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ORIGINAL ARTICLE

Agronomic and qualitative performance of common bean under sugarcane straw and Fomesafen application[1]

Desempenho agronômico e qualitativo do feijoeiro comum cultivado sob palha de cana-de-açúcar e aplicação de Fomesafen

Heytor L. Martins[2,4*], Vitor A. Benedito[2], Pedro A. Silva Martins[2], Arthur N. Campalle[2], Jhansley F. da Mata[3], Vanesca Korasaki[3], Mariana C. Parreira[4], Leandro B. Lemos[2], Pedro L. da Costa Aguiar Alves[2]

[1] Reseach conducted at School of Agricultural and Veterinary Sciences, São Paulo State University (UNESP), Jaboticabal, Brazil
[2] School of Agricultural and Veterinary Sciences, São Paulo State University (UNESP), Jaboticabal, Brazil
[3] State University of Minas Gerais, Frutal, Brazil
[4] Instituto de Investigação e Tecnologias Agrárias e do Ambiente (IITAA), Faculty of Agricultural and Environmental Sciences, University of the Azores, 9700-042 Angra do Heroísmo, Portugal

HIGHLIGHTS:

Straw mulching increases grain size and yield of common beans.
Fomesafen improves the cooking quality and protein content of beans.
Straw cover combined with Fomesafen increased bean growth, grain yield, and protein content.

ABSTRACT: Cultivating legumes in fallow areas can enhance soil fertility and agricultural sustainability, especially when combined with the presence of remaining sugarcane straw and chemical weed control. Thus, the objective of the study was to evaluate the agronomic and qualitative performance of common bean subjected to different amounts of residual sugarcane straw and Fomesafen application. The experimental design was a randomized block design in a 4 × 2 factorial scheme with four replications. The factors were the amounts of straw (0, 1, 5, and 10 t ha^{-1}) and two herbicide application conditions (without and with application - 1.0 L of commercial product per hectare). The soil is classified as Oxisol with a clayey texture. Cultivating the BRS FC104 bean cultivar under sugarcane straw increased grain yield by up to 50.5%, crude protein content by 3.6 percentage points, and leaf area by 33% compared to bare soil. Fomesafen application resulted in higher grain yields and crude protein content, shorter cooking times, and improved sieve yields. Therefore, it is concluded that the use of straw and Fomesafen in the BRS FC104 bean cultivar positively influences grain development, yield, and quality.

Key words: *Phaseolus vulgaris*, residue mulch, post-emergence herbicide, no-tillage system

RESUMO: O cultivo de leguminosas em áreas de pousio pode aumentar a fertilidade do solo e a sustentabilidade agrícola, especialmente quando combinado com a presença de palhada residual de cana-de-açúcar e o controle químico de plantas daninhas. Assim, o objetivo deste estudo foi avaliar o desempenho agronômico e qualitativo do feijoeiro comum submetido a diferentes quantidades de palhada residual de cana-de-açúcar e à aplicação de Fomesafen. O delineamento experimental foi em blocos casualizados, em esquema fatorial 4 × 2, com quatro repetições. Os fatores avaliados foram as quantidades de palha (0, 1, 5 e 10 t ha^{-1}) e duas condições de aplicação do herbicida (sem e com aplicação – 1,0 L do produto comercial por hectare). O solo é classificado como Latossolo Vermelho Escuro eutrófico, de textura argilosa. O cultivo do feijão 'BRS FC104' sobre palhada de cana-de-açúcar aumentou a produtividade em até 50,5%, o teor de proteína bruta em 3,6 pontos percentuais e a área foliar em 33%, em comparação com o solo descoberto. A aplicação de Fomesafen resultou em maior produtividade e teor de proteína bruta, menor tempo de cozimento e melhor rendimento de peneira. Conclui-se, portanto, que o uso de palhada e Fomesafen no cultivo do feijão 'BRS FC104' influencia positivamente o desenvolvimento dos grãos, a produtividade e a qualidade.

Palavras-chave: *Phaseolus vulgaris*, cobertura morta de resíduos, herbicida pós-emergente, sistema de plantio direto

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* Corresponding author - E-mail: heytor.lemos18@gmail.com
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INTRODUCTION

Species of the Fabaceae family, such as soybeans, beans, and peanuts, are frequently used in human nutrition and are widely employed for green manure practices and maintaining soil quality (Reckling et al., 2016; Jensen et al., 2020). In replanting areas, crop rotation is carried out in the spring/summer period when the soil is without cover due to the cutting and planting of sugarcane, leaving it exposed (fallow). However, to protect the soil, the management of crop residues is currently used, along with the sowing of a legume, which leads to an increase in organic material in the soil, intensification of nutrient cycling, reduction of erosion, and improvement of soil fertility (Chen & Weil, 2011; Thorburn et al., 2017). Thus, cultivating beans in planting areas under a fallow system can be a viable and advantageous approach, both from an economic perspective for the bean crop and for the subsequent sugarcane cultivation.

The common bean (*Phaseolus vulgaris* L.) plays a crucial role in the diet of Brazilians, being widely recognized as an excellent source of protein (Mingotte et al., 2013; Amaral et al., 2016). This crop holds a prominent position in both the economic and nutritional aspects of the country and can be cultivated in various regions, with the possibility of up to three annual harvests (CONAB, 2025).

Proper management of the common bean cultivation system, from cultivar selection to post-harvest practices, plays a crucial role in obtaining a high-quality product with desirable phenological characteristics (Mingotte & Lemos, 2018). Soil management (no-tillage system) and higher nitrogen (N) doses applied as topdressing help enhance the qualitative performance of grains of the Pérola cultivar (Farinelli & Lemos, 2010).

However, common bean, like other crops, is subject to interference from weeds (Parreira et al., 2012,2014; Mielle et al., 2019). Given this interference, weed control is essential, with chemical control being the most common method due to its efficiency (Esqueda-Esquivel et al., 2025). Among the herbicides registered for this crop is Fomesafen (AGROFIT, 2025), an herbicide that inhibits the enzyme protoporphyrinogen oxidase (PROTOX), recommended for post-emergence control of broadleaf weeds. Its absorption occurs mainly through the leaves, with low absorption by the roots; after foliar absorption, translocation via the xylem occurs only over short distances, thus it is characterized as a contact herbicide (Marchi et al., 2008; Barroso & Murata, 2021) with good control efficacy (Mancuso et al., 2016; Marchioretto & Dal Magro, 2017).

Recent studies have highlighted that maintaining sugarcane straw on the soil surface after harvest improves soil structure, enhances moisture retention, and facilitates nutrient cycling, while reducing weed emergence and soil erosion (Cherubin et al., 2021; Pimentel et al., 2024). The high C/N ratio of the straw promotes gradual decomposition, contributing to increased organic carbon and nitrogen stocks, which enhance the subsequent crop's development (Pimentel et al., 2024; Martins et al., 2025a).

In renovation areas, the introduction of short-cycle legumes such as common bean (*Phaseolus vulgaris* L.) during the sugarcane fallow period has proven to be a viable practice for maintaining soil fertility and grain yield (Mingotte & Lemos, 2018; Otto et al., 2020). Straw amounts between 5 and 10 t ha^{-1} favor better plant growth, yield, and quality, while also influencing herbicide dynamics and minimizing phytotoxic effects (Concenço et al., 2017; Bohórquez-Sánchez et al., 2023).

Thus, the objective of the study was to evaluate the agronomic and qualitative performance of common bean subjected to different amounts of residual sugarcane straw and Fomesafen application.

MATERIAL AND METHODS

The experiment was carried out at São Paulo State University (UNESP), School of Agricultural and Veterinary Sciences, in Jaboticabal, São Paulo, Brazil (21° 14' 48.14" S; 48° 18' 06.86" W; 594 m altitude), during the autumn–winter season from April to August 2022. Before the experiment was set up, soil samples from the 0-20 cm soil layer were collected for chemical and physical analysis. The soil is classified as an Oxisol with a clayey texture, with particle size analysis indicating 53% clay, 7% silt, and 40% sand.

The chemical analysis of the 0-20 cm soil layer showed the following results: pH ($CaCl_2$) = 4.8, organic matter (OM) = 11 g dm^{-3}, phosphorus (P) = 63 mg dm^{-3}, potassium (K) = 2.2 mmol$_c$ dm^{-3}, calcium (Ca) = 11 mmol$_c$ dm^{-3}, magnesium (Mg) = 5 mmol$_c$ dm^{-3}, H+Al = 31 mmol$_c$ dm^{-3}, sum of bases (SB) = 18.9 mmol$_c$ dm^{-3}, cation exchange capacity (CEC) = 49.3 mmol$_c$ dm^{-3}, and base saturation (V) = 37%. The common bean cultivar used was BRS FC104, characterized by a determinate growth habit (Type I), a very early cycle (65 days), and carioca-type grains (EMBRAPA, 2018).

According to the Köppen classification, the regional climate is Cwa, a subtropical type characterized by dry winters and summer rainfall (Alvares et al., 2013). The region has an average annual temperature of 22.7 °C and an average annual precipitation of 1,353 mm. During the experiment, weather data on rainfall, temperatures, and maximum, minimum, and average humidity were recorded for the Jaboticabal region (Figure 1).

The study was conducted in a randomized complete block design (RCBD) arranged in a 4 × 2 factorial scheme with four replicates. The factors consisted of sugarcane straw amounts (0, 1, 5, and 10 t ha^{-1}) and two herbicide application conditions (without and with Fomesafen application – 1.0 L of the commercial product per hectare – Flex), totaling eight treatments and 32 experimental plots. Each plot consisted of five common bean rows, spaced 0.45 m apart and 5 m in length (11.25 m^2), with the three central rows (6.75 m^2) considered as the useful area. Sowing was done by placing 13 seeds per meter, with fertilization equivalent to 300 kg ha^{-1} of the NPK (4-14-8 formulation), according to the fertilization need.

Sugarcane straw from the IAC 91-1099 variety, collected in the Jaboticabal-SP (Brazil) region, was transported to the experimental area and applied to the plots at rates equivalent to 1, 5, and 10 t ha^{-1} (1.25, 6.25, and 12.50 kg m^2). These doses were defined based on the typical ranges observed in sugarcane-producing regions of São Paulo, where straw retention after mechanical harvest commonly reaches up to 20 t ha^{-1}. However, due to the increasing use of straw for alternative purposes, such as energy generation, the amount left on the soil has decreased in recent years, often remaining close to 10 t ha^{-1}.

For this reason, 10 t ha^{-1} was adopted as the maximum dose in the experiment, and the lower doses (5 and 1 t ha^{-1}) were proportionally reduced to allow the assessment of the effects of decreasing straw cover on soil and crop responses. Proper care was taken to ensure the quality of the plant material, considering that the collection area is well-known and has no history of herbicide application. The collected straw was shredded into small pieces before being applied in the field. A conventional sprinkler irrigation system was installed in the experimental area, with watering intervals of five days, corresponding to approximately 30 mm per event, totaling 390 mm of irrigation throughout the experiment. Additionally, 141 mm of rainfall occurred during the study period.

In treatments where the crop coexisted with weeds, two 0.25 m^2 sampling frames were randomly placed in each plot to characterize the weed community. Immediately afterward, the plots were weeded. The plants within each sampling frame were identified, counted, and collected. Subsequently, their aerial parts were placed in kraft paper bags and then taken to a forced-air circulation oven at 60 °C to reach a constant weight. Abundance assessments were conducted before and after herbicide application, based on the methodology proposed by Mueller-Dombois & Ellenberg (1974). Weed abundance data are provided in the supplementary material (SF1 and SF2).

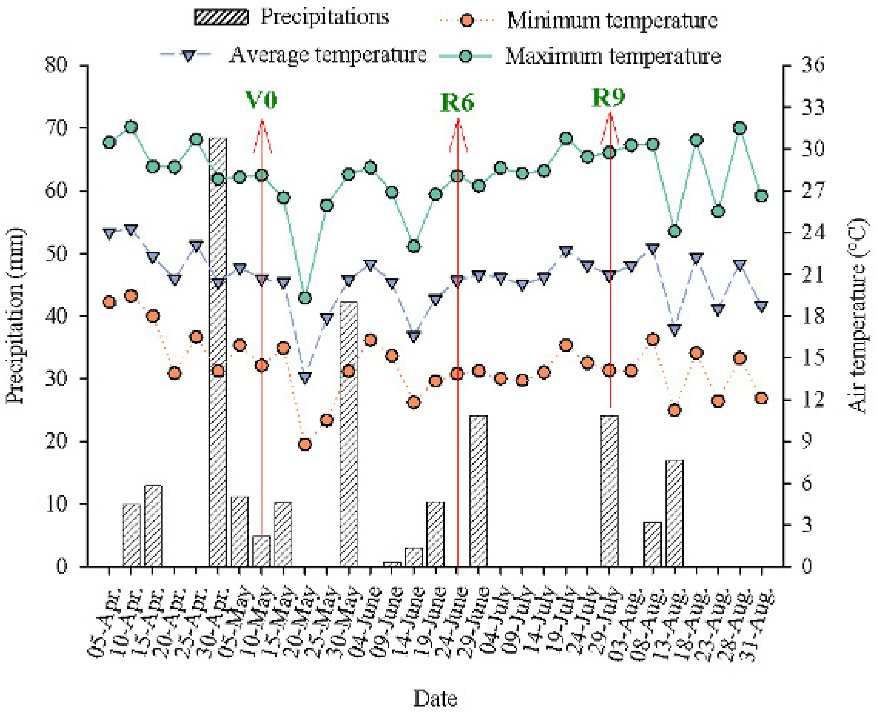
The herbicide used was Flex (Fomesafen), recommended for the bean crop (AGROFIT, 2025), applied 15 days after emergence (DAE) at a dose of 1.0 L of commercial product per hectare, with the addition of the adjuvant Assist at 0.5% v/v. A constant-pressure (CO2) backpack sprayer was used for the applications, equipped with a bar featuring four 110.02 nozzles spaced 0.5 m apart, covering a 2 m strip, and set to distribute 200 L ha^{-1} of spray solution at 2.8 bar pressure. During the application, the following conditions were recorded: start of application at 4:03 p.m.; end of application at 4:32 p.m.; clear sky; air temperature of 29 °C; wind speed: 10.3 km h^{-1}; relative humidity of 46% (Figure 1).

When the crop cycle ended (75 days after sowing [DAS] and 60 days after application [DAA]), four representative plants from the plot were cut at the soil surface level, and their parts were separated. The leaves were measured with a leaf area (LA) meter (LI 3100A, LiCor) and, along with the roots and stems, were dried in a forced-air oven at 60 °C until constant weight was achieved to determine total dry mass (TDM). Using this data, the following characteristics were determined: leaf area ratio (LAR), absolute growth rate (AGR), relative growth rate (RGR), net assimilation rate (NAR), leaf area duration (LAD), and leaf area index (LAI) following the formulas proposed by Benincasa (2003).

At harvest (72 DAE), the plants from the three central rows of each plot were harvested, and the 100-grain weight (P100) was determined using three subsamples from each plot, with moisture standardized to 0.13 g g^{-1} to estimate grain yield, expressed in kg ha^{-1} (Carbonell et al., 2010).

The crude protein content of the grains was determined using the equation (AOAC, 2023) CP = Total N × 6.25, where CP = crude protein content in the grains (%) and Total N = nitrogen content in the grains, obtained according to the methodology proposed by Malavolta et al. (1997).

After harvest, common bean grain samples from each experimental plot were subjected to a set of screens with oblong



V0 - Arrows indicate the initial; R6 - Intermediate, and R9 - Final growth stages of the common bean on their respective dates

Figure 1. Precipitation (mm) and temperature (°C) recorded during the experimental period from April to August 2022

holes 11/64” × 3/4” (4.37 × 19.05 mm), 12/64” × 3/4” (4.76 × 19.05 mm), 13/64” × 3/4” (5.16 × 19.05 mm), 14/64” × 3/4” (5.56 × 19.05 mm), and 15/64” × 3/4” (5.96 × 19.05 mm) under agitation for one minute (Mingotte et al., 2013). The screening yield (SY, %) was determined as the ratio between the weight of grains retained on each screen and the total sample weight of each replication. The yield of screens with oblong holes equal to or greater than 11/64” × 3/4” (4.37 × 19.05 mm) ($SY \geq 11$) was also calculated, corresponding to the sum of grains retained on screens 11/64” to 13/64”. The samples retained on screen 13 were placed in paper bags and used for further qualitative evaluations after 60 days of storage.

To determine cooking time (CT), time to maximum hydration (TMH) of the grains, and hydration ratio (HR), the grains retained on screen 12 were used, following the methodology described by Alves et al. (2020). The level of resistance of the grains to cooking was assessed using the Proctor & Watts (1987) scale. The hydration ratio of the grains was determined over a period of 18 hours (Alves et al., 2020).

The data obtained were tested for normality and homoscedasticity, and then subjected to analysis of variance (ANOVA) using the F-test at significance levels of $p \leq 0.05$ and $p \leq 0.01$. When the F-test showed significance, treatment means were compared using the Tukey test at $p \leq 0.01$ and $p \leq 0.05$.

For MHT, CT, CPC, W100, GY, LA, TDM, AGR, RGR, NAR, LAI, LAR, and LAD, models were fitted, following the recommendations of Venegas & Alvarez (2003). The analysis of the results was performed using regression analysis with the statistical software OriginLab Corporation (2025).

A principal component analysis (PCA) was performed to assess the relationship between the herbicide application factors and straw incorporation on the studied variables. All tests were conducted using Statistica 13.3 software (StatSoft, 2021).

RESULTS AND DISCUSSION

Table 1 presents the weed species identified in the experimental area. Of these, seven species (38.88%) are monocots, distributed among the families Commelinaceae (5.55%), Cyperaceae (5.55%), and Poaceae (27.77%). The eudicot group comprises eleven species (61.12%) across seven families: Amaranthaceae (11.11%), Asteraceae (16.66%), Brassicaceae (5.55%), Convolvulaceae (5.55%), Euphorbiaceae (11.11%), Fabaceae (5.55%), and Rubiaceae (5.55%).

For the plant growth parameters of leaf area (F = 3.28), total dry mass (F = 4.97), relative growth rate (F = 5.21*), leaf area index (F = 4.28*), leaf area duration (F = 2.28*), and leaf area ratio (F = 1.28*) significant effects of the evaluated

Table 1. Families, scientific names, and common names of weeds recorded in all phytosociological surveys

Family	Scientific name	Code*	Common name
	Monocots		
Commelinaceae	*Commelina benghalensis* L.	COMBE	Trapoeraba
Cyperaceae	*Cyperus rotundus* L.	CYPRO	Tiririca
Poaceae	*Cenchrus echinatus* L.	CCHEC	Capim-carrapicho
	Dactyloctenium aegyptium (L.) Willd	DTTAE	Capim-mão-de-sapo
	Digitaria horizontalis Willd.	DIGHO	Capim-colchão
	Eleusine indica (L.) Gaertn.	ELEIN	Pé-de-galinha
	Panicum maximum Jacq.	PANMA	Capim-colonião
	Eudicots		
Amaranthaceae	*Alternanthera tenella* Colla	ALRTE	Apaga-fogo
	Amaranthus lividus L.	AMALI	Caruru
Asteraceae	*Ageratum conyzoides* L.	AGECO	Mentrasto
	Emilia fosbergii Nicolson	EMIFO	Falsa-serralha
	Xanthium strumarium L.	XANST	Carrapicho-carneiro
Brassicaceae	*Raphanus raphanistrum* L.	RAPRA	Nabiça
Convolvulaceae	*Ipomoea hederifolia* L.	IPOHF	Corda-de-viola
Euphorbiaceae	*Euphorbia heterophylla* L.	EPHHL	Leiteiro
	Portulaca oleracea L.	POROL	Beldroega
Fabaceae	*Senna obtusifolia* L.	CASOB	Fedegoso
Rubiaceae	*Richardia brasiliensis* Gomes	RICHBR	Poaia-branca
Solanaceae	*Nicandra physalodes* L.	NICPH	Nicandra

*International Code, according to the Weed Society factors were observed ($p < 0.05$). In contrast, absolute growth rate (F = 3.03ns) and net assimilation rate (F = 2.03ns) were not statistically significant.

In Figure 2A, it can be observed that the absence of straw (0 t ha^{-1}) resulted in lower bean leaf area values. With the increase in straw amounts, there is a trend of increasing values up to 5 t ha^{-1}, followed by a stabilization at 10 t ha^{-1}. It is also observed that, in the treatment with herbicide application, the plants exhibit a greater leaf area for 5 and 10 t ha^{-1}.

In Figure 2B, herbicide application resulted in a linear increase in total dry mass with an increasing straw amount. In the treatment without herbicide, no significant difference was observed, and a low correlation was observed ($Y = 30.95+1.50x-0.12x^2$, $R^2 = 0.36$, $CV = 38.26^{NS}$).

In Figure 2C, in the herbicide treatment, a linear increase in the absolute growth rate is observed with the increase in straw quantity, indicating a positive relationship between the amount of straw and plant growth. In the treatment without herbicide, the relationship followed a quadratic trend. Based on the fitted quadratic model, the maximum absolute growth rate (0.675 g per day) was estimated at 7.5 t ha^{-1} of straw.

In Figure 2D, the relative growth rate showed a linear increase, indicating a positive response to the increase in straw when herbicide was applied. In the treatment without herbicide application, the growth rate follows a quadratic pattern, with an initial increase up to 1 and 5 t ha^{-1} of straw, followed by a decrease at the highest dose (10 t ha^{-1}).

In Figure 2E, the net assimilation rate exhibited a decreasing quadratic trend when herbicide was applied, indicating a reduction in the rate as straw levels increased. In contrast, when the plants were not exposed to herbicide, there was no clear relationship between straw and the assimilation rate. The curve suggests a relatively stable trend, with minor variations across the different straw doses ($y = 19.74+0.15x-0.02x^2$, $R^2 = 0.25$, CV (%) $= 26.63^{NS}$).

The leaf area index of the common bean in this experiment shows a progressive increase with the addition of straw for both management practices (with and without herbicide), as described by the quadratic equation. This indicates a positive response to straw, with continuous growth up to 10 t ha^{-1}, suggesting that herbicide application favored the development of the plants' leaf area (Figure 2F).

For the leaf area ratio (Figure 2G), the herbicide treatment showed a decrease with increasing straw, although the coefficient of determination indicates a weak relationship between the variables. The curve indicates an initial decrease in the leaf area ratio with increasing straw doses up to approximately 5 t ha^{-1}, followed by a tendency toward stabilization at higher straw levels (Figure 2G) ($y = 70.83+1.72x-0.28x^2$, $R^2 = 0.45$, CV (%) $= 38.63^{NS}$). This suggests that the straw may have negatively impacted the leaf area ratio, possibly due to the greater accumulated biomass without a proportional increase in leaf area. In contrast, for the treatment without herbicide application, an initial decrease is observed, followed by stabilization in the leaf area ratio values (Poorter et al., 2012).

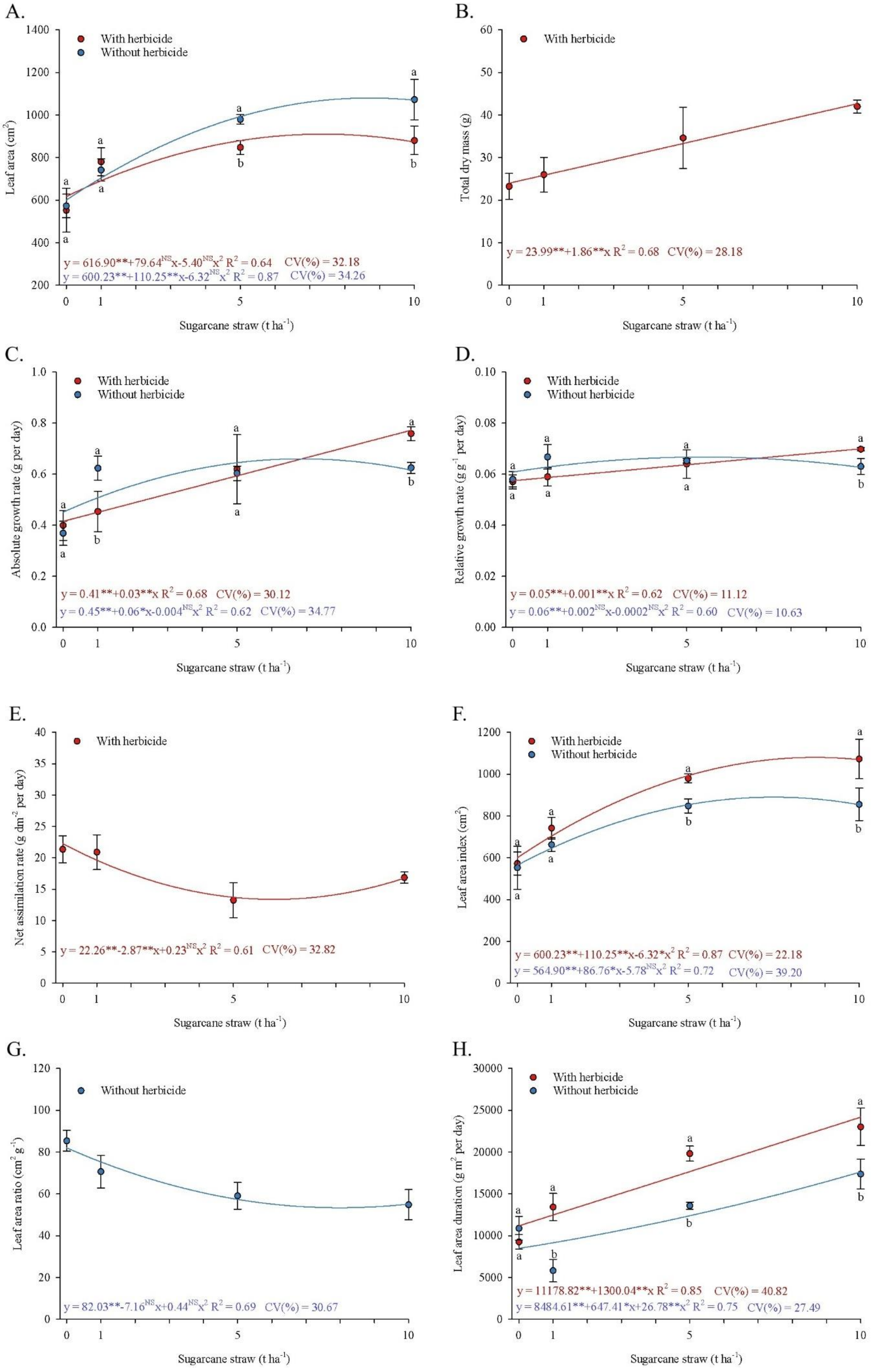
In Figure 2H, it is observed that when herbicide was applied to the common bean, there was a linear increase in leaf area duration with the increase in straw. In the treatment without herbicide application, the relationship followed a quadratic trend, indicating that the effect was not linear, showing an initial gain up to 5 t ha^{-1}, followed by a slowdown in value. The leaf area duration of the common bean was positively influenced by the increase in straw in both treatments, with more significant gains observed in the treatments with herbicide application.

The cultivar used (BRS-FC104), being a super-early, indeterminate cycle cultivar, exhibits rapid development during the vegetative stage, accumulating more biomass over time compared to those with a normal cycle, thereby overlapping with the reproductive phase. Given this rapid and intense growth pattern, the environmental conditions surrounding the plant become even more critical to support its full developmental potential (Bezerra et al., 2009).

Cultivating common beans using a straw mulch system (no-till) can have a significant impact on plant development. The straw acts as a protective layer, covering the soil and creating a more favorable microenvironment for plant growth. This cover helps maintain more stable soil temperatures, minimizes soil compaction, and reduces water evaporation (Thorburn et al., 2017). For example, with sugarcane straw, the soil water loss is reduced by 216% compared to bare soil (Peres et al., 2010), maintaining soil moisture. In this study, growth variables such as leaf area (LA), total dry mass (TDM) (without herbicide), leaf area index (LAI), and leaf area duration (LAD) showed better performance with straw mulch treatments, indicating that this improved plant performance is linked to the conditions mentioned above.

Straw also affects the composition and infestation of weeds (Concenço et al., 2017), which could explain the higher bean grain yield in treatments with greater amounts of straw, in the absence of chemical control. The interaction between herbicide application and straw doses revealed contrasting patterns in the development of common beans. In bare soil (0 t ha^{-1}), herbicide use significantly reduced morphophysiological variables, likely due to phytotoxic effects. At 1 t ha^{-1}, herbicide application mitigated weed competition, resulting in a slight increase in dry mass and leaf area (Martins et al., 2025b). At 5 t ha^{-1}, the best overall performance was observed under herbicide application, with the highest values for absolute growth rate and grain yield, highlighting the synergy between weed suppression and improved soil conditions. At 10 t ha^{-1}, although straw maintained a favorable microclimate, the absence of herbicide led to a decrease in plant growth due to increased competition, whereas the presence of the product sustained high biomass and yield levels (Amini et al., 2023).

The better development of the bean plants in straw mulch treatments shows a stronger relationship with morphophysiological variables, which is tied to the proportion of straw. This involves the C/N ratio interaction, which offers benefits, as the straw mineralizes elements that can enhance the development and growth of both the sugarcane agroecosystem and the crop being grown. The availability of these nutrients from sugarcane straw is a slower process (Giacomini et al., 2003) compared to other



ns - Not significant; * - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$. The vertical bar represents the standard error of the mean (n = 4). Means followed by the same lowercase letter indicate no significant difference between herbicide application and no application at each sugarcane straw amounts, according to Tukey's test ($p \leq 0.05$)

Figure 2. Plant growth variables of the common bean 'BRS-FC104' grown under sugarcane straw amounts, with or without Fomesafen application. LA – Leaf area (A); TDM – Total dry mass (B); AGR – Absolute growth rate (C); RGR – Relative growth rate (D); NAR – Net assimilation rate (E); LAI – Leaf area index (F); LAR – Leaf area ratio (G); LAD – Leaf area duration (H)

crops, due to the high C/N ratio, which reaches 36.8 with an approximate amount of 10 t ha^{-1} (Torres & Pereira, 2014; Mingotte et al., 2019).

The interaction between straw presence and herbicide application had a decisive influence on common bean development and its morphophysiological traits. In treatments with herbicide, increasing straw doses enhanced plant performance, promoting linear increases in total dry mass (Figure 2B), absolute growth rate (Figure 2C), relative growth rate (Figure 2D), and leaf area duration (Figure 2H). These results suggest that combining chemical control with straw input creates more favorable conditions for crop growth and development by reducing weed competition and enhancing photosynthetic efficiency.

In contrast, in treatments without herbicide, the effects of straw were dependent on the amount applied, with predominantly quadratic responses. Growth rates increased up to intermediate straw doses (5 to 7.5 t ha^{-1}) but declined at higher levels, suggesting limited efficiency in the absence of chemical control (Figures 2C-D). Moreover, the net assimilation rate remained relatively stable without herbicide (Figure 2E). Although the leaf area index increased with higher straw amounts, its absolute values were lower compared to those of the herbicide treatments (Figure 2F). These findings demonstrate that, although straw plays a key role in weed suppression and in improving soil microenvironmental conditions, its isolated effect is not sufficient to maximize bean performance. Therefore, the combination of straw and herbicide proves to be a strategic management approach, not only by enhancing weed control but also by mitigating potential phytotoxic effects and promoting a more stable environment for crop development.

Thus, the improvement in soil aggregates, increased organic matter, and the stock of carbon and nitrogen in the soil are linked to the increased input of C and N from the mineralization of straw and, consequently, to the improved plant development (Galdos et al., 2009; Trivelin et al., 2013).

Bean plants showed better development when herbicide was applied, but only when straw was present in the system. This result is interesting because, in addition to straw directly influencing bean development, it also affects weed control, as the residual control of some herbicides can be influenced by the amount of straw (Silva et al., 2021). In contrast, plants grown in bare soil with herbicide application exhibited significant reductions in morphophysiological characteristics compared to the others. This could be due to phytotoxicity, as studies by Mancuso et al. (2016) on cowpea in conventional systems observed that the use of Fomesafen affects plant development, delaying its growth cycle.

The screening yield (SY) for the BRS-FC104 bean cultivar did not show a significant difference between herbicide application and non-application for the SY13 category. For straw quantities, no significant difference was observed for any of the categories. There was a significant interaction between herbicide and straw quantities only for SY12 and SY≥11. The categories SY11 and SY≥11 showed a higher percentage of grains when the plants were not subjected to herbicide application. For SY12, plots that received herbicide application had a higher percentage of grains (Table 2).

In the SY12 category, the interaction analysis showed that the highest straw amount (10 t ha^{-1}) reduced yield when no herbicide was applied. When assessing herbicide presence or absence within each straw level, significant differences were observed only in the 0 and 1 t ha^{-1} treatments, indicating that herbicide application increased the number of grains retained on sieve 12 (Table 3).

Table 2. Screening yield (SY) determined by the percentage of grains of the BRS-FC104 bean cultivar retained on oblong-hole screens in relation to different amounts of straw, with and without Fomesafen application

Source of variation	F test/Mean			
	SY11	SY12	SY13	SY≥11
Herbicide – H ('F' value)	4.48*	4.47*	0.00^{ns}	3.01*
Sugarcane straw – SS ('F' value)	0.67^{ns}	1.37^{ns}	1.88^{ns}	11.80^{ns}
H x SS ('F' value)	0.80^{ns}	3.09*	2.20^{ns}	5.38**
CV (%)	24.37	23.84	12.6	7.23
Factors	Screening Yield (%)			
	SY11	SY12	SY13	SY≥11
Herbicide				
With	35.52 b	37.28 a	5.06	79.41 b
Without	42.66 a	28.90 b	5.01	75.72 a
Sugarcane straw (t ha^{-1})				
0	39.46	34.98	5.45	80.28
1	44.57	30.42	2.58	77.73
5	31.58	38.68	9.23	80.4
10	40.74	38.28	2.82	82.24

11, 12, and 13 - Mesh opening sizes. Means followed by different letters differ according to Tukey's test. * and ** - Denote significance at $p \leq 0.05$ and $p \leq 0.01$, respectively, by the F-test; ns - Not significant. CV (%) - Coefficient of variation

Table 3. Interaction between straw level and herbicide application on grain retention on sieve 12 of the BRS FC104 common bean cultivar

Herbicide	Amount of straw (t ha^{-1})				
	0	1	5	10	Ftest
			SY12 (%)		
With	44.43 Aa	38.14 Aa	43.64 Aa	37.66 Aa	2.29^{ns}
Without	25.52 Bc	18.71 Bc	33.73 Aa	29.90 Bb	3.18*
Ftest	5.70*	6.02*	1.57^{ns}	3.47*	
			SY≥11 (%)		
With	80.37 Ab	81.62 Aab	82.34 Aa	81.44 Aa	6.29**
Without	65.00 Ba	74.65 Ba	76.35 Aa	75.98 Aa	1.54^{ns}
F	15.13*	3.12*	2.30^{ns}	1.91^{ns}	

SY - Screening yield; 11 and 12 - Mesh opening sizes. Means followed by the same letter—uppercase in columns and lowercase in rows—do not differ according to Tukey's test at the $p \leq 0.05$ level. * - Significant at $p \leq 0.05$ by the F-test; ns - Not significant

In the SY≥11 category, interaction analysis showed that in the straw treatments (1, 5, and 10 t ha^{-1}), herbicide application resulted in higher yield. When assessing herbicide presence or absence within each straw level, significant differences were observed only in the 0 and 1 t ha^{-1} treatments, indicating that herbicide application increased the number of grains retained on sieve 11 (Table 3).

Regarding the technological quality parameters — maximum hydration time (F = 6.96*), cooking time (F = 8.96**), crude protein content (F = 4.69**), weight of 100 grains (F = 4.54**), and yield (F = 0.85ns) — most parameters showed significant differences between the evaluated factors ($p < 0.05$), except for yield, which was not statistically significant.

In Figure 3A, the bean plants that were exposed to the herbicide showed a gradual increase in maximum hydration time up to the highest tested straw dose of 10 t ha^{-1}. In contrast, for the treatment without herbicide application, the relationship followed a quadratic trend, with the maximum hydration time estimated at approximately 6.1 t ha^{-1} of straw according to the fitted quadratic model, followed by a reduction at higher doses.

In Figure 3B, the cooking time of bean grains followed a quadratic trend, with a reduction up to approximately 5 t ha^{-1} of straw, followed by an increase at the 10 t ha^{-1} dose for both management practices (with and without herbicide). This pattern suggests that moderate straw levels improve grain physicochemical quality, likely by enhancing soil conditions and plant development, resulting in shorter cooking times. However, excessive amounts of straw may have the opposite effect, possibly due to nutrient immobilization associated with the high C/N ratio of sugarcane straw, which could delay grain softening and increase cooking time (Figure 3B).

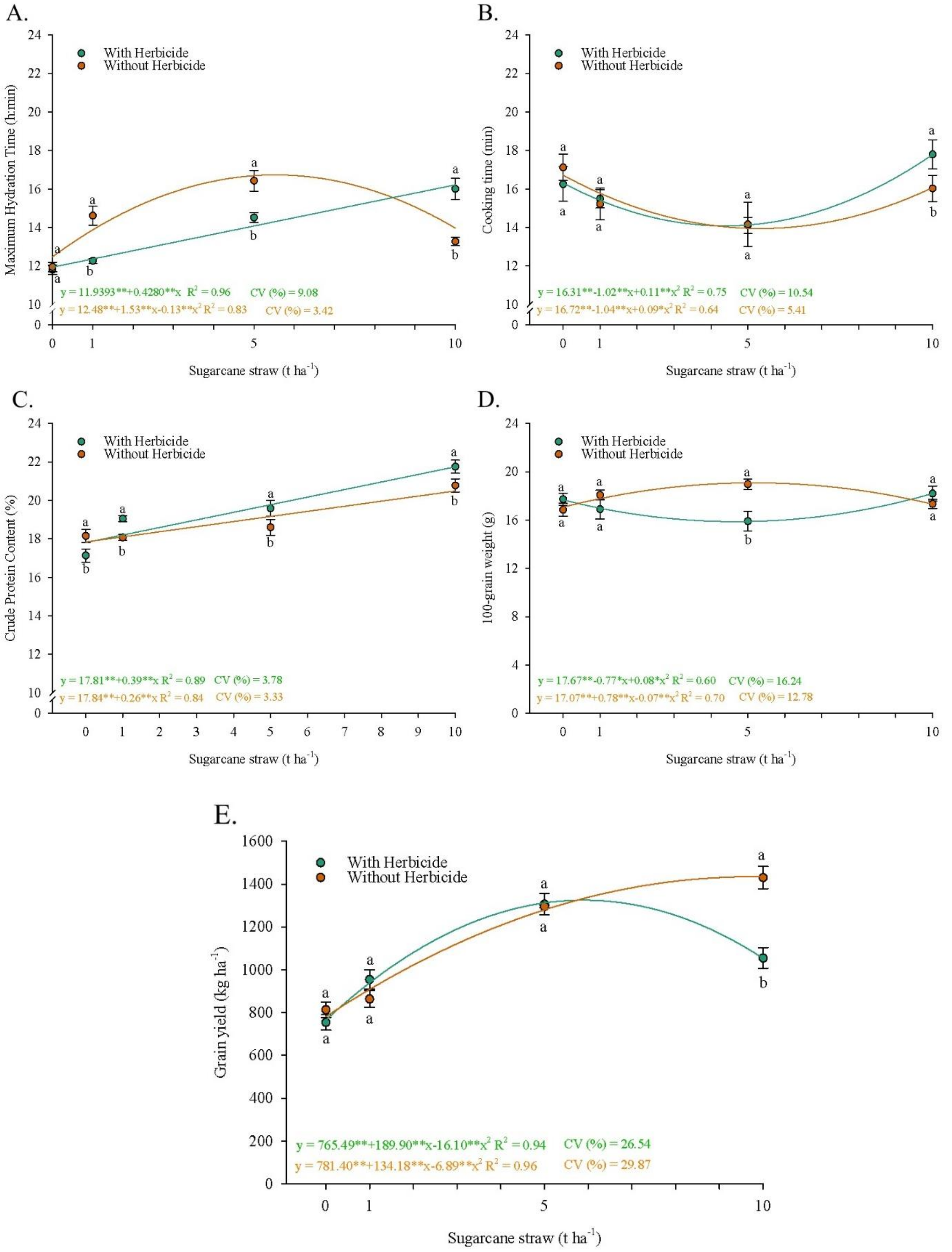
Observing the behavior of crude protein content (Figure 3C), a linear increase was noted with the increase in straw for both management practices. Although the relationship is also positive for grains without herbicide application, the rate of increase in crude protein is slightly lower compared to treatments with herbicide.

In Figure 3D, the 100-grain weight followed a slightly decreasing quadratic trend when herbicide was applied, showing a reduction of up to approximately 5 t ha^{-1} of straw, followed by an increase at higher straw quantities. In contrast, for the treatment without herbicide, the plot followed a slightly increasing quadratic trend, showing a slight increase up to around 5 t ha^{-1} of straw, followed by a small decline in values.

In the treatments with and without herbicide, grain yield (Figure 3E) exhibited a quadratic distribution, with an increasing trend up to 5 t ha^{-1} of straw, followed by a decline. This suggests that intermediate amounts of straw favor grain yield by providing more favorable growth conditions. It is noteworthy that although the initial behavior was similar for both treatments, the treatment without herbicide showed a more pronounced decline at the 10 t ha^{-1} dose. Based on the fitted quadratic models, the estimated maximum grain yield for the treatment with herbicide occurred at 5.9 t ha^{-1} of straw, while for the treatment without herbicide, the maximum was reached at 9.7 t ha^{-1}.

The grain yield values obtained in this study are slightly lower than those reported in other studies under similar management conditions (Carbonell et al., 2010; Mingotte et al., 2019; Bettiol et al., 2020). This is primarily attributed to the use of the BRS-FC104 bean cultivar, a new, very early-cycle genotype, which often results in reduced yield potential compared to medium- or late-cycle cultivars. Additionally, two frost events occurred during the experimental period, which may have negatively influenced physiological processes and final yield. Despite this, the behavior of the evaluated variables, including total dry mass, leaf area, absolute and relative growth rates, and crude protein content, showed similar trends to those described in the literature, confirming the consistency of the responses and the reliability of the observed patterns. These results suggest that in the absence of herbicide, higher levels of straw can continue to provide benefits up to a greater threshold, whereas in the presence of herbicide, the optimum straw level is reached earlier.

For the hydration ratio, no significant difference was observed. Low relationship was observed both for grains with herbicide application ($y = 1.8105 - 0.0112x + 0.0013x^2$, $R^2 = 0.4024$, CV(%) = 2.39) and for those without herbicide application ($y = 1.8422 - 0.0186x + 0.0014x^2$, $R^2 = 0.3847$, CV(%) = 7.53), as values ranged from 1.80 to 1.84.

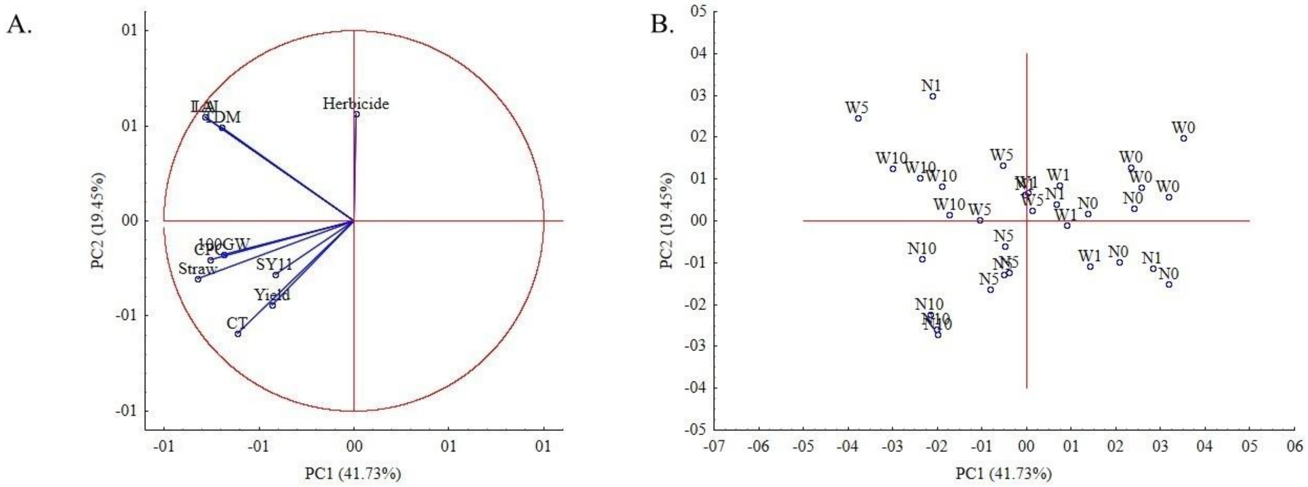


ns - Not significant; * - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$. The vertical bar represents the standard error of the mean (n = 4). Means followed by the same lowercase letter indicate no significant difference between herbicide application and no application at each, according to Tukey's test ($p \leq 0.05$)

Figure 3. Maximum hydration time (A), cooking time (B), crude protein content (C), 100-grain weight (D), and grain yield (E) of the 'BRS-FC104' common bean grown under sugarcane straw amounts, with or without Fomesafen application

In the PCA, PC1 (41.73%) loaded strongly on LA, TDM, and LAI, while PC2 (19.45%) was associated with Straw, CT, CPC, SY11, Yield, and 100GW. This pattern indicates that growth attributes and quality attributes respond only partially in tandem to the experimental factors. The variables leaf area (LA), total dry mass (TDM), and leaf area index (LAI) are highly represented by the first component, indicating a strong correlation with this axis. Conversely, the second component is primarily influenced by variables such as straw, cooking time (CT), seed yield ≥11 (SY11), crude protein content (CPC), grain yield (Yield), and 100-grain weight (100GW) (Figures 4A and B).

Among the straw quantities, it is observed that the variables LA, LAI, and TDM are more closely associated



LA – Leaf area; TDM – Total dry mass; LAI – Leaf area index; CT – Cooking time; CPC – Crude protein content; SY11 – Sieve yield; 100GW – Weight of 100 grains; W0 – With herbicide and without straw; W1 – With herbicide and 1 t ha^{-1} straw; W5 – With herbicide and 5 t ha^{-1} straw; W10 – With herbicide and 10 t ha^{-1} straw; N0 – Without herbicide and without straw; N1 – Without herbicide and 1 t ha^{-1} straw; N5 – Without herbicide and 5 t ha^{-1} straw; N10 – Without herbicide and 10 t ha^{-1} straw

Figure 4. Principal component analysis of the relationship between plant development variables and bean grain quality under different straw levels, with and without Fomesafen application

with treatments that did not receive herbicide and with straw amounts of 5 and 10 t ha^{-1}. In contrast, the quality variables of the beans (CPC, 100GW, SY11, Straw, CT, and Yield) are positioned in the quadrant corresponding to straw amounts of 5 and 10 t ha^{-1} with herbicide application.

Plants from treatments with and without herbicide at 1 t ha^{-1} of straw and without straw are located in the opposite quadrant, indicating a lower influence of these treatments on the common bean.

The qualitative performance of grains exhibits variations and behaviors that depend on the environment in which they are grown (Perina et al., 2014). For the qualitative attributes related to grain yield by sieve size, most grains are retained in the smaller sieves (11 and 12). In treatments with herbicide application, SY12 has a higher number of grains, while SY11 has a greater number when no herbicide is applied. SY12 is considered the minimum size for market acceptance (Carbonell et al., 2010).

According to our results, the total of SY≥11 grains varies from 75 to 82%, which is similar to values found in other studies, where the rates range from 67 to 89% (Carbonell et al., 2010; Mingotte et al., 2019; Bettiol et al., 2020; Leal et al., 2023). Mingotte et al. (2019) reported values ranging from 67 to 75% in their study on beans subjected to no-till planting with *Urochloa ruziziensis* straw, corn, and a mix of both. However, the authors applied top-dressing fertilization, which directly influenced grain yield, whereas the present study used only fertilization at sowing. According to Carbonell et al. (2010), for beans to meet market standards, the percentage of grains retained on sieve 12 (PRGP) should exceed 70%, since grain quality improves with larger size and better grading.

The grain hydration ratio did not show significant differences between treatments, with values generally close to 2 (ranging from 1.7 to 1.8), indicating that the grains can absorb twice their mass in water, corroborating the observations of Mingotte et al. (2020). This fact is related to the interactions between the environment in which the cultivar is grown and its genetic characteristics, where the grains did not exhibit shell hardness, which is associated with the absence of water stress and high temperatures close to harvest time (Carbonell et al., 2003).

Regarding cooking time, the grains of the BRS-FC104 cultivar were generally classified as highly susceptible to cooking, regardless of whether herbicide application was used in the no-straw cultivation. For treatments with straw, all were classified as having medium susceptibility, except for the treatment without herbicide application at 10 t ha^{-1}, where the grains showed normal resistance (21.72) (Proctor & Watts, 1987). This is an important characteristic, as cooking time and fuel scarcity influence consumers (Cichy et al., 2019).

Regarding crude protein content (CPC), the cultivar showed variations when subjected to herbicide application and straw management (Figure 4), with values ranging from 17.6 to 21.2%. The treatment with herbicide application yielded a higher CPC compared to the one without herbicide application (19.38 and 18.90%, respectively). Additionally, higher straw levels in the area were associated with higher CPC in bean grains.

In our study, the CPC values align with those found in standard cultivars (BRS Estilo and BRS Embaixador), which are the most traditional for use in fields. Moreover, the CPC obtained was similar to that observed by Perina et al. (2010), Mingotte et al. (2013), and Alves et al. (2020), ranging between 18 and 23%, indicating that genetic improvement establishes a standard, providing cultivars with desirable traits such as CPC, which is important for nutritional purposes, especially in lower-income communities.

Studies by Nunes et al. (2021) and Zeffa et al. (2020) found that CPC values are inversely proportional to grain yield, which contrasts with the findings of this study, where CPC values are directly proportional to grain yield. However, this should not be taken as a standard, as Perina et al. (2014) and Dias et al. (2021) note that bean plants exhibit low heritability for this trait (CPC), making them susceptible to the environmental dynamics in which they are grown. For example, straw is one of the factors influencing this CPC dynamic, as seen in a study by D'Amico-Damião et al. (2020), who subjected the IAC Alvorada cultivar to a no-till system with *U. ruziziensis* and *Crotalaria spectabilis*.

Grain yield is dependent on multiple factors, including the conditions in which the crop is grown. In this study, herbicide application treatments resulted in a 12% increase in grain yield compared to treatments without herbicide. Some studies (Mancuso et al., 2016; Schmitt et al., 2019) report a reduction in bean grain yield following the application of Fomesafen. However, this study observed the opposite behavior, with higher grain yield in treatments where the herbicide was applied. This result may be linked to the presence of straw, as plants in treatments with straw had higher values compared to those without straw, showing increases of 36.7, 38.06, and 50.56% for increasing straw quantities (1, 5, and 10 t ha^{-1}, respectively) compared to the control.

For all straw systems used in bean cultivation, except for conventional planting, grain yield was higher (Figure 3E). This results from the ability of herbicides to be retained when applied to sugarcane straw. As mentioned by Reddy et al. (1995), plant residues demonstrate significant sorption capacity, sometimes surpassing that of the soil. In this context, the retained compound becomes more susceptible to losses due to photodecomposition, volatilization, and/or hydrolysis triggered by rainfall. In no-till systems, herbicides reaching the soil may degrade more rapidly compared to conventional methods.

Jakelaitis et al. (2006) found that for the BRS Talismã cultivar, Fomesafen applied to corn and brachiaria straw had its effect on plant toxicity reduced compared to application in conventional systems. In no-till systems, due to the absence of soil disturbance and the preservation of straw cover, there is an increase in the surface amount of organic matter. This results in reduced temperature and moisture variations, contributing to increased microbial diversity, activity, and biomass in the soil environment. These factors enhance herbicide degradation, as evidenced by previous studies (Mueller et al., 1998). Additionally, Cobucci et al. (1998) found that high soil moisture reduced the persistence of the herbicide Fomesafen in two latosols evaluated.

Conclusions

1. The addition of sugarcane straw in fallow areas increases leaf area, total dry mass, and leaf area index of common beans.
2. Grain yield of common beans is higher in the presence of sugarcane straw and with the application of the herbicide Fomesafen.
3. The optimal response to Fomesafen application occurs at intermediate sugarcane straw amounts, particularly from 5 to 6 t ha^{-1}, while in bare soil conditions, herbicide use negatively affects plant development and yield.
4. The combined use of sugarcane straw and Fomesafen cannot be broadly recommended for improving qualitative grain attributes, as the effects varied among classes and indicators. For sieve retention, the interaction showed mixed responses: screening yield with herbicide, whereas SY11 increased without herbicide, without herbicide. Cooking time. Cooking time was reduced at intermediate sugarcane straw amounts but increased again at higher amounts, and the maximum hydration time increased under herbicide application.

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Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest: The authors declare no conflict of interest.

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