

Modeling and optimization of operational parameters in pneumatic seeders to enhance corn (*Zea mays*) germination in humid tropical conditions in Costa Rica

Modelado y optimización de parámetros operativos en sembradoras neumáticas para el cultivo de maíz (*Zea mays*) en el trópico húmedo de Costa Rica

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Keywords

Corn (*Zea mays*), pneumatic seeder, emergence uniformity, planting speed, calibration, precision agriculture.

Abstract

This study presents the modeling and optimization of pneumatic seeder calibration parameters to improve corn (*Zea mays*) germination under humid tropical conditions in clay-rich soils of Costa Rica. A factorial experimental design was implemented to evaluate the influence of seed quality, seeding velocity, soil texture, moisture content, and vacuum pressure on seed placement accuracy, germination rate, and plant population density. Results indicate that high soil moisture enhances plant establishment, while moderate water stress promotes increased plant height, revealing a trade-off between density and vigor. Vacuum pressure emerged as the most critical operational factor, significantly improving seed placement and germination uniformity. Excessive seeding speeds negatively affected emergence consistency. The effect of clay content was significant only when interacting with mechanical and environmental variables. A predictive model was developed and validated, integrating moisture, vacuum pressure, and velocity to accurately estimate plant population under varying field conditions. These findings provide actionable insights for precision calibration of pneumatic seeders, contributing to improved crop establishment and productivity in tropical agricultural systems with challenging soil textures.

Palabras clave

Maíz (*Zea mays*), sembradora neumática, uniformidad de emergencia, velocidad de siembra, calibración, agricultura de precisión.

Resumen

Este estudio se enfocó en la optimización de la calibración de una sembradora neumática para el cultivo de maíz (*Zea mays*) en condiciones del trópico húmedo de Costa Rica, específicamente en suelos con alto contenido de arcilla. Se evaluaron los efectos de la calidad de la semilla, velocidad de siembra, textura del suelo, humedad y presión de vacío de la sembradora sobre la germinación y la población de plantas. Los resultados mostraron que la humedad elevada favorece el establecimiento de plantas, mientras que niveles moderados de estrés hídrico promueven mayor altura, evidenciando un compromiso entre densidad y vigor. La presión de vacío fue el parámetro operativo más determinante, mejorando la colocación y germinación de las semillas, mientras que velocidades excesivas redujeron la uniformidad en el establecimiento. El contenido de arcilla mostró efectos significativos solo en interacción con factores mecánicos y ambientales. Se desarrolló un modelo predictivo que integra humedad, presión y velocidad, el cual permite estimar con precisión la población de plantas bajo distintas condiciones operativas y edáficas. Los hallazgos ofrecen directrices prácticas para mejorar la eficiencia de siembra, la uniformidad de emergencia y la productividad en sistemas agrícolas del trópico húmedo.

Introduction

Plant population in corn (*Zea mays*) cultivation is a key determinant of resource use efficiency and final yield, as it regulates intraspecific competition and the distribution of water and nutrients. Uniform germination enables synchronized emergence and homogeneous crop establishment, whereas uneven emergence results in weaker, less competitive plants, negatively impacting productivity[1].

Globally, corn production faces challenges such as climate change, rainfall variability, and increased pest pressure, all of which directly affect emergence uniformity and final plant population[2], [3], [4]. These challenges emphasize the need to improve planting practices to ensure efficient crop establishment.

Seed quality is one of the primary factors influencing emergence. High-vigor seeds germinate rapidly and uniformly, leading to consistent plant stands. Laboratory germination and vigor tests, complemented by field emergence evaluations, help differentiate between normal plants (3–4 leaves, average height of 16.9 ± 2.9 cm) and abnormal plants, demonstrating a strong correlation between lab and field performance [5].

Pneumatic seeder calibration is also critical. Parameters such as seeding speed, vacuum pressure, and seed metering mechanisms affect seed placement accuracy. Excessive speeds or improper calibration can cause mechanical damage, inconsistent depth, and irregular spacing, potentially reducing yield [6], [7], [8]. Vacuum pressure and orifice size are key to minimizing skips and improving uniformity[9].

Soil conditions further influence emergence. Clay and clay-loam soils retain more water than sandy soils, promoting seed water uptake[10]. but compaction and low hydraulic conductivity can restrict germination [11], [12].

Despite global advances in precision agriculture, this study addresses the calibration of pneumatic seeders under humid tropical conditions in Costa Rica, focusing on optimizing vacuum pressure and planting speed to improve corn emergence and plant population.

Methodology

This study evaluated the interactive effects of soil moisture, pneumatic seeder vacuum pressure, and seeding speed on early corn development and crop establishment. The performance of a pneumatic seeder was compared to that of a mechanical seeder under varying soil moisture conditions. Field trials were combined with precise mechanical calibration and digital data analysis to assess seed placement accuracy, emergence rate, and stand uniformity.

The experiment was conducted at the Centro de Cosecha farm (Figure 1), located on the EARTH University campus in Las Mercedes, Guácimo, Limón, Costa Rica. All experimental blocks were established on clayey soils, with minimal variation in their physical and chemical properties.

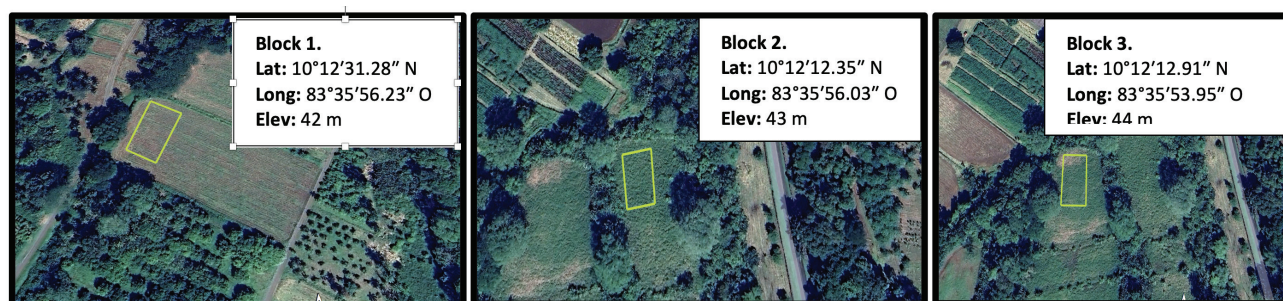


Figure 1. Layout of Experimental Block 1,2 and 3, used for the calibration study at EARTH University.

Equipment

Two seeding systems were evaluated Figure 2: a pneumatic seeder and a mechanical seeder (control). The pneumatic model, Jumil Excellence 04 Double Lines, uses an air suction system to meter and deliver seeds with high precision. Its adjustable vacuum pressure directly affects seed pick-up, release, and placement accuracy—key factors for uniform emergence and optimal stand density[13]. Vacuum pressure was manually set at three levels (−3, 0, +3), and seeding speed varied across 4, 6, and 9 km/h. Seed depth and target population remained constant across treatments.

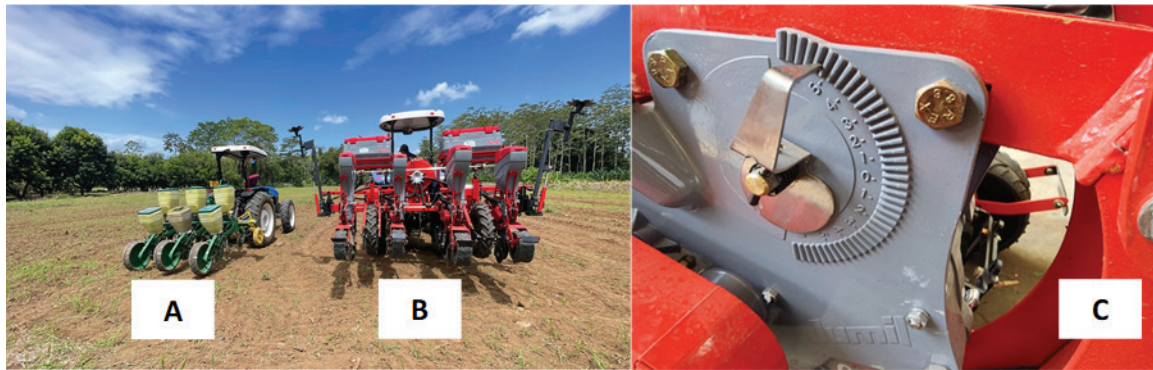


Figure 2. Seeding equipment. (A) shows the mechanical seeder (control) used in the study; (B) shows the pneumatic seeder used in the experiment. (C) Pressure adjustments on the pneumatic seeder, showing the control mechanism used to regulate vacuum pressure during planting.

The mechanical seeder (Tatu T231) operates without suction [14] . relying on a rotating plate or chain to drop seeds into furrows. This gravity-based system is less precise under variable soil moisture conditions. Both seeders were operated at identical row spacing and target population, with matched seeding speeds. This comparative setup allowed the study to assess how pneumatic vacuum pressure interacts with planting speed and soil moisture, in contrast to the mechanical system's fixed metering. The evaluation focused on improvements in seed placement, emergence uniformity, and stand establishment attributable to pneumatic technology.

Prior to planting, the experimental field got a mechanical tillage to establish optimal conditions for the subsequent crop beds. This preparatory step involved two sequential passes with a tractor-mounted implement. Specifically, a 20-inch disc plow was utilized for primary tillage, to ensure precision in the methodology. The dual-pass regimen was essential for achieving the necessary soil pulverization, aeration, and structural homogeneity required to promote root development and efficient water infiltration within the final planting medium, thereby guaranteeing suitable soil conditions for the successful establishment of the target population.

Experimental Design

The corn hybrid HR960 [15] was selected due to its adaptation to humid tropical environments and its dual-purpose use for grain and silage. It is suitable for cultivation from sea level up to 1600 m a.s.l.

To evaluate the influence of seeder calibration and soil conditions on early corn development, a split-block factorial design was implemented across three experimental blocks, each comprising clay-rich soils with slight differences in moisture content and texture (percentages of clay, silt, and sand). Twelve plots measuring 15 m × 5 m were distributed across the blocks. The

experimental factors included three levels of vacuum pressure applied to a pneumatic seeder (P1: -3, P2: 0, P3: +3), a mechanical seeder control (C1), and three seeding velocities (V1: 4 km/h, V2: 6 km/h, V3: 9 km/h), as shown in Table 1.

Table 1. Experimental Seeding Treatments: Seeder Type, Pressure, Speed, and Humidity.

Seeder Type	Vacuum Pressure	Seeding Speed (km/h)	Humidity Condition
Pneumatic	-3	4, 6, 9	High / Low
Pneumatic	0	4, 6, 9	High / Low
Pneumatic	+3	4, 6, 9	High / Low
Mechanical	Control	4, 6, 9	High / Low

Each treatment combination was applied once per block and replicated across two distinct soil moisture cycles to capture variability in field conditions. The schematic layout Figure 3 facilitated comparative analysis of seeder calibration effects under varying edaphic moisture regimes. This configuration enabled precise evaluation of seed placement accuracy, emergence rate, and stand uniformity.

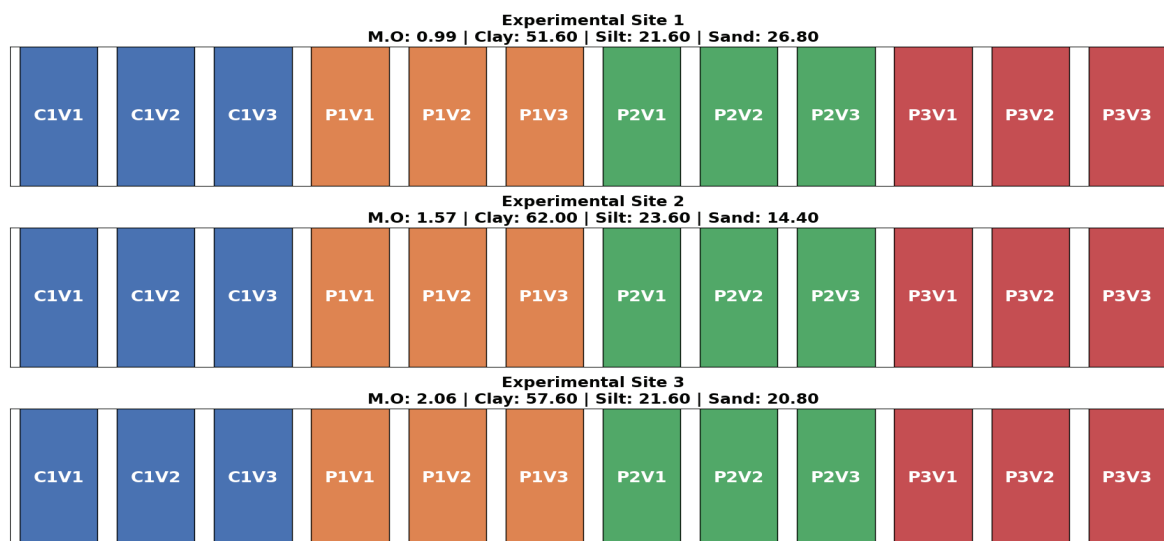


Figure 3. Distribution of experimental blocks for the split-block design, showing treatments in relation to vacuum pressure, seeding velocity, and soil characteristics.

Soil volumetric water content (% VWC) was measured using a TDR 350 time-domain reflectometry probe at five points per block and averaged per cycle. Two moisture cycles were defined: low humidity (22.39% VWC) following dry conditions, and high humidity (37.39% VWC) following rainfall events.

Field Data Collection

To determine the actual plant population, three square subplots, 2 m × 2 m, were established within each plot of treatment. The number of emerged plants was counted eight days after planting. These subplot dimensions were chosen to balance representativeness and feasibility of measurements.

Plant height and stem diameter were measured 15 days after planting. Plant height was recorded from the base of the plant to the base of the newest emerging leaf using a measuring tape, and stem diameter was measured 5 cm above the soil surface using a caliper. All measurements were conducted at the same time of day and with the same instruments to minimize environmental or observational variability.

Statistical Analysis Methods

Data management and visualization were performed using Python [16], with libraries such as pandas[17], [18] for data management and Matplotlib [19], [20] and Seaborn[20] for creating the graphs. A one-way ANOVA was conducted to identify statistically significant differences among treatments, followed by Tukey's Honest Significant Difference (HSD) post hoc test to determine which treatments differed [21].

Principal Component Analysis (PCA)

For multivariate analysis, the variables population, seeding speed, vacuum pressure, block, and soil moisture were selected. First, a data matrix was constructed excluding missing values to ensure consistency. Variables were then standardized using the zscore method via *StandardScaler* from the scikit-learn library. This standardization ensured that variables with larger magnitudes or different units did not dominate the analysis[22].

A PCA was applied to reduce data dimensionality and identify patterns of variation[23]. The first two principal components, which explained a substantial portion of the total variance, were calculated. Results were stored in a new data frame, including categorical variables such as treatment, humidity, and block for easier interpretation. The explained variance of each component was calculated to assess its contribution to representing the original data.

Multiple Linear Regression

A multiple linear regression model was constructed to evaluate the effect of soil moisture, pneumatic seeder vacuum pressure, and seeding speed on the final plant population. Predictor variables included humidity, pressure, and velocity, and the response variable was population. The model was fitted using `LinearRegression()` from scikit-learn, and predictions were obtained with `predict()` [21], [24].

$$Population = \beta_0 + \beta_1 \cdot humidity + \beta_2 \cdot pressure + \beta_3 \cdot velocity \quad (1)$$

Where:

- Population: represents the number of established plants per plot or treatment.
- β_0 : the intercept or constant term of the model, indicating the expected population value when all independent variables are zero.
- $\beta_1, \beta_2, \beta_3$: regression coefficients that measure the individual effect of each independent variable on the population.
- humidity: soil moisture level at the time of planting or during plant establishment.
- pressure: vacuum pressure used in the pneumatic seeder during calibration.

- velocity: forward speed of the seeder during planting.

Model performance was evaluated using the coefficient of determination (R^2) and the Mean Absolute Error (MAE). The relative importance of each predictor was estimated from the absolute values of the regression coefficients. For more robust comparisons, standardized coefficients or permutation importance may also be used.

The primary quantitative metrics employed were:

Root Mean Squared Error (RMSE): measures the average magnitude of prediction errors [25].

$$RMSE = \sqrt{\sum \frac{(y_i - \bar{y}_i)^2}{n}} \quad (2)$$

Mean Absolute Error (MAE): the average absolute difference between predicted and actual values[25].

$$MAE = \sum \frac{|y_i - \bar{y}_i|}{n} \quad (3)$$

Coefficient of Determination (R^2): the proportion of variance in the observed data explained by the model[26].

$$R^2 = \frac{\sum (y_i - p_i)^2}{\sum (y_i - \bar{y}_i)^2} \quad (4)$$

Where:

y_i = observed values of the target variable

p_i = predicted values from the model

$\bar{y}_i$ = mean of observed values

n = number of observations

Lower RMSE and MAE values indicate better model accuracy, while an R^2 value closer to 1 indicates a better fit, signifying that the model effectively captures the relationship between the predictor variables and final plant population.

Results

This section presents empirical results for corn plant diameter and height, These parameters were evaluated across various experimental treatments and two distinct humidity levels (Low: 22.39 %VWC; High: 37.39 %VWC) within three independent experimental blocks (B1, B2, B3). Data visualization was primarily achieved through box plots. Interestingly, plant diameter (Figure 5) exhibited contrasting responses across blocks.

In Block B1, high humidity generally promoted larger diameters, indicating a clear positive effect of moisture availability on stem thickening. In contrast, Blocks B2 and B3 showed smaller diameters overall and were less responsive to changes in humidity, suggesting that local soil or microenvironmental conditions moderated the effect. Despite these block-level differences, consistent treatment patterns were observed. Notably, P2V2 and P3V2 produced greater diameters under high humidity in all blocks, underscoring the advantage of increased soil

moisture for radial growth. For most other treatments, however, the differences among humidity levels were either minor or irregular, reinforcing that optimal combinations of pressure and planting speed are required to achieve uniform benefits across environments. In contrast to diameter, plant height was consistently greater under low humidity across all blocks (Figure 5).

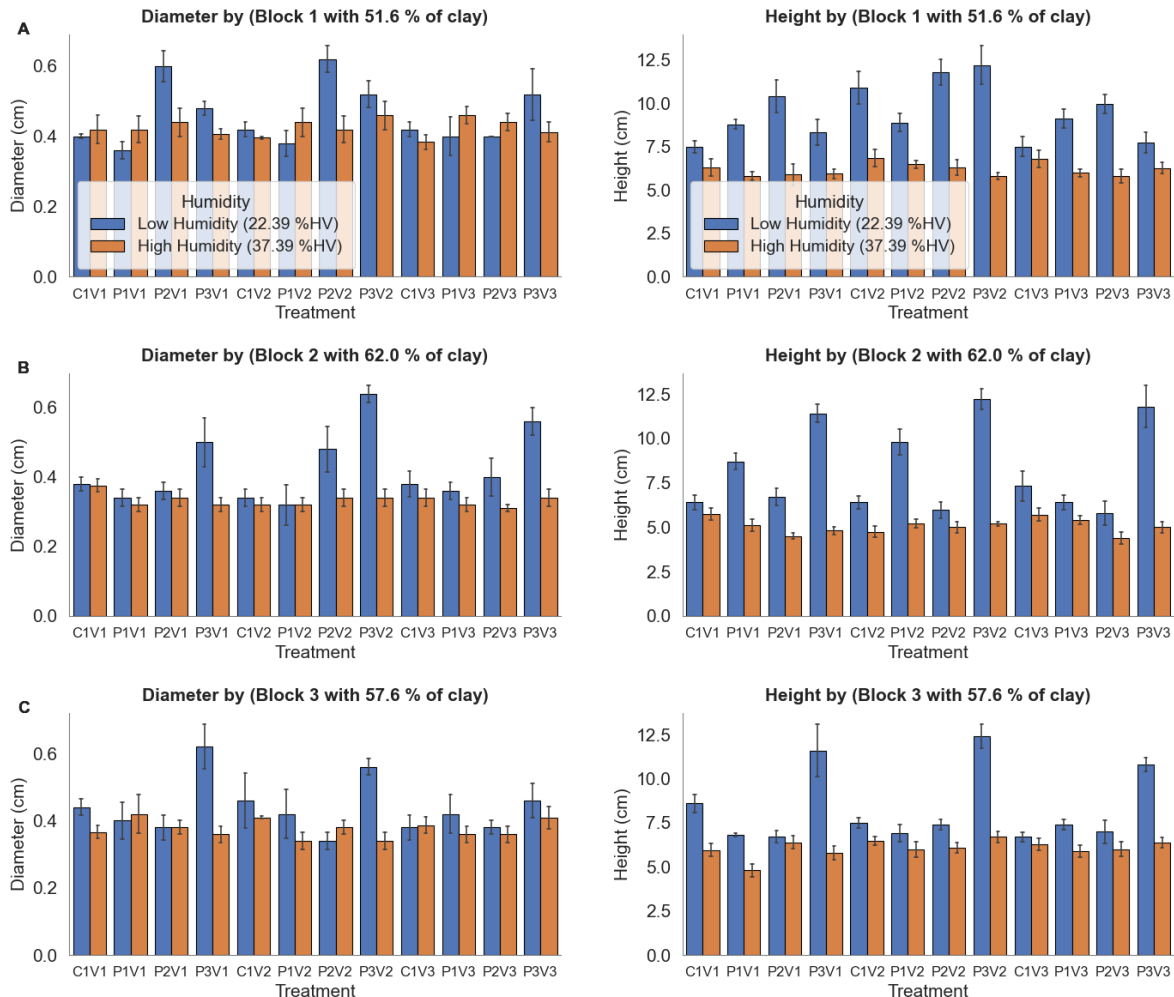


Figure 5.(A) Maize stem diameter (cm) and height (cm) under different treatment and humidity conditions across blocks 1, 2, and 3 (B1-B2-B3). (B) Maize plant height (cm) under different treatment and humidity conditions across blocks (B1-B2-B3).

This indicates a physiological trade-off, where conditions that favor elongation do not necessarily promote radial thickening. While the overall pattern was uniform, the extent of height increased varied slightly by block, with Block B1 producing the tallest plants for several treatments. Among treatments, P3V2 displayed the most reliable performance, achieving greater height under low humidity in every block. These results highlight that plant growth strategies shifted with water availability: low humidity promoted vertical elongation, whereas high humidity supported radial development.

The highest establishment (87 750 plants/ha) occurred under high vacuum pressure and high velocity, while another peak (84 062 plants/ha) was observed at normal vacuum pressure with medium velocity. Notably, population did not increase linearly with velocity, as high vacuum pressure combined with medium velocity produced the lowest overall population (65 750 plants/

ha). This highlights a non-linear relationship in which optimal establishment depends on the precise combination of seeder parameters rather than on individual factors alone. When isolating the effect of humidity (Figure 7A), a clear pattern emerged.

High humidity consistently led to greater population densities across treatments, underscoring the vital role of soil moisture in seed establishment. The difference between high and low humidity conditions was significant, with higher overall averages under increased moisture. This robust relationship highlights humidity as a critical factor influencing population density and, by extension, successful plant establishment, and growth. In contrast, the analysis of block effect (Figure 7B) showed overlapping error bars.

Figura 1. Efectos principales de los factores en la población

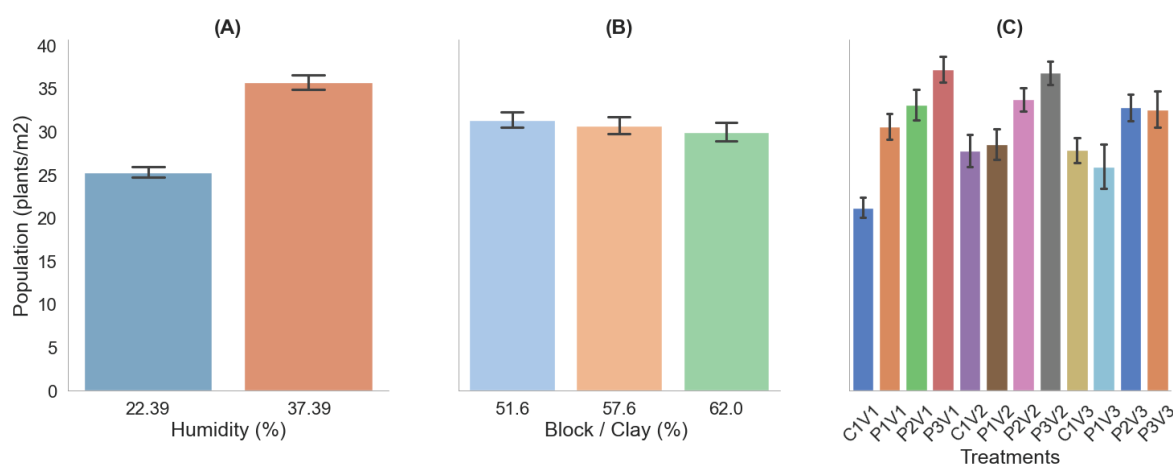


Figure 7. (A) The effect of low soil humidity (22.39 %) and high soil humidity (37.39 %) levels on maize population density (plants per 4 m²). (B) The effect of block differences on maize population density (plants per 4 m²). (C) The effect of different seeder pressure and planting speed treatments on the population density of maize (plants per 4 m²).

Indicating no statistically significant differences in population among B1, B2, and B3. This suggests that, unlike diameter and height, block conditions had little influence on plant population. The overlap of error bars, which represent confidence intervals or standard deviations, implies that any observed variation in mean population across blocks is likely attributable to random chance rather than a true block effect. Treatment effects (Figure 7C) revealed the correlation between each variable on the population.

Increasing vacuum pressure (from P1 to P3) consistently promoted higher populations compared to the control (C), regardless of velocity. The control remained lowest across all conditions, likely due to insufficient suction causing seed loss and irregular spacing. Populations rose steadily with vacuum pressure, reaching their highest values under P3, a trend that held across blocks and humidity levels. Velocity exerted a weaker and less consistent influence, with reductions in population mainly appearing at higher speeds, but its effect was clearly secondary to vacuum pressure. These results emphasize that adequate vacuum pressure is essential for uniform seed pickup and stand establishment, making it the primary driver of plant population. Principal Component Analysis (Figure 8) further clarified the dynamics influencing population establishment.

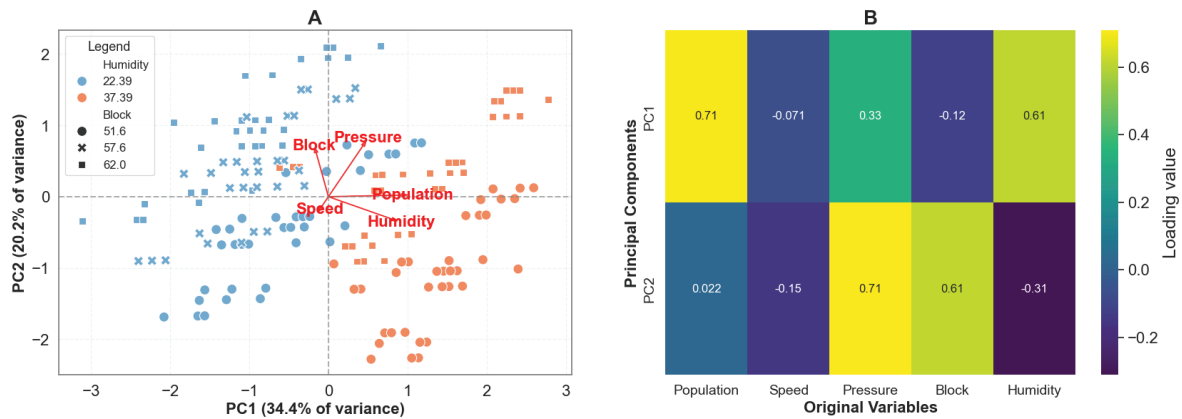


Figure 8. PCA results. (A) shows the biplots for the variables in PC1 and PC2; (B) shows the heat map for the main population predictor variables.

The first component (PC1), which explained 34.4 % of the total variance, was dominated by vacuum pressure and humidity. These variables had the longest vectors and were closely aligned, indicating they are the primary drivers of variance and are strongly positively correlated high vacuum pressure tends to coincide with high humidity. This confirms their significant role in determining population outcomes.

The second component (PC2) explained 20 % of the variance and was primarily associated with block differences. However, this variation did not translate into a statistically significant effect on population, reinforcing earlier results showing negligible block influence. Speed had minimal impact on either component, contributing little to the overall model variance.

Sample clustering revealed distinct groupings by block. Samples from blocks B2 and B3 clustered in regions associated with high vacuum pressure and humidity, while samples from B1 grouped in regions of lower vacuum pressure and humidity. Although block explained a portion of the variance, it was not a primary driver of population differences. Overall, the PCA highlights that population and humidity are the main factors explaining the variation in the data, with vacuum pressure playing a central and consistent role.

Calibration Equation

Building on the population results, a linear regression model was developed to predict population as a function of humidity, pressure, and velocity: The model achieved an R^2 of 0.73 and a MAE of 3.30 plants/ha, demonstrating strong predictive performance overall (Figure 9A).

A positive relationship was observed between measured and predicted populations, with most estimates closely matching observed values, indicating that the model effectively captures the general data trend. However, greater dispersion occurred at lower population values, suggesting reduced accuracy in that range. These results indicate good overall predictive capability, with some limitations in scenarios involving smaller populations. The analysis of variable importance (Figure 9B) reinforces the findings from the previous analysis.

$$\text{Population} = 12.43 + 0.805 \cdot \text{humidity} + 1.194 \cdot \text{pressure} - 0.654 \cdot \text{velocity} \quad (5)$$

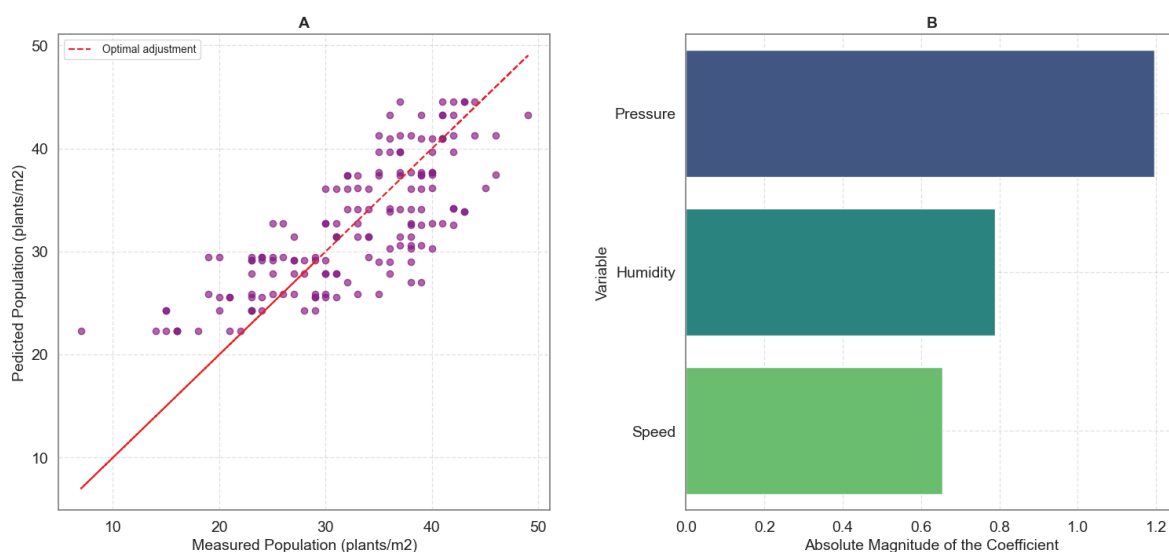


Figure 9. (A) Comparison of Predicted and Measured Population Values from the Linear Regression Model. (B) Relative Importance of Predictor Variables in the Linear Regression Model for Population Estimation.

Vacuum Pressure emerged as the most influential factor, followed by humidity, while velocity had a negative effect and block effects were minimal. Vacuum Pressure had the highest impact ($\beta = 1.1944$), indicating that higher pressure improves population by enhancing seed placement precision. Humidity also contributed positively ($\beta = 0.8049$), highlighting the importance of adequate soil moisture for seed emergence and establishment. In contrast, seeding speed showed a negative effect ($\beta = -0.6545$), suggesting that higher speeds reduce population, likely due to less uniform seed distribution. The block effect was minimal and negative ($\beta = -0.1247$), confirming that variability between plots had little influence compared to the other factors.

Discussion

The analysis of morphological traits and plant population revealed complex interactions among humidity and planting treatments. These factors influenced stem diameter, plant height, and stand population differently, showing that crop establishment is shaped by a combination of environmental conditions and mechanical seeder settings. To explore these relationships more systematically, a Principal Component Analysis (PCA) was conducted to identify the main drivers of variance and complement morphological observations. The following sections describe how these traits respond to both environmental and mechanical factors, with particular emphasis on the role of vacuum pressure in pneumatic seeding.

Stem diameter increased under high-humidity conditions, particularly in treatment P3V2. This aligns with [27], who reported that greater water availability promotes cell expansion and tissue thickening, improving stem rigidity. Similarly, [28] found that adequate moisture reduces lodging risk by encouraging thicker stems. In this study, the combination of higher vacuum pressure (level 3) and moderate speed (V2) likely enhanced seed-soil contact, facilitating uniform germination and early root development. Mechanically, higher vacuum pressure reduces failures in seed suction and release, improving planting precision and enhancing water and nutrient uptake for seedlings[29]. These results demonstrate that vacuum pressure not only affects early seedling growth but also supports the development of structurally stronger plants, especially under favorable humidity conditions.

While stem diameter increased with humidity, plant height exhibited an opposite trend, responding more strongly to low-humidity conditions. Height was greater under moderate water stress, reflecting a physiological adaptation to optimize light capture and reduce competition [30]. In this study, treatment P3V2 under low humidity nearly doubled plant height compared to the same treatment under high humidity, suggesting that an increased auxin-to-gibberellin ratio under stress favors elongation over radial growth [31]. Under low humidity, plants likely activated elongation mechanisms to enhance light interception, a typical drought-avoidance response. Vacuum pressure also indirectly contributed to this pattern by ensuring uniform seed placement, which allowed seedlings to emerge and develop under consistent initial conditions [29]. Thus, mechanical precision interacts with environmental stress to shape plant architecture differently for height and diameter.

Plant population was generally higher under high-humidity conditions, particularly in treatment P3V2, where median values exceeded 40 plants per plot [31] similarly reported that greater water availability during germination improves emergence rate and seedling uniformity. Beyond environmental effects, vacuum pressure played a critical role in determining population uniformity and seeding depth. Adequate suction ensures that each seed adheres to the metering plate until the precise release moment, minimizing skips and multiple seed drops [32]. Higher vacuum stabilizes seed retention for irregular or lightweight seeds, improving within-row spacing and overall stand uniformity [33].

Several studies support these findings. [32] emphasized that vacuum level is a key determinant of seed distribution uniformity, while [34] demonstrated that both vacuum magnitude and metering disc geometry control the stability of seed pickup and release. Insufficient vacuum can cause premature detachment and reduced population uniformity, whereas excessive vacuum can lead to multiple seeds adhering to the same orifice, decreasing singulation efficiency [35] [36]. In addition, vacuum pressure affects seeding depth consistency, reducing variability in emergence timing and promoting synchronous seedling establishment [37] [38]. Synchronous emergence supports early vigor and competitive ability, ultimately enhancing plant growth [31].

At higher planting speeds, the significance of vacuum pressure increases further. Elevated vacuum compensates for inertial forces acting on seeds, maintaining singulation and placement accuracy [36], [39]. Thus, vacuum pressure acts as the central control parameter that harmonizes seed spacing, emergence uniformity, and final population across environmental gradients. Higher stand uniformity reduces intraspecific competition and supports more balanced nutrient uptake, contributing to stronger early growth and yield potential.

To integrate these morphological and mechanical findings, a Principal Component Analysis (PCA) was conducted to simplify the dataset while retaining the most meaningful variance patterns related to maize growth and seeding performance. The first principal component (PC1) explained 34.4 % of the total variance and was primarily influenced by vacuum pressure and humidity, while the second component (PC2) accounted for 20 % resulting in a cumulative explained variance of 54.4 %. Although no universal threshold exists, retaining components explaining over 50 % of the variance ensures interpretability and minimizes information loss [40], [41], [42].

PC1 represented a mechanical–environmental axis, where high vacuum pressure and humidity promoted uniform establishment, while PC2 captured morphological variability linked to plant height and stem thickness. The predominance of PC1 confirms that vacuum pressure and humidity are the main drivers of plant establishment, connecting mechanical seeder calibration with morphological performance. Similar findings have been reported by [29], who demonstrated

that variations in pneumatic pressure significantly affect seed spacing and plant distribution, and by [32], who emphasized that optimal vacuum levels ensure accurate seed singulation and consistent seed depth.

Furthermore, the association between these factors and morphological traits supports prior research showing that adequate soil moisture enhances germination and seedling uniformity [31], while excessive speed or improper vacuum calibration can lead to erratic plant spacing [29], [35]. PCA visualization thus provides an integrative understanding of how both environmental and operational parameters interact to shape maize establishment dynamics.

When interpreted alongside the observed effects on stem diameter, plant height, and final population, the PCA results underscore the synergistic role of environmental (humidity, temperature, and soil texture) and mechanical (vacuum pressure and speed) variables in defining precision planting outcomes [43], [44]. Optimizing these factors ensures uniform seed distribution, synchronized emergence, and stable early crop development, which are essential for improving maize yield potential [33], [36].

Conclusion

This study demonstrates that maize morphology and population dynamics are strongly shaped by both humidity and vacuum pressure, with their interaction playing a decisive role in determining growth outcomes. Humidity proved to be a critical environmental factor: high-humidity conditions consistently supported greater population establishment, particularly under the P3 treatment, while lower humidity favored taller plants. This reflects a physiological trade-off between elongation and establishment, where abundant moisture promotes higher plant density, and moderate moisture stress encourages axial growth.

Among the mechanical factors evaluated, vacuum pressure had the most significant impact. Higher vacuum pressure enhanced seed placement accuracy and emergence, resulting in more uniform stands and greater plant density compared to the control. Seeder speed, within the tested range, did not significantly affect the measured variables. Block effects were minimal, with no statistically significant differences in population, though Block B1 showed slight advantages, likely linked to soil structure or microenvironmental variation. Principal component analysis confirmed that vacuum pressure and humidity were the primary drivers of variation, with speed and block effects playing secondary roles. The predictive model developed performed well, showing strong agreement between predicted and observed population values in medium and high emergence scenarios, though accuracy decreased in low-establishment cases.

Overall, this work achieved its main objective of identifying optimal calibration parameters for a pneumatic seeder in clayey soils. The specific objectives were met by clearly demonstrating the effects of vacuum pressure and humidity on germination, plant morphology, and stand establishment; evaluating their interaction and confirming their influence on seed placement, emergence uniformity, and stand density; and creating a validated predictive model integrating environmental and mechanical factors to guide seeder calibration.

These findings contribute valuable knowledge for precision agriculture, providing practical guidance for adjusting pneumatic seeder settings according to soil moisture and vacuum pressure. Such insights can improve maize establishment and uniformity in humid, clay-rich soils, supporting more efficient, profitable, and sustainable farming systems.

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References

- [1] J. Dufour, "Effects of Plant Spacing Variability and Non-Uniform Emergence on Corn Yield," LSU, 2021. Accessed: Oct. 19, 2025. [Online]. Available: <https://www.proquest.com/openview/63d62347869df6cb9fec0ca147196b4c/1?pq-origsite=gscholar&cbl=18750&diss=y>
- [2] M. Maymon *et al.*, "Characterization of *Fusarium* population associated with wilt of jojoba in Israel," *Plant Pathol*, vol. 70, no. 4, pp. 793–803, May 2021, doi: 10.1111/ppa.13345.
- [3] L. Schneider, T. Müller, and R. Becker, "The effect of climate change on invasive crop pests across regions.," *Agric Syst*, vol. 196, no. 103–112, 2021, doi: <https://doi.org/10.1016/j.agsy.2021.103112>.
- [4] Q. Wei *et al.*, "Future Range Shifts in Major Maize Insect Pests Suggest Their Increasing Impacts on Global Maize Production," *Insects*, vol. 16, no. 6, p. 568, May 2025, doi: 10.3390/insects16060568.
- [5] V. Vasile, A. Tîrziu, E. Nicolae, M. Ciucă, and C. P. Cornea, "SSR Markers are Useful Tools in Wheat Varietal Purity and Genetic Diversity Assessment," *Seed Science and Technology*, vol. 51, no. 2, pp. 145–156, Aug. 2023, doi: 10.15258/sst.2023.51.2.01.
- [6] Y. Wang, Y.-J. Shen, S. Yu, X. Zhang, and D. Xiao, "Climate extremes are critical to maize yield and will be severer in North China," *Clim Risk Manag*, vol. 48, p. 100710, 2025, doi: 10.1016/j.crm.2025.100710.
- [7] C. Wang, H. Yang, J. He, K. Kang, and H. Li, "THE INFLUENCE OF SEED VARIETY AND HIGH SEEDING SPEED ON PNEUMATIC PRECISION SEED METERING," *Engenharia Agrícola*, vol. 43, no. 3, 2023, doi: 10.1590/1809-4430-eng.agric.v43n3e20220183/2023.
- [8] J. W. Cortez, M. Anghinoni, and S. N. S. Arcoverde, "SEED METERING MECHANISMS AND TRACTOR-SEEDER FORWARD SPEED ON CORN AGRONOMIC COMPONENTS," *Engenharia Agrícola*, vol. 40, no. 1, pp. 61–68, Feb. 2020, doi: 10.1590/1809-4430-eng.agric.v40n1p61-68/2020.
- [9] J. C. C. Madaloz *et al.*, "Distribution of corn plants in a pneumatic system with different vacuum pressure adjustments and seed sieves," *Aust J Crop Sci*, no. 14(10):2020, pp. 1568–1574, Oct. 2020, doi: 10.21475/ajcs.20.14.10.p2316.
- [10] K. Romaneckas *et al.*, "How to Analyze, Detect and Adjust Variable Seedbed Depth in Site-Specific Sowing Systems: A Case Study," *Agronomy*, vol. 12, no. 5, p. 1092, Apr. 2022, doi: 10.3390/agronomy12051092.
- [11] P. B. Obour and C. M. Ugarte, "A meta-analysis of the impact of traffic-induced compaction on soil physical properties and grain yield," *Soil Tillage Res*, vol. 211, p. 105019, Jul. 2021, doi: 10.1016/j.still.2021.105019.
- [12] X. Shi, T. Qin, D. Yan, F. Tian, and H. Wang, "A meta-analysis on effects of root development on soil hydraulic properties," *Geoderma*, vol. 403, p. 115363, Dec. 2021, doi: 10.1016/j.geoderma.2021.115363.
- [13] Agroenlace, "Sembradora Abonadora excellence 4 líneas dobles." Accessed: Oct. 20, 2025. [Online]. Available: <https://agroenlace.co/producto/sembradora-abonadora-excellence-4-lineas-dobles/>
- [14] T. Marchesan, "Row crop planter." Accessed: Oct. 20, 2025. [Online]. Available: <https://en.marchesan.com.br/product/detail/STP2-Row-Crop-Planter/en-US>
- [15] Disagro, "HR-960." Accessed: Oct. 20, 2025. [Online]. Available: <https://www.disagro.co.cr/product/hr-960/>
- [16] G. Van Rossum and F. L. Drake, *Python 3 Reference Manual*. Scotts Valley, CA: CreateSpace, 2009.
- [17] T. pandas development team, "pandas-dev/pandas: Pandas," Feb. 2020, *Zenodo*. doi: 10.5281/zenodo.3509134.
- [18] R. Snehkunj, K. Vachiyatwala, and C. Author, "Data Analysis Using Pandas Library of Python," *Acta Scientific COMPUTER SCIENCES*, vol. 4, no. 3, 2022.
- [19] J. D. Hunter, "Matplotlib: A 2D graphics environment," *Comput Sci Eng*, vol. 9, no. 3, pp. 90–95, 2007, doi: 10.1109/MCSE.2007.55.
- [20] M. L. Waskom, "seaborn: statistical data visualization," *J Open Source Softw*, vol. 6, no. 60, p. 3021, 2021, doi: 10.21105/joss.03021.
- [21] Darren Jones, "Python Statistics Fundamentals: How to Describe Your Data," *Real Python*, 2023.

- [22] Scikit-learn, "Principal component analysis (PCA)," 2025, Accessed: Oct. 20, 2025. [Online]. Available: <https://scikit-learn.org/stable/modules/generated/sklearn.decomposition.PCA.html>
- [23] I. T. Jolliffe and J. Cadima, "Principal component analysis: a review and recent developments," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374, no. 2065, p. 20150202, Apr. 2016, doi: 10.1098/rsta.2015.0202.
- [24] F. Pedregosa *et al.*, "Scikit-learn: Machine Learning in {P}ython," *Journal of Machine Learning Research*, vol. 12, pp. 2825–2830, 2011, [Online]. Available: <https://scikit-learn.org/stable/index.html>
- [25] M. W. Liemohn, A. D. Shane, A. R. Azari, A. K. Petersen, B. M. Swiger, and A. Mukhopadhyay, "RMSE is not enough: Guidelines to robust data-model comparisons for magnetospheric physics," *J Atmos Sol Terr Phys*, vol. 218, 2021, doi: 10.1016/j.jastp.2021.105624.
- [26] D. Chicco, M. J. Warrens, and G. Jurman, "The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation," *PeerJ Comput Sci*, vol. 7, 2021, doi: 10.7717/PEERJ-CS.623.
- [27] R. Wulansari, B. Farhana, and N. Fajrina, "Field Emergence Test in Relation to Laboratory Seed Quality Tests of Sweet Corn Seed," *IOP Conf Ser Earth Environ Sci*, vol. 1160, no. 1, p. 012017, Apr. 2023, doi: 10.1088/1755-1315/1160/1/012017.
- [28] N. Shrestha, J. Zhang, and H. Zhang, "Identifying key factors influencing maize stalk lodging. Plant Phenomics," vol. 7, no. 100073, 2025, Accessed: Oct. 21, 2025. [Online]. Available: 10.1016/j.aiaa.2025.01.007
- [29] I. Petrović, F. Vučajnk, S. Trdan, R. Bernik, and M. Vidrih, "The Influence of Planting Speed of a Maize Vacuum Planter on Plant Spacing Variability and Ear Parameters," *Agronomy*, vol. 15, no. 2, p. 462, Feb. 2025, doi: 10.3390/agronomy15020462.
- [30] D. B. Lobell, G. L. Hammer, G. McLean, C. Messina, M. J. Roberts, and W. Schlenker, "Maize yield under a changing climate: The hidden role of vapor pressure deficit," *arXiv Preprint*, 2019, Accessed: Oct. 21, 2025. [Online]. Available: <https://arxiv.org/abs/1910.03129>
- [31] H. Khaeim, Z. Kende, M. Jolánkai, G. P. Kovács, C. Gyuricza, and Á. Tarnawa, "Impact of Temperature and Water on Seed Germination and Seedling Growth of Maize (*Zea mays* L.)," *Agronomy*, vol. 12, no. 2, p. 397, Feb. 2022, doi: 10.3390/agronomy12020397.
- [32] D. Karayel, O. Güngör, and E. Šarauskis, "Estimation of Optimum Vacuum Pressure of Air-Suction Seed-Metering Device of Precision Seeders Using Artificial Neural Network Models," *Agronomy*, vol. 12, no. 7, p. 1600, Jul. 2022, doi: 10.3390/agronomy12071600.
- [33] A. Bozdoğan, B. Demir, and B. Kayisoglu, "Seeding uniformity for vacuum precision seeders," *Sci Agric*, vol. 65, no. 6, pp. 631–637, 2008, Accessed: Oct. 26, 2025. [Online]. Available: <https://www.scielo.br/j/sa/a/ZpsNfMtP4YnVKMQNZ3H7hQg/?format=pdf&lang=en>
- [34] A. Yazgi, "Measurement of seed spacing uniformity performance of a precision metering unit. Measurement," vol. 54, pp. 123–130, 2014, Accessed: Oct. 26, 2025. [Online]. Available: 10.1016/j.measurement.2014.06.026
- [35] M. Haddadi, S. Karimi, and S. Mahapatra, "Optimization of performance parameters for a pneumatic vacuum disc type planter," *SSRN Electronic Journal*, 2025, Accessed: Oct. 26, 2025. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4273465
- [36] S. Mahapatra, R. Singh, and P. Kumar, "Optimization of operational parameters for pneumatic air-suction planters," *Sci Rep*, vol. 15(1), 2025, Accessed: Oct. 26, 2025. [Online]. Available: <https://www.nature.com/articles/s41598-025-98448-4>
- [37] A. Ozmerzi, D. Karayel, and M. Topakci, "Effect of sowing depth on precision seeder uniformity," *Power Machinery*, pp. 257–263, 2002.
- [38] Michigan State University Extension, "Stand uniformity: Planter tips that can impact seed placement and planting depth," 2023.
- [39] GroundCover, "Precision planting study yields encouraging results," *Grains Research and Development Corporation*, 2024, Accessed: Oct. 26, 2025. [Online]. Available: <https://groundcover.grdc.com.au/innovation/precision-agriculture-and-machinery/precision-planting-study-yields-encouraging-results>
- [40] H. Abdi and L. J. Williams, "Principal component analysis," *WIREs Computational Statistics*, vol. 2, no. 4, pp. 433–459, Jul. 2010, doi: 10.1002/wics.101.
- [41] I. T. Jolliffe and J. Cadima, "Principal component analysis: a review and recent developments," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374, no. 2065, p. 20150202, Apr. 2016, doi: 10.1098/rsta.2015.0202.

- [42] F. Pedregosa *et al.*, "Scikit-learn: Machine learning in Python," *Journal of Machine Learning Research*, vol. 12, no. 2825–2830, 2011, Accessed: Oct. 20, 2025. [Online]. Available: <https://jmlr.org/papers/v12/pedregosa11a.html>
- [43] S. Stewart, N. Kitchen, M. Yost, L. S. Conway, and P. Carter, "Planting depth and within-field soil variability impacts on corn stand establishment and yield," *Agrosystems, Geosciences & Environment*, vol. 4, no. 3, Jan. 2021, doi: 10.1002/agg2.20186.
- [44] J. C. Vargas, "Evaluación de velocidad siembra de maíz forrajero con sembradora neumática en el distrito de Vitor, provincia y departamento de Arequipa ," Universidad Nacional de San Agustín de Arequipa, Arequipa, 2020. Accessed: Oct. 26, 2025. [Online]. Available: <https://45.231.83.156/handle/20.500.12996/4595>

Declaración sobre uso de Inteligencia Artificial (IA)

Para la revisión gramatical y ortográfica de este artículo, empleamos la herramienta de IA *Perplexity, Claude*. Esta nos permitió identificar errores y mejorar la fluidez del texto. No obstante, realizamos una revisión final para garantizar que el artículo cumpliera con los estándares de calidad de la revista.