 1.5 m (134.48 t ha^{-1}) and single 0.9 m (131.93 t ha^{-1}) spacings showed slightly higher numerical values.

In the first ratoon, contrasting trends emerged. The single 1.5 m spacing increased markedly to 161.32 t ha^{-1} (+20% compared with plant cane), whereas the single 0.9 m spacing showed a sharp decline to 98.07 t ha^{-1} (−26%). The double and triple spacings also declined to 102.44 and 101.23 t ha^{-1}, respectively.

In the second ratoon, the single 1.5 m spacing maintained high productivity (152.49 t ha^{-1}), while the triple spacing recovered significantly to 140.10 t ha^{-1}, surpassing its initial value by 25%. The single 0.9 m spacing partially recovered to 119.23 t ha^{-1}, whereas the double spacing remained low at 108.86 t ha^{-1}.

Considering cumulative yield across the three harvests, the single 1.5 m spacing showed the highest overall performance, totaling 448.29 t ha^{-1}. Across cycles, this spacing consistently sustained the highest yields and exhibited the greatest stability, with values exceeding 150 t ha^{-1} from the first ratoon onward. In contrast, the single 0.9 m spacing displayed marked yield instability, with a sharp decline from plant cane to the first ratoon, followed by only partial recovery. The double spacing showed the lowest overall performance, whereas the triple spacing exhibited a delayed response, with substantial yield gains only in the second ratoon.

These results demonstrate that the single 1.5 m spacing combines high initial productivity with strong ratoon longevity, whereas the narrow 0.9 m spacing and the double configuration may compromise yield sustainability. The decline observed in the 0.9 m treatment during the first ratoon is likely related to increased competition for water and nutrients associated with higher plant density, compounded by low rainfall in October 2022, which may have restricted early ratoon development. Rossi Neto et al. (2018) similarly reported reduced plant mass under narrow row spacing (< 1.0 m) compared with wider configurations.

Other studies have also reported yield advantages at 1.5 m row spacing. Khan et al. (2021) reported yields of 104.7 t ha^{-1} at 1.5 m compared with 98.2 t ha^{-1} at 0.9 m, and Silva et al. (2017) observed that the double spacing only surpassed the 1.5 m spacing from the second ratoon onward. The delayed recovery observed in the triple spacing in the present study suggests that this configuration may allow yield compensation through increased stalk mass per plant when environmental conditions are favorable, even when the number of stalks per meter remains stable.

Overall, the single 1.5 m spacing emerged as the most efficient configuration for sustaining high sugarcane productivity across successive harvest cycles, combining high initial yields with strong ratoon persistence and yield stability. In contrast, the narrow single 0.9 m spacing and the double spacing showed yield declines after plant cane, highlighting the risk of early stand degradation under high plant density.

Therefore, adopting the 1.5 m spacing appears to be the most suitable strategy for ensuring long-term yield stability in sugarcane production systems under similar edaphoclimatic conditions.

4. Conclusions

Row spacing significantly affected the productive performance and yield stability of sugarcane over three consecutive harvest cycles. The single 1.5 m spacing consistently sustained the highest yields (>150 t ha^{-1}) and stalk density, demonstrating superior ratoon longevity and stand stability. In contrast, the single 0.9 m and double spacings exhibited yield declines and reduced stand persistence over time. Therefore, adopting the 1.5 m spacing is recommended as an effective strategy to enhance the long-term productivity of sugarcane under similar edaphoclimatic conditions.

Authors' Contribution

Pimentel, G. V.: Conceptualization, methodology, supervision, project administration, and writing – review and editing. Silva, L. D. R.: Investigation, data curation, formal analysis, writing – original draft, and writing – review and editing. Goulart, J. P. L.: Investigation, field evaluations, data collection, and writing – original draft. Peixoto, M. R.: Formal analysis, data curation, writing – original draft, and writing – review and editing. Freitas, J. C.: Investigation, field evaluations, data collection, and writing – original draft. Costa, N.: Formal analysis, writing – review and editing, and manuscript revision.

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