

Agronomic response of wheat varieties (*Triticum aestivum* L.) to different seeding rates in Oxisol soils from Canindeyú, northeastern Paraguay

Alcides Rubén Villalba Arriola^{1,2*}, Marcos Fabian Sanabria Franco³, Elida Auxiliadora Peralta², Marcelo Helguera⁴, Javier Mendoza², Carlos Alcides Villalba Algarin^{3,5*}

¹Instituto Paraguayo de Tecnología Agraria, Campo Experimental Yhovy, Canindeyú-Paraguay

²Facultad de Ciencias Agrarias-Universidad Nacional de Canindeyú, Canindeyú-Paraguay

³Escola Superior de Agricultura Luiz de Queiroz- Universidade São Paulo, Piracicaba-Brasil

⁴Instituto Nacional de Tecnología Agropecuaria, Centro de Investigaciones Agropecuarias, Instituto de Fisiología y Recursos Genéticos Vegetales, Córdoba-Argentina

⁵Instituto Paraguayo de Tecnología Agraria, Centro de Investigación Capitán Miranda, Capitán Miranda-Paraguay

Corresponding author: Alcides.villalba@ipta.gov.py and carlos.villalba@ipta.gov.py

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Abstract: The lack of systematic studies on seeding rates has hindered efforts to maximize the productive potential of wheat varieties cultivated in Oxisol soils of Paraguay. Optimizing seeding rates improves resource-use efficiency and enhances yield performance. This study evaluated the agronomic response of six popular wheat cultivars grown at five seeding rates: 180, 270, 420, 540, and 720 plants m⁻². The experiment was conducted in Colonia Yhovy, Canindeyú, Paraguay, during the 2021 growing season, using a randomized complete block design with three replications in a bifactorial arrangement (6 cultivars × 5 seeding rates). Measured variables included tillers m⁻², spikes m⁻², thousand kernel weight, grain yield (kg ha⁻¹), and harvest index. Data were analyzed using ANOVA and Tukey's test ($\alpha = 0.05$). Cultivars and seeding rates significantly influenced tillers m⁻², spikes m⁻², and thousand kernel weight. Spike density and grain yield were unaffected by cultivar but varied with seeding rate. The 540 plants m⁻² seeding rate maximized tiller production, while spikes m⁻² increased linearly with seeding rate. Thousand kernel weight decreased at higher seeding rates, with 420 plants m⁻² producing the highest grain yield and harvest index. Cultivars demonstrated similar genetic potential, highlighting the importance of seeding rate management to fully exploit wheat's genetic yield potential.

Key words: Productive potential, management, environmental resources, productivity.

Abbreviations: ANOVA: analysis of variance; TKW: thousand kernel weight; HI: harvest index.

Introduction

Wheat (*Triticum aestivum* L.) has become a cornerstone of Paraguayan agricultural production. Between 2008 and 2022, the planted area expanded by 13.8%, reaching 433,144 hectares (MAG, 2022). This growth has been driven primarily by technological advances, particularly genetic improvement (Kohli et al., 2015), enabling Paraguay, despite its subtropical climate, to emerge as a producer and exporter of this typically temperate-climate crop (Servín and Viñales, 2014). Winter wheat cultivation plays a strategic role in no-till systems by providing soil cover through crop residues, enhancing production system sustainability, improving resilience, and supporting essential ecosystem services that mitigate environmental imbalances (Balbinot Junior et al., 2024; García-Ruiz et al., 2019; Wang et al., 2022).

Despite significant advances in genetic improvement, wheat productivity has been increasingly constrained in recent years by biotic and abiotic factors, including soil quality degradation, high temperatures, and water stress during critical growth stages of the crop. These challenges limit the expansion of cultivated areas and compromise both grain yield and industrial quality (Quintana et al., 2013). To mitigate these effects and maximize the genetic potential of wheat varieties, optimizing agronomic practices is essential (Amanullah et al., 2010; Aula et al., 2022). In this context, selecting locally adapted cultivars and implementing appropriate seeding rates are key strategies to enhance productivity (Alsulaiman et al., 2023; Butkovskaya and Kozulina, 2021; Sciencia et al., 2023).

Seeding rate and varietal characteristics determine a crop's capacity to efficiently capture and utilize light, water, and nutrients (Melash et al., 2023; Villalba Algarin et al., 2024). Excessive seeding rates intensify intra-plant competition,

reducing tillering, spike and kernel size, while increasing susceptibility to diseases and lodging (Laghari et al., 2011). Conversely, insufficient seeding rates decrease soil coverage and resource use efficiency, limiting yield potential (Abdulkerim et al., 2015; Lollato et al., 2019). However, under low seeding rates, varieties with high tillering capacity can compensate for reduced plant density per unit area, promoting a more balanced crop development (Abdulkerim et al., 2015; Bastos et al., 2020; Valério et al., 2013).

Over recent decades, the scientific community has documented diverse agronomic responses of wheat varieties to different seeding rates across the world (Abdulkerim et al., 2015; Aula et al., 2022; Bastos et al., 2020; Butkovskaya and Kozulina, 2021; Fischer et al., 2019; Laghari et al., 2011; Sciencia et al., 2023). However, no universal strategy has been established, as crop response varies according to genetic potential, region-specific agronomic management practices, and edaphoclimatic conditions (Beres et al., 2020; Melash et al., 2023). This context demands region-specific research to generate precise, locally applicable data for each production system (Amanullah et al., 2010).

Paraguay cultivates numerous wheat varieties, both locally developed and introduced (Kohli et al., 2015). Yet studies determining optimal seeding rates for these varieties remain limited, hindering full exploitation of their genetic potential. To address this knowledge gap, the present study aimed to evaluate the agronomic response of different wheat varieties to varying seeding rates in Canindeyú Department, Paraguay.

Results

All response variables were significantly affected by at least one of the analyzed factors: wheat variety and/or sowing density (Figs. 1 and 2).

Thousand-kernel weight

Thousand-kernel weight (TKW) was affected by both variety and sowing density, with no significant interaction between these factors (Fig. 1a). The C31 variety showed a 21.59% increase in TKW compared to TRK, which had the lowest TKW values. TKW exhibited a negative linear trend with increasing sowing densities, where higher plant densities resulted in lower TKW (31.8 g at 270 plants m⁻² vs 30.0 g at 720 plants m⁻²) (Fig. 1b).

Grain yield

Regarding grain yield, no significant effect was observed among wheat varieties, nor any factor interaction (Fig. 1c). However, sowing densities independently significantly impacted this variable. Grain yield increased up to intermediate densities (270-420 plants m⁻²), reaching 3,768-3,778 kg ha⁻¹, while higher densities (540-720 plants m⁻²) reduced grain yields by up to 8.15% (Fig. 1d).

Harvest index

Harvest index (HI) was significantly affected by both varieties and sowing densities, with no significant interaction (Fig. 1e). The CD150 variety showed the highest HI, contrasting with C31 and TRK varieties that exhibited 15.6% and 17.8% lower resource utilization efficiency, respectively. The HI- plant density relationship showed maximum values at 420 plants m⁻² (Fig. 1f).

Tiller numbers

Tiller numbers showed statistically significant differences depending on variety and sowing density, with no interaction between these factors (Fig. 2a). The TRK cultivar exhibited the highest tiller density in the study (1,134 tillers m⁻²), while C31 showed the lowest value (897 tillers m⁻²), representing a 26.4% difference. When evaluating sowing density versus tiller number, a quadratic response was observed, with progressive increase until reaching maximum values at 540 plants m⁻² (Fig. 2b). Spike number was influenced solely by sowing density, showing a positive linear correlation with increasing plant density (Fig. 2c). Therefore, the highest spike density occurred at the maximum plant density (720 plants m⁻²) with values 57.1% higher than the lowest plant density evaluated (180 plants m⁻²) (Fig. 2d).

Discussion

Exploring the productive potential of plant varieties and sowing densities under local agroclimatic conditions is crucial for optimizing resources use and addressing edaphoclimatic challenges in agricultural production. This approach not only aims to increase yields but also strengthen food security and economic development in agriculture-dependent countries like Paraguay (Sciencia et al., 2023; Villalba Algarin et al., 2024). Our study evaluated the agronomic response of local and introduced wheat varieties in Paraguay under different sowing densities, providing valuable insights for optimizing crop management and promoting a much more efficient and sustainable production in the region.

Among the agronomic traits analyzed, thousand-kernel weight (TKW) serves as both an industrial quality indicator and a yield component in wheat. Among the studied varieties, C31 showed the highest TKW values, which we may attribute to a superior adaptation to regional climatic conditions (Cabrera-Arredondo et al., 2022). Unlike other varieties, C31 was specifically developed by IPTA for warmer regions, conferring a greater tolerance to elevated temperatures during the critical grain-filling stage (Fig. 3d). Heat-tolerant varieties typically maintain higher photosynthetic efficiency under such conditions by reducing reactive oxygen species damage, thereby improving photoassimilate allocation (Hou et al., 2024; Pant et al., 2025). Notably, while C31 demonstrated improved TKW, this advantage did not extend to grain yield, which

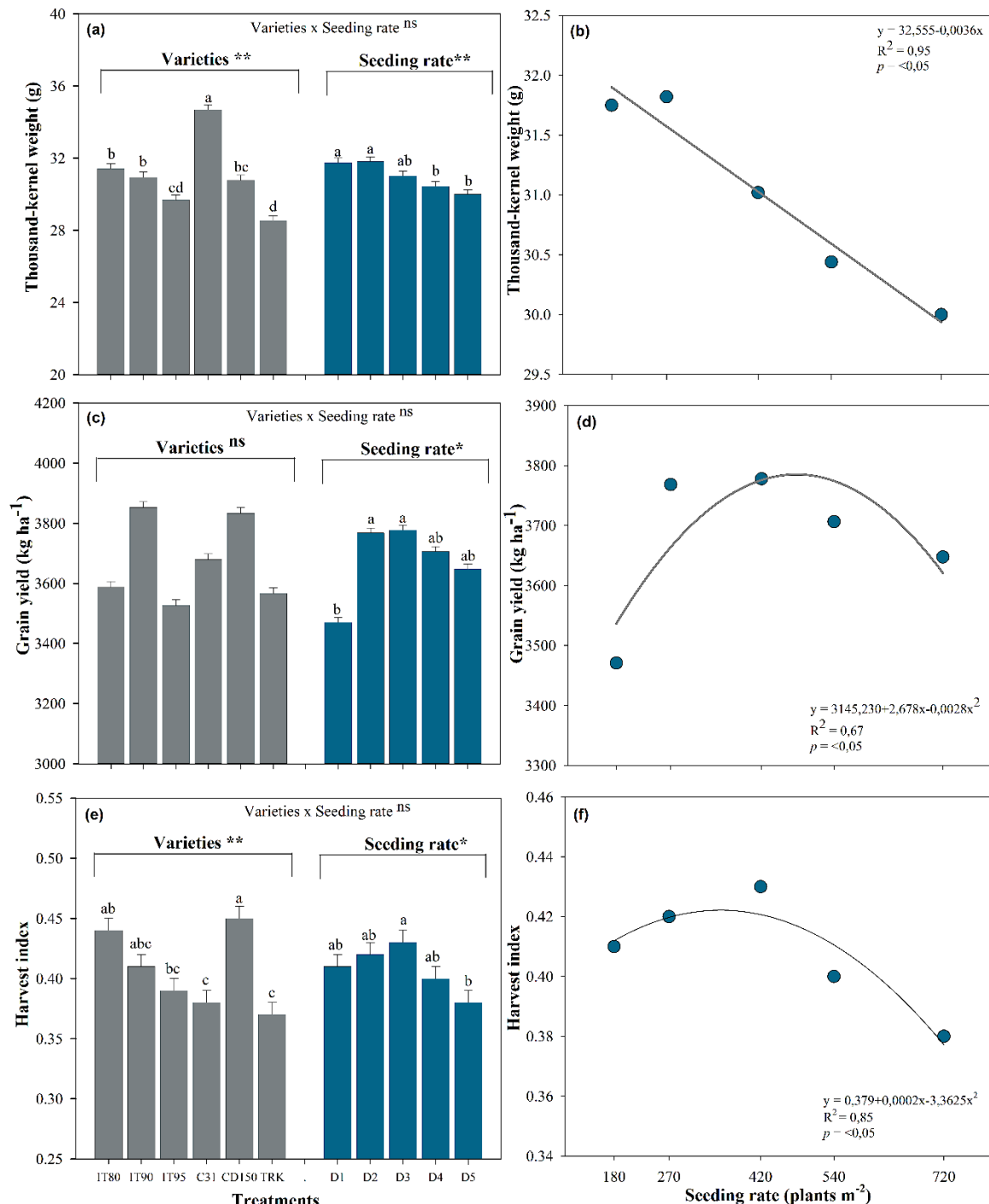


Fig. 1. Thousand-kernel weight (a-b), grain yield (c-d), and harvest index (e-f) in response to wheat varieties and different seeding rates in the Department of Canindeyú, Paraguay. Varieties: IT80 = Itapúa 80; IT90 = Itapúa 90; IT95 = Itapúa 95; C31 = Canindé 31; CD150 = Coodetec 150; TRK = TORUK. Seeding rates: D1 = 180 plants m⁻²; D2 = 270 plants m⁻²; D3 = 420 plants m⁻²; D4 = 540 plants m⁻²; D5 = 720 plants m⁻². Vertical lines above the bars represent the standard error of the means ($n = 3$). Identical letters indicate statistical similarity between treatments for each factor. * = significant at 5% probability, ** = significant at 1% probability, ns = not significant according to Tukey test ($p \leq 0.05$).

showed no significant varietal differences (Fig. 1c). A similar pattern can be described for Harvest index and tiller number, with significant differences among varieties that are not translated to significant yield differences among varieties (Figs. 1e and 2a). On the other hand, regardless of variety, TKW decreased significantly with increasing sowing density in a linear fashion with a negative slope (Figs. 1a, 1b). At explored higher plant densities, intensified competition for water, light, and nutrients limits resource availability during grain filling, ultimately reducing final TKW (Villalba Algarín et al., 2024; Rodríguez et al., 2016; Tumini, 2020). Elevated plant densities would exacerbate intraspecific competition, constraining both production and efficient allocation of photoassimilates to developing kernels (Feng et al., 2024). Consequently, plants lose their capacity to maintain optimal grain filling, explaining the observed TKW reduction at higher densities.

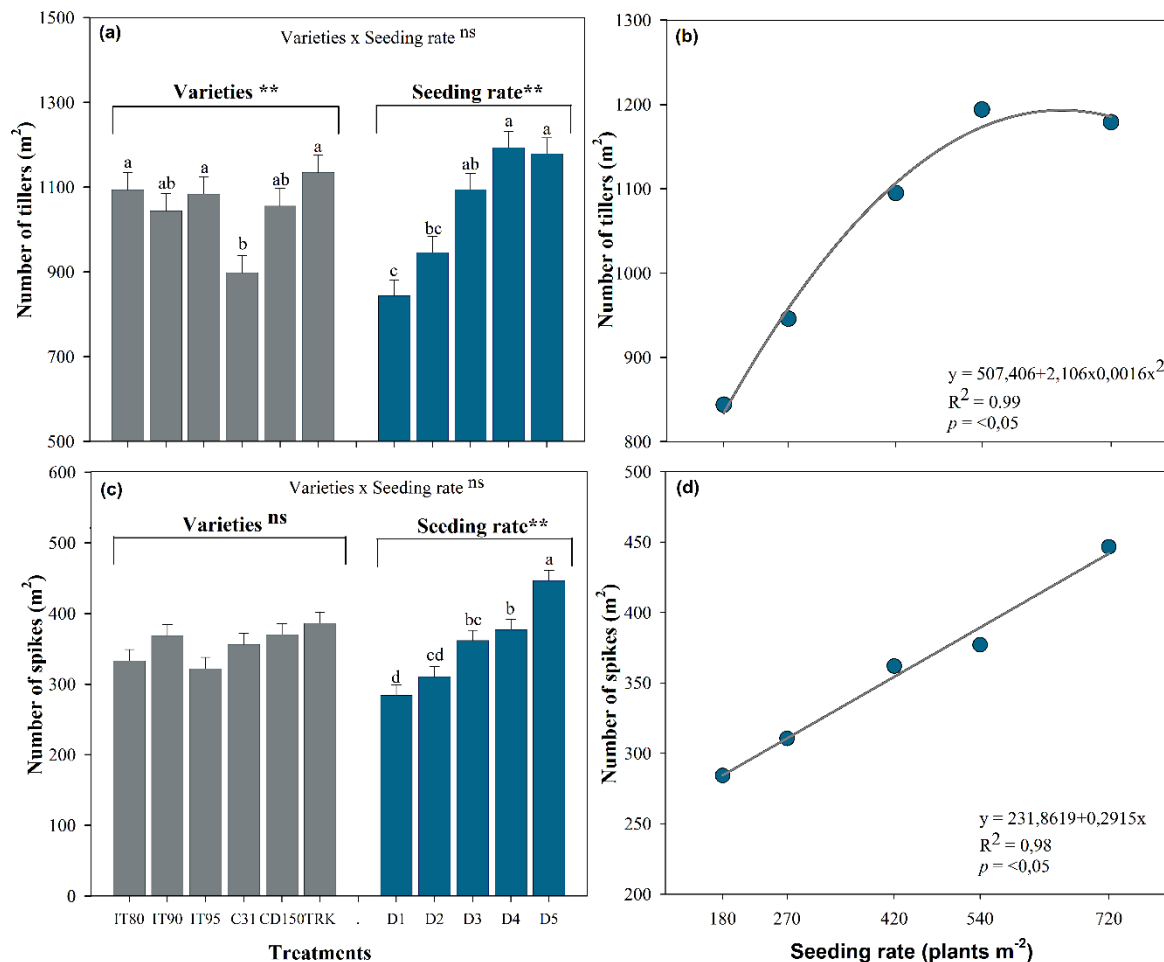


Fig. 2. Number of tillers (a-b) and number of spikes (c-d) in response to wheat varieties and different seeding rates in the Department of Canindeyú, Paraguay. Varieties: IT80 = Itapúa 80; IT90 = Itapúa 90; IT95 = Itapúa 95; C31 = Canindé 31; CD150 = Coodetec 150; TRK = TORUK. Seeding rates: D1 = 180 plants m⁻²; D2 = 270 plants m⁻²; D3 = 420 plants m⁻²; D4 = 540 plants m⁻²; D5 = 720 plants m⁻². Vertical lines above the bars represent the standard error of the means ($n = 3$). Identical letters indicate statistical similarity between treatments for each factor. * = significant at 5% probability, ** = significant at 1% probability, ns = not significant according to Tukey test ($p \leq 0.05$).

Unlike varietal effects, plant density significantly affected grain yield in a quadratic response (Figs. 1c, 1d) - contrasting with the linear decline observed for TKW. This pattern may arise because high plant densities primarily would inhibit grain number per spike through abortion of basal and apical spikelets. Furthermore, it has been described that under high plant densities, both grains per spike and kernel diameter are reduced due to environmental resource limitations (Feng et al., 2024). Conversely, at lower plant densities (<250 plants m⁻²), while grain filling was more efficient, the smaller number of plants and spikes per unit area fail to compensate for the lower population.

Consistent with our results, previous studies reported that sowing densities between 250 and 400 plants m⁻² create optimal conditions for maximizing wheat productivity by promoting a balanced resource distribution (Abd al-Dahi and Al-Taweel, 2021; Batool et al., 2022; Holman et al., 2021). Within this range, crops achieve over 90% solar radiation interception, supporting efficient growth (Satorre, 1999), while simultaneously optimizing production costs and reducing susceptibility to lodging, pests, and diseases through proper density management (Bastos et al., 2020). The lack of statistically significant yield differences among varieties in our study may be attributed to prevailing climatic conditions that potentially limited the expression of yield potential and hindered the surpassing of regional yield thresholds. Despite this, the average yields recorded in this study (ranging from 3,470 to 3,778 kg ha⁻¹) remained within expected values for most evaluated varieties (Cabrera et al., 2023).

Key agronomic traits of wheat, initially determined by varietal genetics, can be modified by different sowing densities. This phenomenon affects a variety's potential to acquire resources for aerial biomass production and, consequently, its conversion into harvestable yield (Dai et al., 2016; Ren et al., 2022). In this study, harvest index (HI) was influenced by wheat varieties, with CD150, a widely adopted cultivar with superior adaptation to local climatic conditions, demonstrating the highest values. Conversely, when plant populations exceeded the optimal threshold (420 plants m⁻²), HI declined due to excessive competition for production inputs (Feng et al., 2024).

The tillering profile, as a morphological trait, is influenced by the interaction between genotype, environment, management and their synergies (Melash et al., 2023). An optimal tillering architecture allows compensatory mechanisms within a defined optimal range to offset a cultivar's inherent tillering capacity limitations (Shang et al., 2021; Juárez, 2011). In

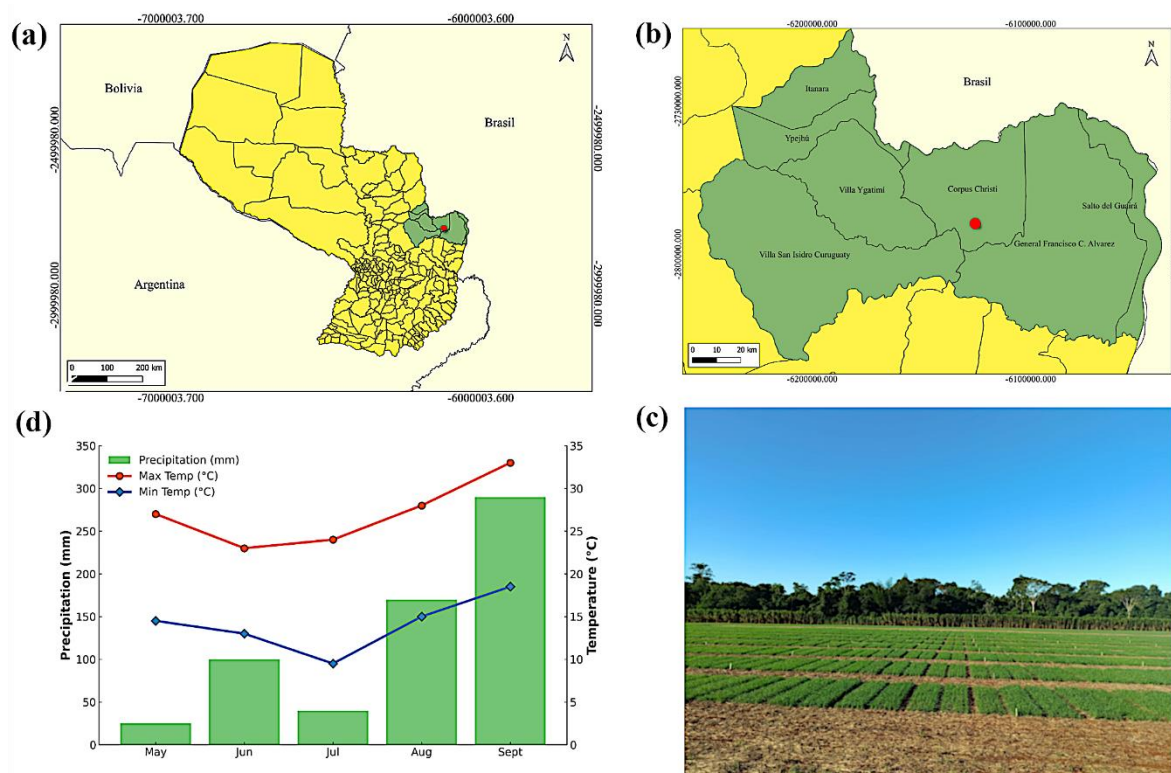


Fig. 3. Geographic location and environmental characterization of the experimental site. (a) Map of Paraguay showing the location of the Canindeyú department (in green); (b) detailed map of Canindeyú with the experimental site indicated by a red dot; (c) general view of the experimental area under field conditions; (d) monthly climatic data during the experimental period (May–September), including precipitation (green bars), minimum temperature (blue line), and maximum temperature (red line).

agreement with this principle, our results show tiller density was significantly affected by both varieties and sowing (plant) densities. From a genetic perspective, auxin-responsive genes are known to play fundamental roles in tiller development (Li et al., 2021), while light conditions interfere with auxin biosynthesis (Halliday et al., 2009) - explaining why high planting densities (>540 plants m^{-2}) compromise lateral shoot formation through intense intrapopulation competition. Regarding yield components, spike number per plant represents a key variable that under ideal environmental conditions reflects each cultivar's genetic potential. Current research indicates that higher spike density per square meter increases grain yield by compensating for limiting factors such as reduced spike size or grains per spike (Martínez, 2012; Gasparotto, 2014; Ballesteros, 2017; Ledesma-Ramírez et al., 2024).

The harvest index, which represents the proportion of total biomass converted to grain, serves as a key parameter for evaluating a crop's physiological efficiency in transforming dry matter into marketable yield (Ren et al., 2022). In this study, both variety and sowing density significantly influenced HI without interaction effects, indicating independent contributions. Among varieties, CD150 exhibited the highest HI, suggesting superior photoassimilate allocation to grains. This trait likely stems from genetic characteristics favoring optimal canopy architecture and balanced vegetative-reproductive phase partitioning (Bastos et al., 2020). In contrast, C31 and TRK showed the lowest HI values, reflecting relatively poor biomass partitioning efficiency—potentially due to excessive vegetative tissue accumulation or reduced spike production per unit biomass (Amanullah et al., 2010).

Regarding sowing densities, HI followed a quadratic response peaking at 420 plants m^{-2} . This aligns with studies demonstrating that intermediate densities optimize resource distribution (light, water, nutrients), minimizing intraspecific competition while enhancing reproductive allocation (Feng et al., 2024; Aula et al., 2022). Suboptimal densities limit spikes per unit area, whereas excessive densities promote vegetative growth without proportional grain yield increases, thereby reducing HI (Bastos et al., 2020; Holman et al., 2021).

Notably, HI reflects both management responses and environmental adaptation. In subtropical regions like Canindeyú, where thermal fluctuations and water availability may become limiting factors, balancing vegetative biomass with grain yield is critical for achieving high physiological efficiency levels (Assefa et al., 2023; Schweier et al., 2016). Our results demonstrate that intermediate sowing densities combined with adapted varieties (e.g., CD150) optimize HI, providing a viable agronomic strategy to maximize wheat production efficiency in Paraguay.

Materials and methods

Experimental site and conditions

The experiment was established in 2021 at the Yhovy Research Farm of the Paraguayan Institute of Agricultural Technology (IPTA), located in Canindeyú Department, Paraguay ($24^{\circ}17'55''$ S, $54^{\circ}59'19''$ W) (Fig. 3). The climate is warm-temperate

Table 1. Soil composition of the experimental site.

Soil depth	pH CaCl ₂	SOM %	P mg dm ⁻³	K ⁺cmol _c dm ⁻³	Ca ⁺²	Mg ⁺²	BS %
0-20 cm	5.5	3.1	6.3	1.14	4.70	1.60	58.17

with a mean annual temperature of 21.6°C and average annual rainfall of 1,622 mm (DINAC, 2020). Figure 1 shows the minimum and maximum temperatures and precipitation records during the research. The soil is classified as an Oxisol, specifically within the Rhodic Kandudox taxonomic subgroup according to the Soil Taxonomy system (López et al., 1995). Pre-experiment laboratory analyses of soil chemical properties (0-20 cm depth) are detailed in Table 1.

Plant materials

Six wheat varieties were used in this study: IT80 = Itapúa 80; IT90 = Itapúa 90; IT95 = Itapúa 95; C31 = Canindé 31; CD150 = Coodetec 150; and TRK = Toruk. Canindé and Itapúa varieties were developed by the IPTA breeding program and released between 2015 and 2018, the Coodetec 150 variety belongs to the Coodetec breeding program (now Corteva) and was released in 2013, while the Toruk variety was developed by Biotrigo Brasil and released in 2018.

Experimental design, crop establishment and management practices

The varieties were sown at five different densities: D1 = 180 plants m⁻²; D2 = 270 plants m⁻²; D3 = 420 plants m⁻²; D4 = 540 plants m⁻²; and D5 = 720 plants m⁻². The experiment was arranged in a randomized complete block design with a bifactorial structure (variety × sowing density), resulting in 30 treatments. Each treatment was replicated three times, totaling 90 experimental plots. Plots consisted of six wheat rows (0.18 m between rows) and were 5 m long, covering an area of 5.4 m² per plot.

Seed viability for each variety was initially calculated based on thousand-kernel weight and germination potential to adjust the required seeding rate for achieving target plant densities, following the methodology proposed by Abboye et al. (2020): Seeds (kg m⁻²) = (Sowing density × Kernel weight) / (Germination percentage × 10)

where: Sowing density = plant number per square meter for each treatment, Kernel weight = Average weight per kernel (g), Germination percentage = Expected field germination rate expressed as 0–100%. The factor 10 was used to convert unit grams to kilograms.

Sowing was conducted on 11 May 2021 under no-till conditions using a SEMEATO experimental planter adapted for wheat, tractor-mounted with a six-row capacity (18 cm row spacing). A base fertilization of 20, 40, and 20 kg ha⁻¹ of N, P, and K, respectively, was applied, adjusted according to soil analysis and crop nutritional demands.

Pest management during the growing cycle included applications of: imidacloprid (55 mL ha⁻¹), acetamiprid (50 g ha⁻¹) and lufenuron 5% (100 mL ha⁻¹). For disease control, preventive and curative fungicides were applied including *Azoxystrobin 30% + Benzovindiflupyr 15%* (200 g ha⁻¹) for leaf spots and leaf rust. Weed control was performed at tillering (30–35 days after emergence) using *Metsulfuron-methyl 75%* (8 g ha⁻¹). Harvesting was conducted at commercial maturity (growth stage Z 9.2; Zadoks et al., 1974) using a Wintersteiger Nurserymaster Elite experimental plot combine.

Assessment of agronomic traits in the experiment

All evaluations were conducted in the usable area of each experimental unit, which comprised the four central rows measuring 4 m in length (totaling 2.88 m²), while excluding the two border rows and 0.50 m from each end to minimize edge effects. The number of tillers per square meter was evaluated 45 days after crop emergence at the elongation stage (Z 3.1; Zadoks et al., 1974). Spike density was determined at physiological maturity (Z 9; Zadoks et al., 1974) through direct counting within a 1 m² sampling area. Harvest index was calculated as the ratio of grain weight to total aboveground biomass weight using a 1 m² subsample (Sciencia et al., 2023). Thousand-kernel weight was determined using a manual seed counter by averaging ten 100-kernel samples, then extrapolating to 1,000 kernels and expressing the result in grams (g). Grain yield was calculated from the average weight obtained from the usable area of each experimental unit, extrapolated to kilograms per hectare (kg ha⁻¹) and adjusted to 13% moisture content.

Statistical analyses

The data were subjected to normality testing using Shapiro-Wilk test. Differences in all variables were tested with analysis of variance (ANOVA). Variables showing significant differences were compared using Tukey's test at a 5% significance level. All variables underwent correlation analysis to examine the influence of sowing density on their behavior.

Conclusions

Investigating wheat population densities can help maximize agronomic benefits from nationally produced and adapted varieties. Currently, the lack of information on basic agronomic practices, particularly optimal sowing densities under local conditions, is reducing natural resource use efficiency.

The evaluated varieties (IT80, IT90, IT95, C31, CD150, and TRK) demonstrated similar genetic potential. Therefore, optimizing sowing density management emerges as a viable strategy to enhance production efficiency. Sowing density directly influences wheat yield components, creating ideal conditions to unlock varieties' maximum genetic potential.

Author Contributions

Conceptualization, A.R.V.A. and C.A.V.A.; methodology, A.R.V.A.; software, M.F.S.F.; validation, A.R.V.A.; formal analysis, A.R.V.A. and C.A.V.A.; investigation, A.R.V.A., M.F.S.F., E.A.P. and C.A.V.A.; resources, A.R.V.A.; data curation, A.R.V.A.; writing original draft preparation, A.R.V.A., E.A.P. and C.A.V.A.; writing review and editing, A.R.V.A., M.F.S.F., M.H., J.M. and C.A.V.A.; visualization, A.R.V.A.; supervision, A.R.V.A.; project administration, A.R.V.A.; funding acquisition, A.R.V.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding authors upon reasonable request.

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