

Evaluation of tillage method and planting density in a rice (*Oryza sativa L.*) cultivation

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Abstract: Enhancing the productivity of rice (*Oryza sativa L.*) cultivation in the municipality of Palermo, Huila, is an imperative necessity. Tillage methods and planting density are factors that can significantly influence production costs. This underscores the need to identify more efficient and sustainable agricultural practices that can increase production without substantially raising costs for local farmers. The primary objective of this study is to analyse the impact of different tillage methods and planting densities on rice production. A 2×2 factorial experimental design was implemented over an area of two hectares, divided into plots subjected to conventional tillage (three passes with a harrow) and minimum tillage (one pass with a harrow and one pass with a chisel), using planting densities of 100 kg ha⁻¹ and 150 kg ha⁻¹. The monitoring process included the phenological evaluation of the crop, from germination to harvest. The results indicate that a planting density of 150 kg ha⁻¹ in combination with minimum tillage (LM150) exhibited a higher number of tillers per square metre (1192) and achieved the greatest height during the maximum tillering stage (82 cm). The analysis of variance (ANOVA) confirms significant differences between treatments, particularly during the tillering phase and at harvest maturity. It is concluded that minimum tillage with higher planting density can significantly improve yields, offering a promising strategy for local farmers. To support decision making, it is recommended that a detailed techno-economic assessment be conducted-comparing specifically input costs, labor requirements, and net profitability between high- and low-density treatments under both tillage systems-in order to determine the most profitable and sustainable approach to rice cultivation in the region.

Keywords: rice cultivation, planting density, phenology, agronomy

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1 Introduction

The increase in population leads to a greater demand for food. The Food and Agriculture Organization (FAO) of the United Nations (UN) projected that by 2050, it would be necessary to increase food production by 70%, and in developing countries, production should double (Schifter and

González, 2022). Rice is one of the most important staple food crops, feeding more than half of the world's population (Yuan et al., 2017). By 2024, it is projected that rice production in Colombia could exceed 3 million tonnes (Sectorial, 2023). Historically, Huila has been one of the departments with the highest contribution to rice production in

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Colombia (Tocagón Villagrán, 2022). Efforts have been made to improve the productivity and profitability of rice cultivation in El Juncal, a village in the municipality of Palermo, considering factors such as soil analysis, the nutritional requirements of rice varieties, and the climatic characteristics of the area (DISAN, 2024). This project aims to provide the obtained information to the general community, especially to the local farmers of the Association of Users of the Medium-Scale Land Adaptation District of El Juncal (ASOJUNCAL), so that they understand how different planting densities and appropriate land preparation can achieve higher production and yield of rice crops, without the need for many agricultural tools and implements, saving time and money in the preparation and planting tasks.

An appropriate soil structure is fundamental for improving soil fertility and increasing agricultural productivity (Bronick and Lal, 2005). Soil degradation over time reduces its production capacity (Wang, 2022); compacted soils reduce crop yields as they hinder root penetration, water infiltration, and gas exchange, directly affecting growth and production (Masola, 2020). Efforts to reduce soil compaction should not only focus on using less aggressive implements but also on minimising machinery passes over agricultural land (Gómez-Calderón et al., 2018). Minimum tillage aims to combine mechanisation tools with the characteristics of zero tillage (Porrás et al., 2022), as the latter maintains permanent crop cover, replenishes the soil with residues and stubble, and improves carbon sequestration and soil absorption capacity (Hassan et al., 2022).

In the study by Villalobos et al. (2009), different types of tillage were evaluated using various implements and depths: T1 traditional: disc plough (25 cm), mechanical hoe or spade (30 cm), and subsoiler (65 cm); T2: vibro plough (25 cm), chisel plough (35 cm), and mechanical hoe or spade (30 cm). They concluded that the highest production in both cases was achieved with spade tillage; additionally, the chisel plough had the lowest

production. It is important to note that the study did not consider potential future soil loss or degradation (Villalobos et al., 2009). In the study by Briceño and Álvarez (2010), the method of soil preparation and rice planting was compared using T1: minimum tillage seeder on dry soil with a Vence Tudo TSM 22000 seeder, 100 kg ha⁻¹ of dry seed, and a planting depth of 2-3 cm, with rows spaced 17 cm apart and a planting width of 3.60 m. T2: the soil was prepared using the puddling method, applying one pass of a heavy harrow and three passes of a light harrow, the field was flooded, two passes of a rotovator were performed, and the area was drained before planting in saturated soil using an agricultural aircraft, applying 150 kg ha⁻¹ of seed. Both plots used the Fedearroz 50 variety. Sampling of the vegetative, reproductive, and maturation periods of the rice was conducted in each plot. The results showed that the minimum tillage method was superior in terms of production, profitability, and sustainability compared to the puddling method, yielding a cost/benefit ratio 75% lower than puddling, and saving 37.06% in soil preparation and planting tasks. The evaluation of the vegetative period determined that in minimum tillage, the plants were taller, with more tillers per plant and more leaves per tiller, and similarly produced more panicles, resulting in a 13.06% higher grain yield (Briceño and Álvarez, 2010).

On the other hand, depending on the variety of rice seed, a certain amount per hectare is recommended for planting (Kamai et al., 2020). However, farmers often resort to planting larger quantities, thereby increasing production costs and potentially affecting crop yield, causing economic losses for the producer (Farooq et al., 2011). In rice cultivation, a low planting density can cause extra tiller generation, resulting in unsynchronised grain maturation and possibly lower yield (TRAXCO, 2017). Conversely, a too high density can lead to issues such as stem rot and grain calcification, negatively impacting quality and yield (Fahad et al., 2018). It can also result in intense competition among plants for resources like light, water, and nutrients,

leading to slower growth and increased lodging, which reduces yield due to plant stress (Arias-Badilla et al., 2020). Additionally, higher density can make rice crops more susceptible to diseases and pests, as ventilation is reduced and humidity may be higher, creating a favourable environment for their development (Pangga et al., 2013).

This raises the question: How does primary tillage preparation and the management of different planting densities influence the rice crop production? This project aimed to evaluate the effect on rice crop yield (*Oryza sativa* L.) through four treatments in a 2×2 factorial arrangement, involving two primary tillage managements and two different planting densities, conducted over a two-hectare area at the University of Surcolombiana Farm.

2 Materials and methods

The University of Surcolombiana has an experimental farm located in the municipality of Palermo-Huila, San Miguel village, 9 kilometres from the main campus, specifically at coordinates N $2^{\circ}53'9.12''$, W $75^{\circ}18'26.09''$. For the development of the research, an area of 2 hectares was allocated for the planting of certified Fedearroz 2020 seeds to study rice cultivation through four treatments in a 2×2 factorial arrangement, involving two primary tillage managements and two different planting densities. The field was divided into two plots: the first plot

received the conventional treatment T1: three cross passes of a harrow; and the second plot received the minimum tillage treatment T2: one pass of a harrow and one pass of a chisel plough. For land preparation, the entire field was micro-levelled (land plane) and ridged with a bund. Additionally, fertilisation, pest, disease, and weed control were applied according to the agronomist's specifications. Once the soil was adequately prepared according to topographic parameters, irrigation type, and conditioned for cultivation, planting densities of 100 and 150 kg ha⁻¹ were sown. Therefore, the treatments were designated as follows: T1 with a planting density of 100 kg ha⁻¹ is identified as (LC100), T1 with a planting density of 150 kg ha⁻¹ is identified as (LC150); T2 with a planting density of 100 kg ha⁻¹ is identified as (LM100), T2 with a planting density of 150 kg ha⁻¹ is identified as (LM150).

For the statistical analysis of soil samples, each plot was divided into three blocks, and three samples were collected from each block to obtain sufficient random data. The work area is presented in Figure 1. For sampling, the conditioned Latin hypercube method was used, aiming to obtain data that would allow spatial predictions of the properties over the area. Thus, using QGIS® and RStudio® (open-source software), three randomly distributed sampling points were established in each sub-block (Figure 2), resulting in 36 samples being taken.

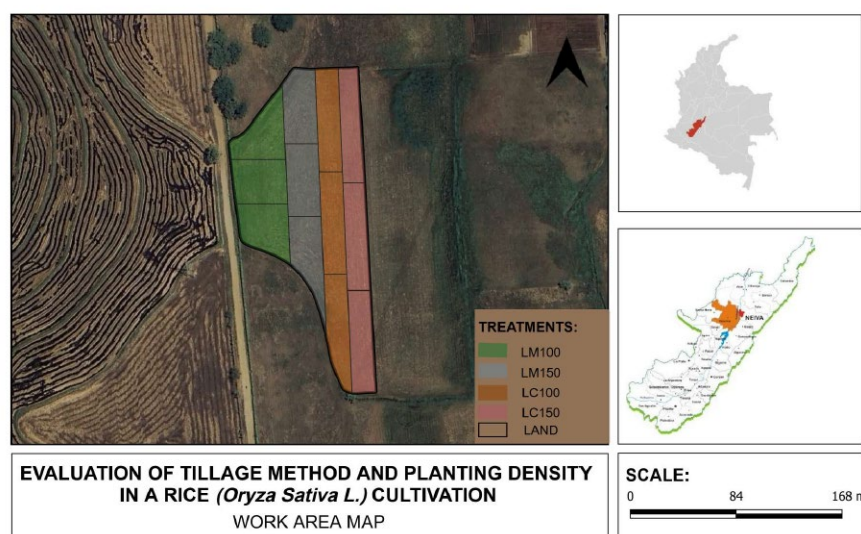


Figure 1 Location of work area

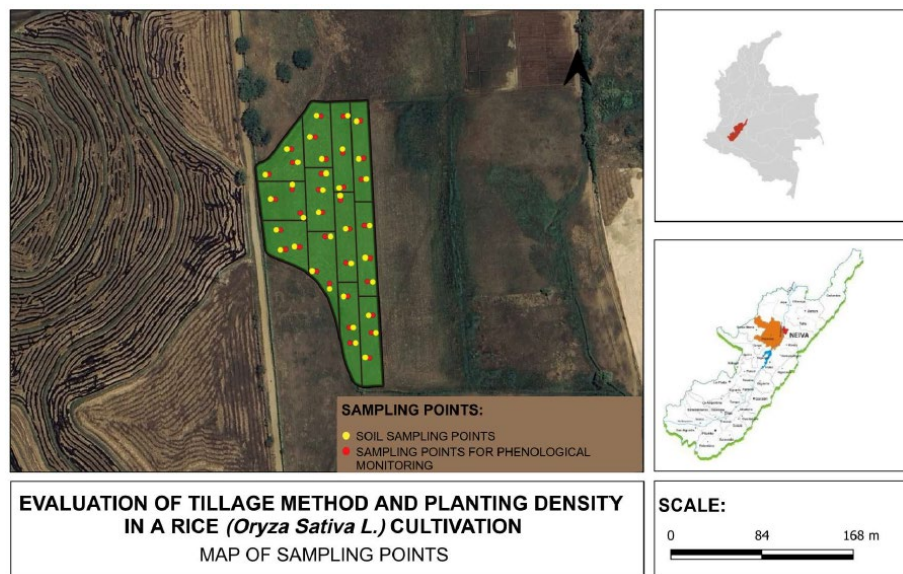


Figure 2 Map of sampling points

2.1 Vegetative and productive monitoring

In order to have a better analysis of the development of the crop, different measurements were made throughout the season, using a "50 cm×50 cm" gauging device (Figure 3) which was placed on the ground with a location flag. For the establishment

of the location of the gauges, the conditioned Latin hypercube method was used again, using QGIS® y RStudio® to ensure randomly distributed sampling points in each sub-block, therefore, 18 gauges were fixed, the location of which can be seen in Figure 2.



Figure 3 Gauge frame located at sampling point

Development monitoring was carried out following the steps recommended by Fedearroz:

(1) The first sampling was taken after a period of 8 to 10 days after germination (dag) of the rice, in this control a count of the initial population of plants was made in each of the plots.

(2) The second measurement was made during 25 and 30 dag, counting the tillers of the whole gauging and measuring the height of the aerial part of three random plants from the base to the highest leaf.

(3) In the course of 35 and 38 dag, there was maximum tillering and the beginning of flower primordium, therefore, a tillering count of the whole gauger was made and, again, the height was measured.

(4) At maximum fruit set (70-75 dag), the tillers were counted again in the whole gauging unit and the height of the plants was measured for each sub-block.

(5) Then, at flowering (85-90 dag), the panicle count was carried out in the whole gauging unit. At

this stage no heights were measured so as not to mistreat the plants loaded with grains in order to avoid an increase in natural losses.

(6) Finally, at harvest maturity (105-110 dag), panicles were counted again in the whole gauger, and plant height was measured again, this time up to the last grain. This time the entire 50×50 frame was cut. All the panicles were shelled. Full kernels were separated from empty kernels. The full kernels were set aside to remove 1000 kernels and the weight of these 1000 kernels was taken.

For the harvesting process, the ASOJUNCAL's Massey Ferguson combine harvester was used, and for the purposes of optimising this process it had to be correctly calibrated. This procedure was of utmost importance to validate the productivity analysis by corroborating the resulting grain count per cultivated plot.

2.2 Fertilisation and phytosanitary management

During rice cultivation, fertilisation and phytosanitary pest management were carried out following the instructions of the project's agronomist advisor, assigned by the Surcolombiana University farm.

2.3 Statistical analysis

Once the results of the physical studies and the productivity of the crop were obtained, they were processed and analysed by means of a Shapiro-Wilk statistical study to determine the normality of the samples and subsequently an Analysis of Variance (ANOVA) was carried out, thus performing a global test to determine if there are significant differences between the samples, and with Fisher's Least

Significant Difference (LSD) statistical method the effect of this experimental study is identified and quantified, managing to find the existence or not of significant differences in each of the parameters analysed by pairs of various groups of samples, where the confidence interval was 95%.

The decision to use 36 samples—derived from 3 blocks, 3 sub-samples per block, and 4 treatments—was based on spatial representatively and resource availability. This sampling structure ensured adequate coverage of the experimental area while maintaining operational feasibility. Additionally, the sample size was sufficient to detect moderate treatment effects with a 95% confidence level, as confirmed by the statistical power observed in the ANOVA results.

3 Results and discussion

3.1 Evaluation of phenological monitoring

During the research, different periods of the crop were studied to analyse the phenological progress, taking into account the variables of initial population, tillers and panicles, as well as the data on plant and panicle heights.

3.1.1 Initial population

The initial population of rice seedlings (plants m⁻²) was evaluated 10 days after germination (DAG). The results showed a clear influence of planting density on germination rates. Treatments with higher seed density (150 kg ha⁻¹) consistently produced more seedlings per square meter than those with lower density (100 kg ha⁻¹), as shown in Table 1.

Table 1 Average initial population per treatment

Treatment	LM100	LM150	LC150	LC100
Plants m ⁻²	176	233	258	149

To statistically validate these differences, a one-way ANOVA was performed. The data met the assumption of normality according to the Shapiro-Wilk test ($p > 0.05$ for all treatments), and the variances were reasonably homogeneous across groups. The ANOVA revealed significant differences between treatments ($p = 0.00013 < 0.05$), with a

mean square error (MSE) of 3684.33 and a total sum of squares (SST) of 185615.56. The effect size (η^2) was calculated as: $SS_{\text{Between}}/SS_{\text{Total}} \approx 0.365$. This indicates that 36.5% of the variability in initial population is explained by the treatment effects (tillage type and seed density), which is considered a moderate to large effect.

Post-hoc analysis using Fisher's LSD test confirmed significant pairwise differences between LM100–LM150 ($\Delta = 57$), LM100–LC150 ($\Delta = 82$), LM150–LC100 ($\Delta = 84$), and LC150–LC100 ($\Delta = 108$), all exceeding the LSD threshold of 58.28. In contrast, comparisons between treatments with the same planting density (LM100–LC100 and LM150–LC150) showed no significant differences, reinforcing that planting density is the primary driver of initial population, rather than tillage method.

According to the Fedearroz Technical Guide (Fedearroz-FNA, 2014), optimal rice yields are

achieved with 250–300 plants m^{-2} . Only the LC150 treatment met this criterion (258 plants m^{-2}), while the others fell short. This suggests that although higher density improves initial population, it may not always be necessary or cost-effective, especially if final yield is not significantly impacted.

Figure 4 presents a box-and-whisker plot illustrating the distribution of initial population across treatments, highlighting the variability and confirming the statistical findings.

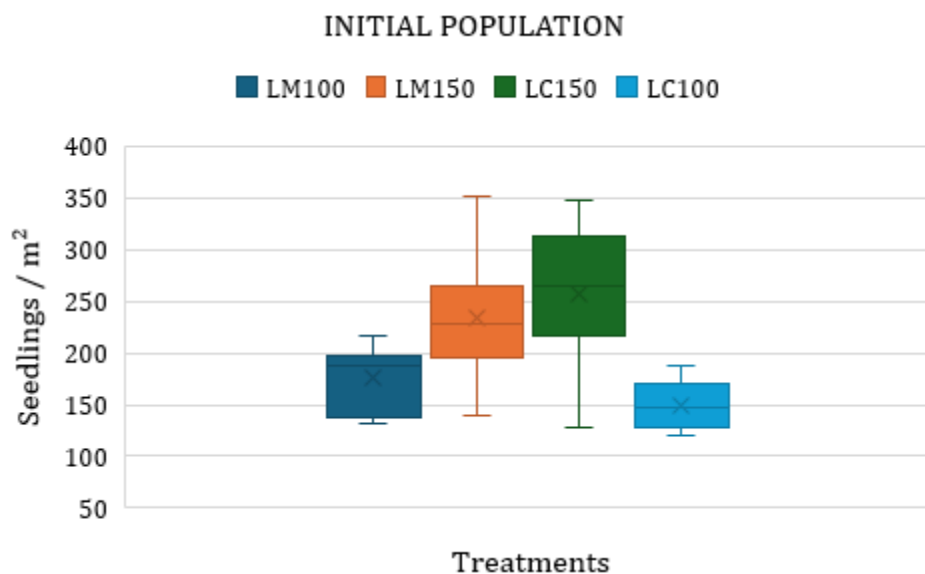


Figure 4 Whisker box for initial population

3.1.2 Monitoring of the crop in each phenological period

During the study, various samplings were conducted to analyse the phenological progress of the rice crop (*Oryza sativa* L.), as shown in Figure 5, with the aim of statistically comparing the number of tillers and panicles across treatments. The data obtained in each sampling period presented a normal distribution according to the Shapiro-Wilk test ($p > 0.05$), which allowed the application of ANOVA with a 95% confidence level. Additionally, the variances across treatments were reasonably homogeneous, supporting the robustness of the statistical comparisons.

In the tillering period, the ANOVA showed no significant differences between treatments ($p = 0.147$), with a mean square error (MSE) of 41036.44

and an effect size (η^2) of 0.072. This indicates that only 7.2% of the variability in tiller count was explained by the experimental factors. The tiller readings were similar for all treatments, regardless of the applied densities and tillage method. This is consistent with the findings of Páez (1991), who noted that higher planting density tends to reduce individual tillering due to intra-specific competition.

In the maximum tillering period, the ANOVA revealed significant differences ($p = 0.010$), with an MSE of 32454.00 and an effect size η^2 of 0.182, indicating that 18.2% of the variability was attributable to the treatments. Fisher's LSD test identified significant differences between LM100 and LC150 ($\Delta = 279$), and between LC150 and LC100 ($\Delta = 176$), with LC150 showing notably superior performance. This result aligns with the observations

of López and Hernández (2023), who reported that conventional tillage promotes better tillering and a higher proportion of effective tillers.

In the maximum booting stage, although LC150 maintained higher average values, the ANOVA did not detect significant differences ($p = 0.073$), with an MSE of 8109.89 and η^2 of 0.115. The variability within treatments diluted the statistical impact of the differences.

During flowering, panicle counts were statistically similar across treatments ($p = 0.334$), with an MSE of 5838.89 and a very low effect size η^2 of 0.014, suggesting minimal influence of tillage or planting density at this stage.

Finally, at harvest maturity, panicle counts remained consistent among treatments. The ANOVA confirmed no significant differences ($p = 0.420$), with an MSE of 6909.67 and an effect size η^2 of approximately 0.003, indicating negligible treatment impact on this final yield component.

In summary, while planting density and tillage method influenced early vegetative development—particularly during maximum tillering—their effect diminished in later stages. These findings support the hypothesis that early vigor may be enhanced by specific combinations of tillage and density, but final yield components are more resilient to these factors.

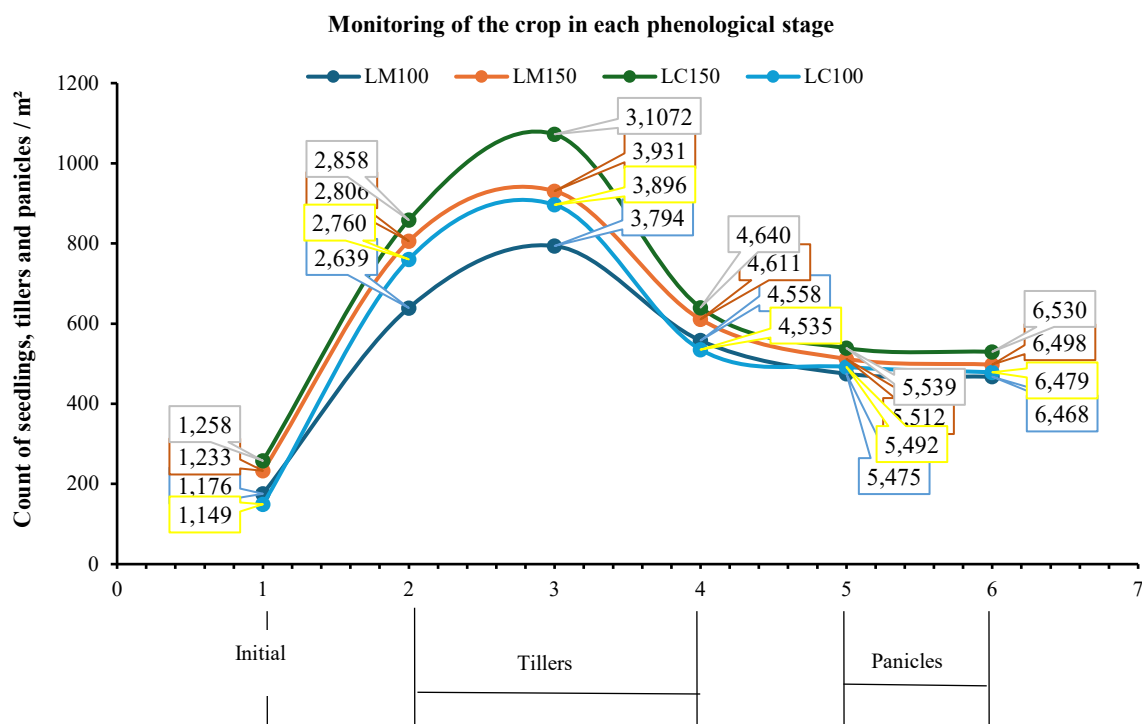


Figure 5 Phenological monitoring of the crop

3.1.3 Monitoring of plant heights in each phenological period of the crop

The results demonstrate a normal distribution according to the Shapiro-Wilk test in each of the sampled periods. This confirms the validity of applying ANOVA to evaluate differences in plant height across treatments. Additionally, the variances between groups were sufficiently homogeneous to support the robustness of the analysis.

The ANOVA statistical analyses show that during the tillering and maximum tillering periods, the

heights between some treatments present significant differences. In the tillering stage, the ANOVA yielded a p -value of 0.00015, with a mean square error (MSE) of 64.31 and an effect size (η^2) of 0.151, indicating that 15.1% of the variability in plant height was explained by the treatments. Significant differences were observed between LM100–LC150 ($\Delta = 8$), LM150–LC100 ($\Delta = 5$), and LC150–LC100 ($\Delta = 10$), all exceeding the LSD threshold of 4.

In the maximum tillering period, the ANOVA also revealed significant differences ($p = 0.0024$),

with an MSE of 62.11 and η^2 of 0.103. The treatments LM100–LC150 ($\Delta = 6$), LM150–LC100 ($\Delta = 5$), and LC150–LC100 ($\Delta = 8$) showed differences greater than the LSD value. LC150 exhibited notably greater growth during the initial phases, suggesting a positive interaction between conventional tillage and higher planting density. However, this effect cannot be attributed solely to either factor. The fact that LM150 also showed considerable height suggests that planting density may have a stronger influence than tillage method.

In the maximum booting and harvest maturity periods, the ANOVA showed no significant differences ($p = 0.073$ and $p = 0.420$, respectively), with MSE values of 40.60 and 64.31, and effect sizes η^2 of 0.102 and 0.003. These results indicate that, by these stages, plants had reached their maximum development, and the influence of the treatments had diminished. All treatments met the standards provided by the Fedearroz 2020 seed technical sheet, which specifies optimal plant height between 90 and 100 cm (Fedearroz-FNA, 2014; Serrato Rivera and Trujillo

Valencia, 2024).

Figure 6 presents the graph relating plant height at different phenological stages. Despite the significant differences observed during the initial growth stages, the final result is homogeneous, as all plants conform to the expected genetic behavior of the rice variety used. As López and Hernández (2023) explain, the genetic uniformity of the Fedearroz 2020 variety leads to convergence in plant height at maturity, regardless of the initial treatment conditions.

The behavior observed in the LM150 treatment is due to the improvement in soil structure and root development efficiency, which favors water and nutrient absorption and translates into greater plant height during key phenological stages. This effect has been supported by recent studies such as that of Hassan et al. (2022), who demonstrated that reduced tillage improves water retention and soil aeration, promoting more vigorous plant growth under similar subtropical conditions: “Zero tillage improves soil structure and water retention, leading to enhanced plant growth parameters such as height and biomass.”

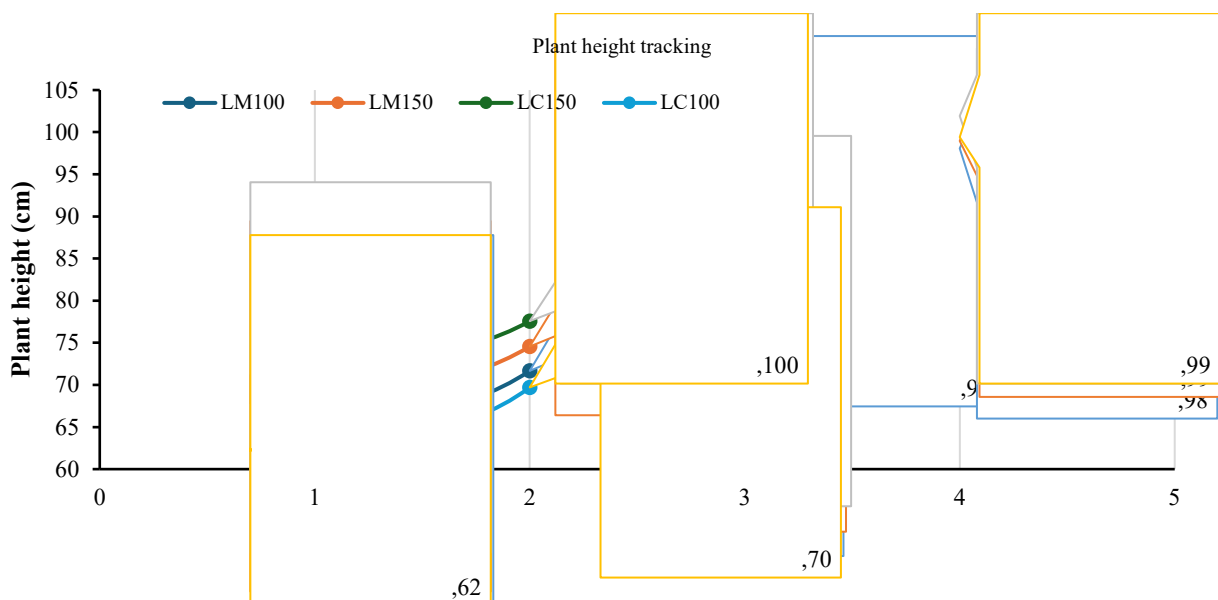


Figure 6 Tracking of plant heights

3.2 Harvest and crop yield

For the harvesting stage, the John Deere 4425, a modern harvester belonging to ASOJUNCAL, was used. This machine was selected for its efficiency and ability to adapt its performance to the specific characteristics of the 2 hectares where the four experimental treatments were implemented. Once the

harvest was completed, the production was carefully transported to the Grupo Diana mill, where the respective purchase of the harvested product took place. This process includes not only the reception of the agricultural material but also a series of quality analyses to determine the state of the product before processing. At the conclusion of this stage, it was

determined that the total gross weight of the resulting load was 15,020 kg. This figure is crucial as it represents not only the quantity harvested but also the economic potential of the effort made during cultivation.

Additionally, important measurements such as the moisture content, which was 25.26%, were recorded. This factor is fundamental as it directly influences the quality of the final product and its proper preservation. Such a specific moisture content requires special attention in the storage and processing stages to avoid deterioration and ensure the integrity of the product. A percentage of impurities of 3.50% was also identified, which is a relevant datum for the overall quality assessment of the product. These indices are key indicators that can influence the market acceptance of the crop.

It is important to note that the value of the load on the day the product was sold was 205,000 COP. This amount not only reflects the immediate economic value of the harvest but also represents the result of the agronomic and management decisions implemented throughout the campaign. This income will be crucial for the evaluation of the profitability of the treatments applied in the plots and for the planning of future harvests. To determine the yield of each of the treatments, the total weight of the gauges was used so that by means of unit conversion mechanisms it could be converted from grams per gauge to kilograms per half hectare, which would represent the production per treatment, and thus carry out the sum of all the treatments and then make a comparison with the real weight shown on the scales, determining the difference between these, Table 2.

Table 2 Theoretical vs. actual weight projection

	Weight 1000 grains per perforator (g)	Total weight per saddlebag (g)	Projection of theoretical total weight (kg 0.5ha ⁻¹)	Summation theoretical total weight projection (kg)	Actual bascule weight (kg)	Gap (%)
LM100	28,5	212,2	4244,4			
LM150	28,5	224,4	4488,9			
LC150	25,9	252,6	5051,1	18622,2	15020	19,34
LC100	28,2	241,9	4837,8			

The discrepancy presented in Table 2 reflects the difference between the theoretical total weight and the total weight recorded on the scale. This discrepancy arises from various losses that occur throughout the crop development cycle. Among the main causes of these losses are pests, weeds, natural losses, and losses that occur during harvesting.

It is essential to highlight that, when referring to natural losses, we are talking about situations where crop lodging occurs due to adverse weather conditions, such as strong winds. These phenomena not only cause the detachment of leaves and stems but can also lead to the loss of seeds and panicles, significantly affecting the final yield of the crop. Additionally, it is relevant to mention that pests and weeds compete for vital resources such as water, nutrients, and light, which decreases plant productivity and contributes to the observed discrepancy.

On the other hand, losses during harvesting are another critical factor impacting total yield. These losses can originate from improper calibration of the machinery used in the harvesting process or from malfunctions in said machinery. When machines are not correctly adjusted, they may not collect all parts of the crop, leaving behind a significant percentage of the harvest. These aspects are evident in Figure 7.

In order to determine the real weight of each of the treatments, an adjustment was made to the theoretical total weight, discounting the percentage of under-feeding (19.34%), thus determining the total weight (kg ha⁻¹) as shown in Table 3, and applying unit conversions, this weight is converted to Ton ha⁻¹ and then to Bul ha⁻¹, the latter is determined in order to know the income per treatment, since one load of rice is equivalent to 2 bulks. Finally, the income is added up to determine the percentage corresponding to each treatment.



Figure 7 Factors affecting crop yield

Table 3 Yield and revenue of each treatment per ha

Treatments	Theoretical total weight (kg ha ⁻¹)	Total weight weighbridge (kg ha ⁻¹)	Total scale weight (Ton ha ⁻¹)	Total weight scale (Bul ha ⁻¹)	Revenue
LM100	8488,9	6846,8	6,85	109,5	\$ 11.228.794
LM150	8977,8	7241,1	7,24	115,9	\$ 11.875.479
LC150	10102,2	8148,1	8,15	130,4	\$ 13.362.853
LC100	9675,6	7803,9	7,80	124,9	\$ 12.798.474
		TOTAL			\$ 49.265.600

According to the National Administrative Department of Statistics (DANE, 2023), the average yield for rice cultivation in Colombia in the first half of 2023 is 6.4 tonnes ha⁻¹. However, the department of Huila has an average yield of 7.3 tonnes ha⁻¹. Based on this, it can be observed that all treatments meet the general yield in Colombia. Nevertheless, when comparing the yield presented by DANE with the per hectare yields of the treatments in this study, the treatments LC150 and LC100 meet the departmental standards, exceeding the average by 10% and 6% respectively. In the case of LM150, it is 1% below this average, while LM100 is 7% short of meeting this average, as shown in Table 3.

The yield data per treatment were analysed statistically to determine whether the differences observed in grain weight and income were significant. The data met the assumption of normality according to the Shapiro-Wilk test ($p > 0.05$ for all treatments), and the variances across groups were sufficiently homogeneous to justify the use of ANOVA.

The analysis revealed no statistically significant differences in yield between treatments ($p = 0.294$), with a mean square error (MSE) of 5303.30 and an effect size (η^2) of approximately 0.015. This indicates that only 1.5% of the variability in yield was explained by the experimental factors (tillage method and planting density), suggesting a high degree of

uniformity in productivity across treatments.

These results imply that, although differences in input costs and labor requirements exist between treatments, the yield itself remains statistically consistent. Therefore, the decision-making process should not rely solely on yield performance, but rather incorporate a comprehensive techno-economic assessment. Such an evaluation should compare input costs, operational efficiency, and net profitability to

identify the most sustainable and cost-effective strategy for rice cultivation in the region.

The sample size used—based on 18 spatially distributed gauges—was considered adequate to capture representative variability within each plot, ensuring the reliability of the statistical conclusions. This uniformity in yield is illustrated in Figure 8, which presents the distribution of performance per treatment and visually supports the statistical findings.

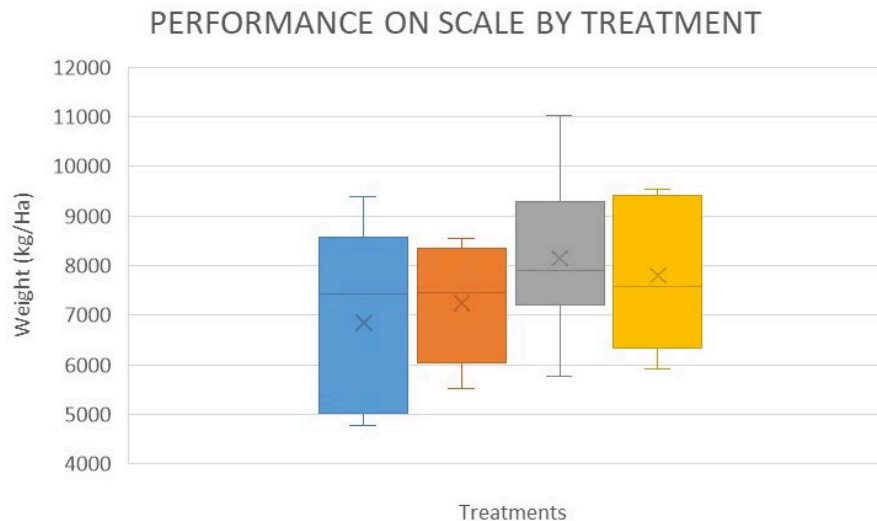


Figure 8 Weighing performance per treatment

4 Conclusion

When evaluating rice yields in the four treatments, it was observed that the LC150 treatment showed the highest values, attributable to the combination of conventional tillage and high planting density. However, this type of tillage has a potential effect on soil structure in the long term. In the case of LC100, yields are comparable, with the advantage of a lower seeding density that could reduce the cost of production. The minimum tillage treatments (LM150 and LM100) showed similar performance in terms of yield, highlighting that the use of less intensive tillage practices represents a more sustainable alternative, by reducing the physical impact on the soil without significantly compromising productivity.

In terms of planting density, it was observed that this variable does affect the initial population, as a higher number of seeds sown results in greater seedling germination. However, as the crop develops, this condition diminishes, presenting a similarity in the treatments at the end of the crop cycle. In this

context, and as mentioned in the previous paragraph, it is observed that although there is a slight difference between the two planting densities implemented in each type of tillage, equivalent to 1% in income, costs, and profits, these do not generate significant changes in yield that would justify using a higher quantity of seed.

When comparing the types of tillage LM150 vs LC150 and LM100 vs LC100, it is noted that conventional tillage (LC) is much more efficient in terms of yield than minimum tillage (LM). Although LC has a production cost 1% higher than LM, it also has a 3% higher income, thus generating a profit 5% higher than LM.

These findings not only provide practical guidance for rice producers in Colombia, but also align with broader trends in sustainable agriculture. The combination of minimum tillage and lower seed density reflects principles of direct seeding systems, which are increasingly adopted in tropical climates to reduce soil disturbance, conserve moisture, and lower

input costs. As highlighted by Hassan et al. (2022), such practices contribute to long-term soil health and climate-resilient crop production, enhancing the universal relevance of the strategies evaluated in this study.

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