



Article

Can Fertilization Methods and Soil Management Affect Operational Efficiency and CO₂ Emissions from Fuel Consumption in Bean Cultivation?

Aldir Carpes Marques Filho ^{1,*} , Weverton Caetano Nunes ¹, Carlos Eduardo Silva Volpato ¹, Murilo Battistuzzi Martins ² , Jordan Alexis Castillo Coronado ¹ , Lucas Santos Santana ³ , Josiane Maria da Silva ³ , Vanessa Ribeiro ² and Joaquim Tenório Neto ²

¹ Agricultural Engineering Department, Federal University of Lavras (UFLA), Lavras 37200-900, MG, Brazil; wcnunes@yahoo.br (W.C.N.); volpato@ufla.br (C.E.S.V.); lubey98@hotmail.com (J.A.C.C.)

² Agronomy Department, University of Mato Grosso do Sul State (UEMS), Cassilândia 79543-899, MS, Brazil; murilo.martins@uems.br (M.B.M.); vanessaribeiro1602@gmail.com (V.R.); netotenoriojn_91@hotmail.com (J.T.N.)

³ Institute of Agricultural Sciences, Federal University of Jequitinhonha and Mucuri Valleys (UFVJM), Av. Universitária, Unai 38610-000, MG, Brazil; santana.santos@ufvjm.edu.br (L.S.S.); silva.josiane@ufvjm.edu.br (J.M.d.S.)

* Correspondence: aldir@ufla.br

Abstract

The common bean (*Phaseolus vulgaris* L.) is an important food crop in tropical agriculture. However, fertilization and soil management methods for common beans require further investigation to reduce production costs and increase sustainability. Furthermore, cultivation methods can directly affect GHG emissions. Thus, this study evaluates the CO₂ emissions from fuel consumption as a function of soil management and fertilization methods on the common bean crop. The randomized block design was used in a 2 × 3 factorial scheme with six repetitions composed of two fertilization systems (spread and furrow) and three soil management systems: conventional tillage—CT, minimum tillage—MT, and no-tillage—NT. The productive performance of common beans varies according to fertilization methods and soil management. Field capacity in the (CT) was impaired due to the various mechanized soil preparation operations with 0.30 and 0.32 ha h^{−1}, without a significant effect from the fertilization method. CT system resulted in higher CO₂ emissions of 175.74 kg ha^{−1} and 165.50 kg ha^{−1}; thus, in soil conservation management, these same values were up to 58% lower, with the lowest rates for NT. Crop yield in the MT system presented the best result compared to the CT and NT, with an appropriate cost–benefit ratio for bean production in tropical crops.

Keywords: soil tillage; soil conservation; regenerative agriculture; agriculture mechanization



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1. Introduction

Global food security is being affected by climate change, mainly subsistence crops such as common beans [1]. Therefore, studying new soil management practices and evaluating emissions from mechanized systems [2] can elevate agriculture to more sustainable levels. Brazil is one of the world's largest producers of common beans, as cultivation is possible in all seasons [3]. In tropical regions, leguminous vegetable consumption represents a great source of energy and proteins for human nutrition, ensuring greater food security and reducing malnutrition rates [4,5].

Common bean (*Phaseolus vulgaris* L.) is the essential legume for direct human food consumption [1]. In Brazil, common beans are produced mainly by small- and medium-sized farmers [6]. With the growth of cultivated areas by 0.2%, total production increased by 3.2% and productivity by 3.0% in the 2024/25 harvest [7].

Mechanized soil preparation for bean farming can have a significant impact on production costs and plant performance, as well as driving higher emissions due to increased demand for fossil fuels [8,9]. Among soil preparation methods, conventional tillage or conventional preparation promotes greater soil mobilization by incorporating surface biomass and maintenance of bare soil surface. Furthermore, this preparation method involves various equipment, which can increase fuel consumption, soil slippage, and compaction. However, the minimum tillage reduces mechanized operations, where the soil is prepared site-specific, making it more conservation-oriented [10], and the smaller number of agricultural operations with machines results in fuel savings. In the no-till systems, the soil is disturbed only in the planting furrow, keeping the soil permanently covered with mulch [11], improving the chemical, physical, and biological conditions [12], and this conservationist management provides better conditions for cultivation and can increase productivity.

Since the common bean is a crop relevant to food security and human health, soil preparation methods and fertilization management can even affect the nutritional quality of this product; therefore, it becomes imperative to evaluate the effect of these management practices in tropical soils [13,14].

Soil fertilization for bean crops occurs essentially in two ways: the first is by depositing the fertilizer directly in the planting furrow, and the second is by spreading the fertilizer on the soil surface, depending on the technology or machinery adopted. Fertilization methods can affect the productive performance of common beans [15], as these crops typically rely on symbiotic nitrogen fixation and require lower doses of chemical fertilizers during the productive cycle [16,17].

Agricultural mechanization, primarily based on combustion engines, plays a key role in soil tillage operations, but also contributes to carbon dioxide (CO₂) emissions and fuel consumption [18,19]. Despite technological advances, digital and telemetry systems capable of estimating emissions and controlling tractor operating efficiency remain limited in agriculture [20]. Therefore, fuel flow monitoring using flow meters assists in the process of monitoring agricultural operations. In this context, agricultural machinery managers can optimize fuel costs and reduce environmental impact by properly regulating parameters such as tractor power, working speed, machine age, pollutant emissions and soil moisture [21–23].

Intensive mechanization and soil management practices have a direct influence on the climate change process [24–26]. Strategies integrating productive efficiency, economic sustainability, and emission reduction have become a global priority [27].

In this context, the adoption of sustainable agricultural practices and more efficient soil management methods becomes essential to balance crop productivity with environmental impact mitigation. Therefore, this study evaluated the effects of soil management systems and fertilizer placement methods on operational efficiency, mechanization costs, fuel-related CO₂ emissions, and grain yield in common bean cultivation.

2. Materials and Methods

2.1. Site of Study

The experiment was conducted on an experimental farm at the Federal University of Lavras, Ijaci farm, Minas Gerais, Brazil. The study was conducted in the southeastern Brazil region, under the geographic coordinates of latitude 21°9'40.61" S and longitude

44°55'30.04'' W, situated at an altitude of 853 m. In this region, the climate classification is tropical type Cwa according to Köppen and Geiger, humid temperate with dry winter, with an average temperature of 20.4 °C and average annual rainfall of 1508 mm.

The soil type in the experimental plots was classified as a Typic Hapludox or a Red-Yellow Latosol [28], with clayey texture. The experimental area was previously cultivated in a conservationist tillage system with beans and corn, and the experiment was installed after the corn harvest. The area was divided into cultivation strips with 4 blocks, 6 experimental plots in each block. Each experimental unit was 20 m long and 3.3 m wide with a plot area of 66 m², and a 10 m wide path was left between the blocks to allow machine maneuvers and stabilization before starting data acquisition (Figure 1).

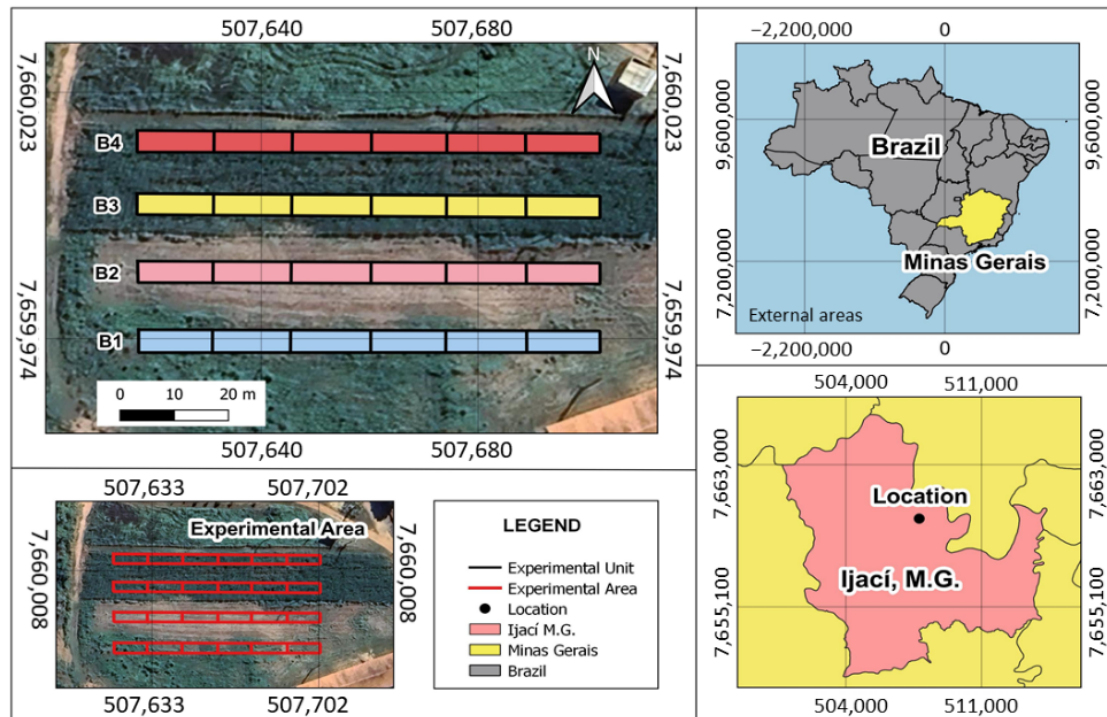


Figure 1. Experimental area location.

The experimental design was installed in a randomized block (RBD), in a 2 × 3 factorial scheme with four replications. Within each block, the six treatment combinations (two fertilization systems × three soil management systems) were randomly assigned to the experimental plots before field operations began. After establishing the experimental plots and blocks, the machines were prepared for crop establishment, and evaluations were carried out individually at each stage of the bean production cycle. The machines were instrumented with sensors, and their movement in the field was monitored by a GNSS system and a time and motion log spreadsheet.

Each experimental plot (66 m²; 20 m × 3.3 m) constituted the experimental unit for all evaluated variables. All measurements were obtained independently within each experimental plot after the machinery had reached stable operating conditions. The 10 m buffer zone between blocks was specifically established to allow equipment maneuvering and stabilization before entering the experimental plots, thereby minimizing potential edge and acceleration effects and ensuring that data collection was performed under steady-state operating conditions.

2.2. Soil and Fertilization Management

Soil management practices were carried out in two conservation systems, with straw cover, and one conventional system, with completely bare soil. Thus, the research related three soil management systems: CT—conventional tillage; MT—minimum tillage and NT—no-tillage, and two fertilization methods: total area surface (spread) and deep fertilization (furrow).

The CT treatment, represented by non-conservationist intensive management, consisted of one pass with a heavy harrow equipped with 20 disks, each 30 inches in diameter, operating at a depth of 0.20 m, followed by two passes of a soft leveling harrow featuring 44 disks, 22 inches in diameter, working at a depth of 0.10 m. The MT treatment consisted of a single pass with a scarifier operating at a 0.35 m depth with 0.06 m wingless scarifier tips. In the no-tillage (NT) treatment, the soil remained undisturbed, the beans were planted directly on the remaining corn straw area, without any type of soil disturbance. The sowing operation was identical across all treatments, employing the same seeding equipment and operating conditions.

The fertilization methods involved two ways of depositing fertilizer in the soil: the first was by broadcasting it over the entire area, and the second was by applying it deep in the sowing furrow, below the seeds, at the time of planting.

2.3. Machines and Data Collection

For all operations, the same agricultural tractor was used, equipped with a volumetric sensor device to assess fuel consumption. The traction source used was a AGCO Valtra, São Paulo, Brazil, model A950 4 × 2 tractor with front-wheel drive (TDA), engine power of 69.8 kW (95 hp) at 2300 rpm, equipped with 14.9–24 tires on the front axle and 23.1–26 on the rear axle, to pull a level and heavy harrow, scarifiers, boom sprayer and a Jumil precision fertilizer seed.

The scarifier adopted for the MT system had 7 rods, Inroda brand, São Paulo, Brazil, model LNC, with a 0.35 m depth reach. CT soil preparation used a Baldan super-heavy harrow with twenty 30-inch disks (0.76 m diameter). Soft leveling and soil uniformization before planting were done with a lightweight Tatu Marchesan, São Paulo, Brazil, model GN44 with 24, 22-inch disks (0.55 m diameter).

A Jumil, São Paulo, Brazil, model JM2680PD trailed seeder-fertilizer with 6 rows spaced 0.55 m apart and a mass of 2370 kg with a pneumatic vacuum metering mechanism for seed distribution was used for planting. The seeder-fertilizer was adjusted to distribute approximately 255,000 seeds per hectare. In furrow, the fertilizer Fertipar, Varginha, Minas Gerais, type NPK 8-28-16 was used at 400 kg ha⁻¹.

The fertilizer broadcasting was performed using the manual topdressing system under conditions proportional to the recommended dose and application rate for each experimental plot. For topdressing, the fertilizer Fertipar, Varginha, Minas Gerais, type NPK 30-0-20 was used at a dosage of 400 kg ha⁻¹. Fertilization recommendations followed the technical models traditionally adopted by local farmers based on soil correction manuals for the tropical region.

All crop protection management, including herbicides and pesticides, was carried out across the entire area, uniformly applied over all experimental plots. Herbicide applications were carried out in all samples equally, using a KO, São Paulo, Brazil, model KO brand sprayer, which has a 600 L tank, a mass of 460 kg and a 12 m bar with 26 nozzles.

In all mechanized farming operations, data on machine times and movements, as well as information related to fuel consumption, were acquired.

Carbon dioxide emissions were assessed solely based on fuel consumption, excluding CO₂ flux from the soil, N₂O emissions, emissions from fertilizer manufacturing, and carbon

sequestration. The tractor that performed the field operations was instrumented with two mechanical flow meters at the engine's fuel inlet and outlet.

Fuel consumption was recorded by means of an electromechanical flowmeter through electrical pulses that were transformed into mL s^{-1} by the digital flowmeter and sent to the display where the value of the plot was recorded and after the value was noted, it was reset. The recorded data were converted into liters per hour, based on the flowmeters, the density of the diesel oil (0.84 g mL^{-1}) and the consumption time per plot. To achieve effective field capacity, operational fuel consumption and the fuel consumption per hectare of beans produced, Equations (1)–(3) are presented.

$$Efc = \frac{Atr}{\Delta t * 0.36} \quad (1)$$

where Efc = Effective field capacity (ha h^{-1}); Atr = Useful area plot (m^2); Δt = Time spent traveling (s), 0.36 = Constant Conversion ($\text{m}^2 \text{ s}^{-1}$ to ha h^{-1}).

$$OFC = \frac{Ch}{Efc} \quad (2)$$

where OFC = Operational fuel consumption (L ha^{-1}); Ch = Volumetric consumption (L h^{-1})

$$Ct = \frac{OFC}{P} \quad (3)$$

where Ct = Fuel consumption per unit of grain produced (L kg^{-1}); P = Grain yield (kg ha^{-1}).

To determine the tractor operating efficiency (Eot), we adopted Equation (4).

$$Eot = \frac{Tp}{Tt} * 100 \quad (4)$$

where Eot = Machine efficiency (%); Tp = Productive time (h); Tt = Total time (h).

To determine fuel costs, we applied Equation (5).

$$C = Cca * Pc \quad (5)$$

where C = Fuel cost area (USD ha^{-1}); Cca = Consumption per area (L ha^{-1}); Pc = Fuel price (USD L^{-1}).

In addition to fuel consumption and working time assessments, a study of tractor slippage on different surfaces was conducted, depending on soil management, with and without straw cover (CT, MT and NT). Tractor slippage was determined using the ratio between the average times recorded with load and the average time recorded without load for each condition studied. The times with load and without load were obtained by digital stopwatch, obeying the same gear and engine speed conditions. Tractor slippage was calculated according to Equation (6).

$$P = \frac{Tsc}{Tcc} * 100 \quad (6)$$

where P = Slippage (%); Tsc = Average time spent to travel the length of the plot without load, in s; Tcc = Average time spent to travel the length of the plot with load, in s.

2.4. Operational Costs

The operational cost was defined as the sum of resources to produce a given product in a certain period. The cost of implementing the crop was used as a theoretical basis in this analysis. The prices of the machines and implements used in this study were collected

in the southern region of Minas Gerais in July 2024 and dollarized, considering each dollar (USD \$1.00) equivalent to BRL \$5.45 Brazilian Real (in March 2026). The economic analysis calculations and operational costs were made in accordance with [29].

The tractor's energy performance was assessed by estimating the carbon dioxide (CO₂) emissions generated during field operations. Emissions were calculated based on the fuel consumption, considering a conversion factor of 3.76 kg CO₂ per liter of diesel consumed in each operation. This ratio represents the amount of CO₂ emitted by the combustion of diesel fuel, as reported by Manzone and Calvo [30] and Šarauskis et al. [31].

2.5. Data Analysis

The data processing was developed according to each research stage, which involved theoretical cost analyses, assessments of machine consumption and emissions in the field.

Statistical analysis of machines performance and fuel consumption was applied in the Shapiro–Wilk test to assess data normality, followed by Levene's test to verify variances homogeneity. Mean and normality tests were initially applied to assess tractor slippage. This procedure was adopted to isolate this variable from fuel consumption costs. Upon identifying significant differences through analysis of variance (ANOVA), Tukey's post hoc test was employed at a 5% significance level. Descriptive statistics were used to evaluate bean yield data. All statistical procedures were conducted using Minitab v.16 and SISVAR v.6.6 software.

3. Results and Discussion

3.1. Machines Performance

The effective field capacity is defined as an indicator of the actual performance of agricultural machinery during field operations, being directly influenced by working speed and implement width, while considering the area of soil effectively mobilized by the equipment [32,33].

Our results showed that the greater the mechanization intensity, the lower the effective field capacity. This is due to the need for numerous mechanized operations with periods of downtime and overlaps. This lost time generates additional costs for the production process. The highest operational capabilities were achieved in NT, followed by MT and CT (Figure 2). These results are attributed to the fact that this system requires fewer mechanized operations, allowing higher travel speeds and greater operational efficiency. Furthermore, these findings are consistent with [34], who reported that tractor operating speed directly affects effective field capacity and that increases in speed reduce total field working time.

Conventional tillage (CT) showed the lowest field capacities (0.30 and 0.32 ha h⁻¹ for spread and furrow, respectively), due to the higher degree of soil mobilization, which increases resistance to forward movement and reduces tractor operational speed [35,36]. Minimum tillage (MT) presented intermediate values (0.48 and 0.51 ha h⁻¹), reflecting a balance between soil conservation and operational efficiency. Analysis of variance for field capacity revealed significant differences among soil preparation systems, but no differences between fertilization methods. The coefficient of variation was 7.95%, a value considered acceptable in field experiments according to Gordón-Mendoza and Camargo-Buitrago [37], indicating satisfactory experimental precision. Overall, the higher values observed under no-tillage indicate greater efficiency in time and fuel use, factors that directly contribute to reducing operational costs and enhancing the economic and environmental sustainability of common bean cultivation.

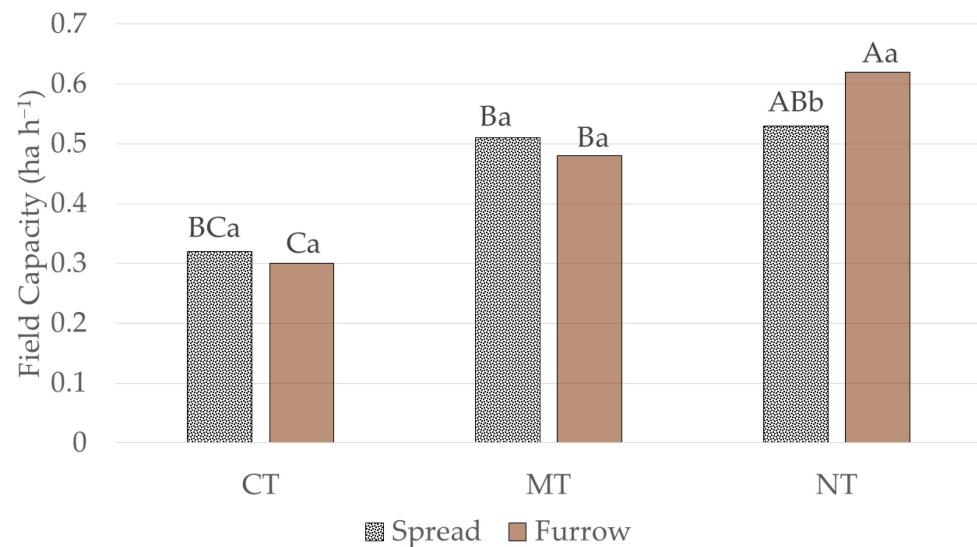


Figure 2. Field capacity in three soil preparation systems and two fertilization methods. The means followed by the same uppercase letter for soil management (CT, MT and NT) and the same lowercase letter to fertilization mode (inter soil management) do not differ from each other at a 5% probability level, according to the Tukey test. C.V. (%) = 7.95%.

Direct slippage results are important for determining the tractor's suitability for fertilizer applications and soil preparation methods. Because soil surface area can reduce traffic and traction efficiency, this result may indicate an isolated parameter in the discussion of other cost and operational efficiency variables. Slippage is influenced by the load applied to the ground and the effectiveness of tractor operations and is important information as it provides guidance on how to optimize tractor use within the limits of slippage in specific agricultural conditions [38]. Our results clearly show that slippage was controlled for all treatments, without significantly affecting total machinery costs or fuel consumption.

In Table 1, the slippage ANOVA showed that there was no difference between the treatments and the systems, with a 17.23% coefficient of variation. Wheel slip should not exceed 15–16%, which lowers field performance and increases the soil structure disruption [39]. Although there was no statistical difference between the treatments, it was observed that in the no-tillage system (NT), there was an increase in slippage, which can be attributed to the increase in traction resistance in the wheel movement [40], because the straw on the ground undergoes deformation and increases the tire's contact on the ground.

Table 1. Wheel slip under three soil management systems and two fertilization methods.

Soil Management	Spread Fertilizer	Furrow Fertilizer
CT	7.50 Aa	6.75 Aa
MT	7.55 Aa	7.50 Aa
NT	7.75 Aa	7.55 Aa
Overall average	7.60	7.27

Averages followed by the same capital letter in the column and the same lowercase letter in the row do not differ from each other, at 5% probability, by the Tukey test—C.V. (%) = 17.23.

In contrast, other research shows that conventional soil preparation can increase slippage by up to 17% compared to direct planting [41]. Furlani et al. [36] observed a decrease in slippage with increasing speed, when evaluating the performance of a seeder-fertilizer in the direct planting system.

3.2. Mechanization Costs and CO₂ Emissions

The individual average costs for crop management are described in Table 2. Among the total costs, sowing operations represent a significant portion, followed by tractor and labor costs. These costs are significant in bean crop management, and reduced mechanized activities, as in the NT and MT systems, can increase the economic efficiency of the production process.

Table 2. Hourly costs calculated for tractors and implements in (USD h⁻¹). CD = Depreciation cost; CJ = Interest cost; CA and CS = Accommodation cost and insurance cost; CMO = Labor cost; CM = Maintenance cost and FC = Fuel cost.

	CD	CJ	CA and CS	CMO	CM	FC
Agricultural Tractor	3.6	1.32	1.2	4.71	4.42	14.66
Heavy Harrow	1.07	0.27	0.12	0.25	1.72	
Soft Harrow	1.78	0.46	0.21	0.29	2.75	
Spreader	1.24	0.45	0.20	0.07	1.98	
Sprayer	1.31	0.48	0.22	0.27	2.28	
Sow	4.16	1.52	0.69	0.43	6.82	

Seeding represents a significant portion of crop production costs, due to the cost of essential inputs such as seeds and fertilizers. Furthermore, operational yield is relatively low due to slow operating speeds and lower effective field capacity. According to [42,43] the increase in the cost of operations related to machine maintenance, therefore carrying out an analysis of the factors associated with failures can help in determining maintenance, influencing operational costs.

There was a significant difference in CO₂ emissions for the soil preparation systems, but there was no difference between the soil fertilization methods (Figure 3). The coefficient variation was 7.95%, with a significant difference observed between the three preparation systems. Conventional tillage (CT) presented the highest CO₂ emissions, followed by minimum tillage (MT) and no-till (NT), respectively.

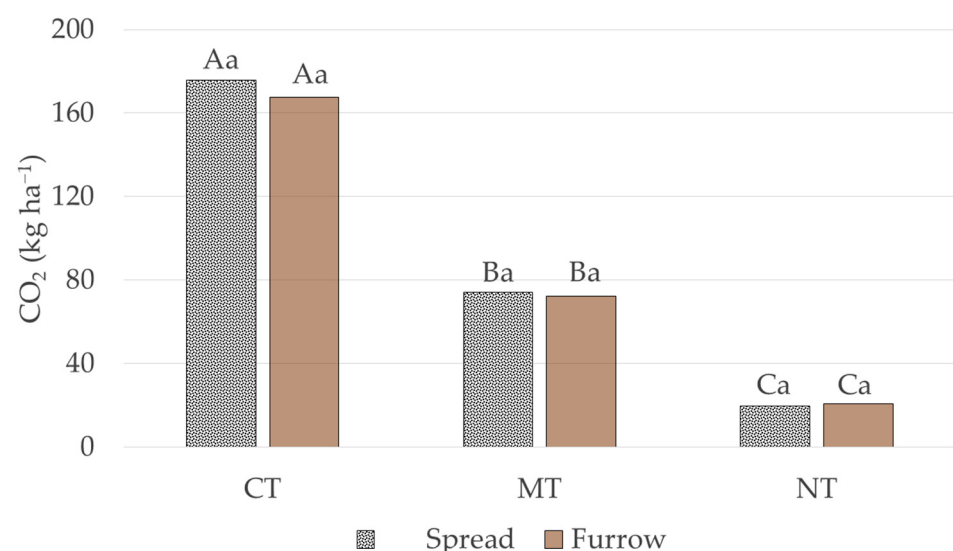


Figure 3. CO₂ emissions in three soil preparation systems and two fertilization methods. The means followed by the same uppercase letter for soil management (CT, MT and NT) and the same lowercase letter to fertilization mode (inter soil management) do not differ from each other at a 5% probability level, according to the Tukey test. C.V. (%) = 7.95.

Conventional tillage (CT) requires greater agricultural operations for the crop process, resulting in higher CO₂ emissions of 175.74 and 165.50 kg ha⁻¹ in spread and furrow, since carbon dioxide CO₂ emissions are closely linked to fuel consumption [18]. Depending on agricultural practices and soil properties, different implements are used for soil preparation, and fuel consumption rates may vary. When implementing combined soil preparation, hourly fuel consumption increases compared to conservation systems such as reduced tillage and no-tillage [9,44]. Key factors influencing emissions and fuel consumption include the shape of the areas and the routes followed by the machines, as these influence the emissions model and energy demand of mechanized systems [2].

Conservation tillage (MT) by minimizing soil preparation operations for sowing provided 74.1 in spread and 72.4 kg CO₂ ha⁻¹ in furrow (Figure 3), providing a reduction in emissions of up to 58%, but this reduction may be even higher, corroborating with [45], who found that investigating productivity performance and CO₂ emissions under different sowing practices resulted in a reduction of 137.4 kg CO₂ ha⁻¹ in conservation tillage (straw) compared to cultivation without straw, resulting in a 71.4% reduction in CO₂ emissions. Naturally, if energy consumption falls, and soil management preserves carbon and reduces fuel demand, the efficiency of production systems will increase and costs can be minimized.

No-till (NT), by eliminating soil disturbance and the mechanized operations associated with land preparation, exhibited the lowest CO₂ emissions, with values of 19.6 and 20.7 kg CO₂ ha⁻¹ for broadcast and furrow planting, respectively. Overall, these results highlight the potential of no-tillage systems to substantially reduce CO₂ emissions compared with more intensive tillage practices [45]. Consequently, the reduction in energy demand and machinery use associated with soil management contributes to lower fuel consumption, improved carbon conservation, and enhanced production efficiency.

The costs in CT were 2.34 times higher than in MT, and 8.51 times higher than in NT (Figure 4). This resulted in a higher operational cost for CT when compared to MT and NT. It can be observed that, in general, all costs were higher in CT, in relation to MT and NT, respectively. Hourly fuel consumption is an essential factor that must be analyzed, being a direct variable that influences the total costs of mechanized activities [46].

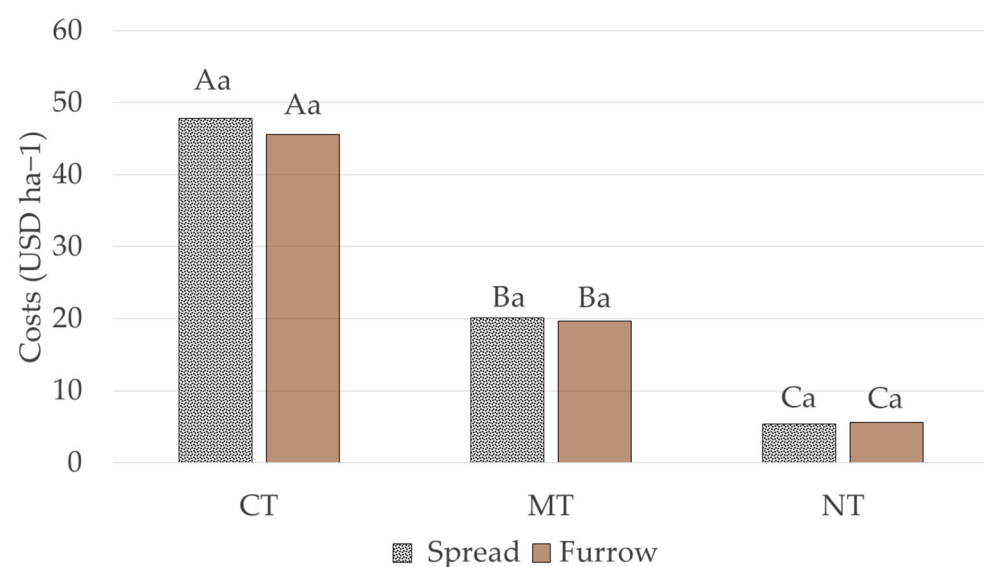


Figure 4. Costs of mechanized production in three soil preparation systems and two fertilization methods. Means followed by the same uppercase letter for soil management (CT, MT and NT) and the same lowercase letter to fertilization mode (within each soil management system) do not differ significantly at the 5% probability level according to Tukey's test. C.V. (%) = 7.95.

Conservation soil management can reduce fuel consumption, CO₂ emissions, time required for field preparation, and the overall production cost compared to conventional tillage systems [31,47]. However, the fertilization method, even though it subtly affected emissions and energy consumption, due to the load demand imposed by furrowing elements in the soil during the deposition of fertilizer in depth, did not present a significant difference in costs and emissions.

Recent research on soil preparation has evaluated CO₂ emissions close to 79.7 and 84.2 kg ha⁻¹, where fields with greater time efficiency, with more elongated shapes and requiring fewer maneuvers, showed a 5.5% reduction in consumption and emissions [2]. Future research may be promising by integrating studies of the relationship between area shape and soil management type to seek more efficient ways of managing mechanization. There is a bidirectional causality between mechanization and emissions: mechanization generates more carbon, but increased emissions also put pressure on technological innovation [48] and warn that it is highly dangerous for biodiversity [27].

3.3. Crop Yield

A significant difference in bean crop yield was observed between the three preparation systems, with MT presenting average production values higher than those observed in NT. On average, MT provided a superiority of 7.55% and 39.83% in relation to CT and NT, respectively (Figure 5).

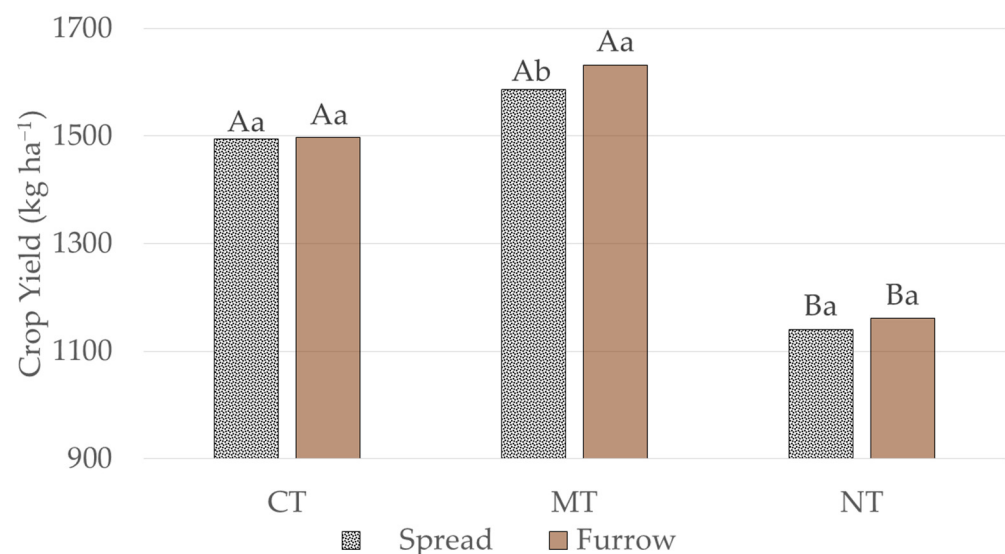


Figure 5. Bean crop yield in three soil preparation systems and two fertilization methods. The means followed by the same uppercase letter for soil management (CT, MT and NT) and the same lowercase letter to fertilization mode (inter soil management) do not differ from each other at a 5% probability level, according to the Tukey test. C.V. (%) = 17.23.

The highest productivity was observed in minimum tillage (MT) with furrow, as mechanical scarification breaks the surface layers of compacted soil, improving soil physical conditions for better development of the root system and improving the efficiency of soil exploration by the roots, which has a direct effect on the transport of nutrients and water from the roots to the aerial part of the plants, increasing photosynthesis and photoassimilates transport to the grains, leading to better grain filling and optimizing productivity [49,50].

The no-tillage system (NT) resulted in lower bean productivity for both fertilization methods (1141 and 1161 kg ha⁻¹, respectively), which may be associated with compaction of the topsoil due to lack of tillage. This effect can occur due to intense machine traffic, especially with low volumes of straw on the soil. In addition, the literature research shows

that this compaction in the topsoil can impair the soil profile, the development of taproots and secondary roots at depth, and reduce water and nutrient absorption, leading to limited development and productivity of economically important crops such as beans [51,52].

Regarding cost, no-tillage (NT) management promoted the lowest cost compared to other treatments. The no-tillage has shown advantages from an economic perspective, as there is a reduction in energy expenditure in soil preparation and thus becomes a viable alternative to cultivation in relation to other soil preparations [53].

Although no-till farming (NT) has resulted in lower productivity, this system provides several other advantages that can be beneficial for adoption in bean cultivation, as this planting model disturbs the soil only in the planting furrow, keeping the soil permanently covered, contributing to soil protection, reducing the risk of soil erosion, minimizing compaction when there is a high volume of straw, acting as a barrier to direct tire soil contact and enriching the soil with organic matter through the CO₂ sequestration process [11,54–56].

Rivero-Herrada et al. [57] reported no differences in the grain yield of beans cultivated under no-tillage and conventional systems. However, Ghimirey et al. [58] observed higher yields under the conventional system, while Hernández-Escobar et al. [59] reported greater bean productivity under the no-tillage system when intercropped with maize. In the present study, crop yield showed no significant differences to fertilization in spread and furrow soil management, consistent with the findings of Martins et al. [60].

Mechanization is a key factor in strengthening food security and modern agricultural development, but it must be accompanied by supportive policies and technological innovation. Furthermore, mechanization can reduce operational costs and improve agricultural competitiveness [23,61]. Our study shows that, in addition to representing operational costs, mechanized systems can also promote greater productivity, but the financial balance between production costs and crop yields treats with advantage conservation systems such as NT and MT.

The alternation of different agricultural species in the same field and the constant maintenance of vegetation cover promote improvements in soil fertility, in addition to breaking pest cycles through greater biological diversity. This causes an increase in organic matter, reduces erosion, and fixes more nitrogen in the soil [12]. Our results showed that, in addition to the benefits already described for soil carrying capacity, conservation management can mitigate emissions and reduce the production costs of bean crops.

Furthermore, investing in machines and systems powered by clean and sustainable energy can promote the benefits that the high operational efficiency of mechanization demonstrates, while maintaining severely reduced emission levels [48]. Integrating decision-support tools such as georeferenced data, agricultural machinery telemetry, spatial analysis and soil condition mapping, and other available agricultural technologies are also indispensable factors in providing a balance between sustainable production and the rational use of agricultural machinery, representing an important direction for future research.

4. Conclusions

The productive performance of common beans varies according to fertilization methods and soil management. The production model and mechanized operations have a direct impact on crop production efficiency, highlighting soil preparation as the most influential factor in production costs and fuel-related CO₂ emissions from mechanized field operations. The main findings of this research are summarized as follows:

- (1) Field capacity in the conventional soil management system (CT) was impaired due to the various mechanized soil preparation operations, without a significant effect from the fertilization method.

- (2) Conventional tillage (CT) resulted in higher fuel-related CO₂ emissions from mechanized field operations of 175.74 kg ha⁻¹ in spread fertilization and 165.50 kg ha⁻¹ in furrow fertilization. In soil conservation management, these same values were up to 58% lower, with the lowest rates for NT.
- (3) Yield responses varied across systems, with minimum tillage (MT) showing the most balanced performance in terms of productivity compared to CT and NT, indicating a more stable agronomic response under the evaluated conditions.
- (4) Overall, the adoption of soil management strategies significantly affects both economic and environmental outcomes. Among the evaluated systems, minimum tillage (MT) emerged as the most balanced alternative, optimizing productivity while reducing production costs and environmental impacts under tropical conditions.

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