# Enhancing Pea Productivity and Disease Control via Sowing Density and Trellising Net System Synergies

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**Abstract**

Pea (*Pisum sativum* L.) productivity depends on canopy architecture and planting density. This field study assessed the interaction between a trellising net system (TS; present vs. absent) and three sowing densities (80, 40, and 27 kg·ha$^{-1}$) on growth, yield components, and disease incidence in cultivar Pairumani 1. Trials were conducted in Cohajoni, Sorata, from March to July 2024, using a randomized complete-block, split-plot design with three replications. Statistical analysis revealed a highly significant TS × density interaction for pod length ($p < 0.01$), and significant TS × density interactions for plant height, grain weight per pod, and green-pod yield ($p < 0.05$). The TS × 80 kg·ha$^{-1}$ treatment produced the highest green-pod yield (8.0 t·ha$^{-1}$), which was more than 30% higher than comparable non-trellised treatments. Trellising improved canopy stability and light interception, reduced lodging, increased the number of grains per pod and mean pod weight, and reduced pod-weight variability. Trellised plots also showed a marked (~70%) reduction in powdery mildew (*Erysiphe pisi*) incidence, which is attributed to improved aeration and reduced canopy humidity. Higher sowing density increased area-level yield via population compensation but intensified intraspecific competition, thereby reducing pods per plant. For field technicians, combining trellising with approximately 80 kg·ha$^{-1}$ maximizes green-pod yield and crop health, provided it is integrated with balanced nutrition, adequate water management, uniform sowing, and regular disease monitoring. Results are specific to the tested cultivar, season, and environment; therefore, multi-season, multi-site validation and an economic assessment comparing trellising input costs with yield gains are recommended before wider adoption.

**Keywords:** *Pisum sativum*, pod quality, plant architecture, canopy management, disease management, legume cultivation

## 1. Introduction

Peas (*Pisum sativum* L.) are a globally important legume crop, valued for their high protein content and their contribution to soil fertility via biological nitrogen fixation (Carlson-Nilsson et al., 2021). In Bolivia, particularly in the inter-Andean valleys, pea cultivation holds substantial economic and social importance for smallholder farmers. These regions present distinct agroecological challenges, including high altitudes, complex topography, and climatic conditions that impose thermal stress and management limitations on crop production.

Despite these challenges, research has demonstrated that improved pea varieties can achieve yields ranging from 6 to 16 t ha$^{-1}$, substantially exceeding the average yield of local varieties, which is approximately 3.7 t ha$^{-1}$ (Maiza et al., 2015). These findings underscore the yield potential associated with improved cultivars and the central role of agronomic practices in enhancing pea productivity (Wu et al., 2023a).

Among various agronomic factors, sowing density plays a critical role in influencing plant growth and yield. It affects intraspecific competition, light interception, and canopy architecture, which collectively influence yield components and overall crop health (Carr et al., 2024). Recent studies have highlighted nonlinear yield responses of peas to sowing density, indicating the importance of optimizing plant population to balance competition and efficient resource use (Prusiński & Borowska, 2022).

Lodging is another major constraint in pea cultivation, as it disrupts canopy structure, increases disease susceptibility, and reduces harvest efficiency. While the development of semi-leafless pea varieties has contributed to mitigating lodging risk (Checa et al., 2020), physical support systems remain essential, especially for climbing types and in environments with high lodging incidence. Trellising systems not only provide mechanical support but also improve canopy aeration and light penetration, potentially enhancing yield and pod quality.

Given the edaphoclimatic characteristics of the inter-Andean valleys of La Paz, characterized by water seasonality, cold nights, and a high susceptibility to lodging in tall pea varieties, it is hypothesized that a combined strategy integrating optimal sowing density with effective trellising systems can enhance resource capture, reduce lodging, and improve overall crop health. This hypothesis aligns with recent findings suggesting that integrated management of canopy density and architecture can improve agronomic stability and yield across contrasting environments (Prusiński & Borowska, 2022).

Therefore, the objective of this study was to evaluate the interaction between sowing density and trellising net systems in pea cultivation, aiming to generate locally relevant technical evidence to support site-specific management recommendations for the conditions of the inter-Andean valleys of La Paz.

## 2. Method

### *2.1 Description of the Study Area*

The experiment was conducted between March and July 2024 in the community of Cohajoni, Sorata, La Paz, Bolivia, at an elevation of 2,650 m above sea level (15°43'57.19" S, 68°41'23.09" W). During the experimental period, climatic conditions remained within ranges considered suitable for pea (*Pisum sativum* L.) cultivation, with minimum daily temperatures varying between 4 and 12 °C and maximum daily temperatures ranging from 20 to 27 °C (SENAMHI, 2024). Irrigation was performed using a sprinkler system, and all standard agronomic practices recommended for pea production in the region were consistently adopted throughout the trial.

### *2.2 Pea Cultivar and Treatments*

The genetic material used in this study was the pea cultivar 'Pairumani 1', which is recommended for cultivation in valley and high-altitude regions between 1,500 and 3,000 m a.s.l. and has an average green pod yield of 4-6 t $ha^{-1}$. The experiment was conducted using a randomized complete block design with a split-plot arrangement, with three replications. The evaluated factors were (i) the trellising system (TS) at two levels (with and without trellising nets) and (ii) the sowing density (SD) at three levels (Table 1).

Table 1. Description of treatments based on combination of factors

| Treatment | Trellising net system | Sowing Density (kg $ha^{-1}$) |
|---|---|---|
| T1 | with | 80 |
| T2 | with | 40 |
| T3 | with | 27 |
| T4 | without | 80 |
| T5 | without | 40 |
| T6 | without | 27 |

### *2.3 Response Variables*

A range of agronomic and health-related response variables was measured on the pea plants to evaluate treatment effects. The variables assessed are described in Table 2.

Table 2. Response variables evaluated and description of the assessment methodology

| Variables | Methodology |
|---|---|
| Plant height (PH) | Plant height was measured at physiological maturity using a measuring tape on four randomly selected plants per experimental unit, recording the distance (cm) from the root collar to the apex of the main stem. |
| Number of flowers per plant (NFP) | The number of flowers per plant was recorded at full flowering by counting flowers on four randomly selected plants per experimental unit, from which the mean value was calculated. |
| Number of pods per plant (NPP) | The number of pods per plant was recorded at physiological maturity by counting pods in four randomly selected plants per experimental unit, and the mean value was subsequently calculated. |
| Pod length (PL) | Pod length was measured at physiological maturity by randomly selecting four pods from the middle section of four plants per experimental unit. Length was determined using a digital caliper (cm), and the mean value was subsequently calculated. |
| Pod weight (PW) | In the same pods used for length measurements, pod weight was determined using a calibrated electronic scale, and the average weight per pod (g) was subsequently calculated. |
| Pea number per pod (PNPP) | The number of peas per pod (PNPP) was determined by directly counting the peas in each pre-weighed pod per experimental unit. |
| Pea weight per pod (PWP) | Pea weight per pod (PWP) was determined by weighing all seeds from each pod on a calibrated electronic scale. |
| Pea diameter (PD) | Pea diameter was determined by randomly selecting five peas per experimental unit, measuring each with a vernier caliper in millimeters, and calculating the mean value. |
| Pod weight per plant (PWPP) | Pod weight per plant was measured at physiological maturity by harvesting and weighing all pods from four randomly selected plants per experimental unit, expressed in grams. |
| Pod yield (PY) | Pod yield per hectare was calculated from the total green-pod weight per experimental unit and expressed in (t $ha^{-1}$). |
| Presence of diseases | Disease presence was assessed in each experimental unit during vegetative, flowering, and fruiting stages using a binary scale: 0 = absence and 1 = presence of visible symptoms. |
| Disease incidence (%) | Disease incidence was assessed as the proportion of affected plants per experimental unit during vegetative, flowering, and fruiting stages. |

### *2.4 Experimental Procedure*

The experiment was established on a 338.8 $m^2$ plot. Sowing was conducted according to the target plant densities: 80 kg $ha^{-1}$ (plant spacing: 0.1 m; row spacing: 0.8 m), 40 kg $ha^{-1}$ (plant spacing: 0.2 m; row spacing: 0.8 m), and 27 kg ha$^{-1}$ (plant spacing: 0.3 m; row spacing: 0.8 m), with two seeds per planting hole.

The trellising net system was installed 40 days after crop emergence (Figure 1). Wooden stakes 1.8 m in height and 4 cm in diameter were positioned at 3 m intervals. A polypropylene trellising mesh, 1.2 m high and featuring 15 × 17 cm openings, was then carefully deployed to minimize mechanical damage to the plants.

Figure 1. Trellising net system installed for pea plant tutoring

Cultural practices included hilling performed two months after sowing and manual weeding carried out across the plots. Phytosanitary management targeted cutworm (*Agrotis ipsilon*), leafminer (*Liriomyza huidobrensis*), and aphid (*Myzus persicae*) through the application of lambdacyhalothrin at a rate of 200 mL ha$^{-1}$. Prior to flowering, an organic foliar fertilizer, Neem-K, containing nitrogen, phosphorus, and humic acids, was applied at a rate of 2 L ha$^{-1}$.

Harvest was performed manually when pods reached commercial maturity, characterized by well-formed, tender peas prior to hardening. Pods were detached from the peduncle following standard local practices, by pressing the thumb on the calyx to avoid mechanical damage to the pods.

*2.5 Statistical Analysis*

The experiment was conducted using a randomized complete block design with a split-plot arrangement and three replications. Statistical analyses were performed using a linear mixed-effects modeling approach, implemented with the *lmer* function from the *lme4* package in R (version 4.5.1). In the model, blocks were treated as a random effect, while the factors trellising net system and sowing density were included as fixed effects. Degrees of freedom for significance tests were approximated using the Satterthwaite approximation method.

When significant interactions were detected, the effects of individual factors were further explored through multiple comparisons using Tukey's test ($p \leq 0.05$), supported by interaction plots to facilitate visualization of response patterns. In cases where no significant interaction was observed, the main effects of each factor were analyzed independently using Tukey's test ($p \leq 0.05$). Additionally, the coefficients of variation (CV) and determination ($R^2$) were calculated to assess the experimental precision and the goodness of fit of the model, respectively.

## 3. Results and Discussion

In summary, the analysis of variance demonstrated that the interaction between the trellising net system (TS) and sowing density (SD) was significant for several important key agronomic variables. Specifically, significant interactions were observed for plant height (PH; F = 5.489*), pod length (PL; F = 9.303**) (Tables 3), pea weight per pod (PWP; F = 6.324*), and pod yield (PY; F = 6.324*) (Tables 4), indicating that the combined and interdependent effects of TS and SD significantly affect plant growth and productivity.

Table 3. Analysis of variance (F values) for the main effects of the trellising net system (TS) and sowing density (SD), and adjustment of the model for morpho-agronomic variables in peas

| Source of Variation | PH | FNP | NPP | PL | PW |
|---|---|---|---|---|---|
| TS | 8.287* | 8.820* | 7.919 ns | 25.569** | 37.675* |
| SD | 2.536 ns | 0.079 ns | 4.053 ns | 2.066 ns | 2.790 ns |
| TS × SD | 5.489* | 1.207 ns | 0.846 ns | 9.303** | 3.732 ns |
| $R^2$ | 0.57 | 0.49 | 0.51 | 0.73 | 0.44 |
| CV (%) | 10.87 | 18.00 | 7.10 | 8.34 | 21.47 |

R2: coefficient of determination. CV (%): coefficient of variation. PH: plant height. FNP: number of flowers per plant. NPP: number of pods per plant. PL: pod length. PW: pod weight. Significance level: ** - 0.01, * - 0.05. ns = not significant.

Additionally, the trellising net system as an independent factor had a significant effect on the number of flowers per plant (FNP; F = 8.820*), pod weight (PW; F = 37.675*), pod number per plant (PNPP; F = 15.960*), and pod weight per plant (PWPP; F = 19.211*) (Tables 3 and 4). These results emphasize the role of trellising in promoting reproductive development, improving pod formation, and enhancing overall yield performance in pea cultivation.

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Table 4. Analysis of variance (F values) for the main effects of the trellising net system (TS) and sowing density (SD), and adjustment of the model for morpho-agronomic variables in peas

| Source of Variation | PWP | PNPP | PD | PWPP | PY |
|---|---|---|---|---|---|
| TS | 19.374* | 15.960** | 2.613 ns | 19.211* | 17.007 ns |
| SD | 5.176* | 0.358 ns | 4.281* | 17.954** | 52.77** |
| TS × SD | 6.342* | 2.989 ns | 3.061 ns | 2.820 ns | 5.660* |
| R2 | 0.40 | 0.56 | 0.54 | 0.96 | 0.82 |
| CV (%) | 24.03 | 16.64 | 7.77 | 4.59 | 18.32 |

R2: coefficient of determination. CV (%): coefficient of variation. PWP: pea weight per pod. PNPP: pea number per planta. PD: pea diameter. PWPP: pea weight per plant. PY: pea yield. Significance level: ** - 0.01, * - 0.05. ns = not significant.

The sowing density had a significant effect on PD (F = 4.281*), indicating its influence on pea diameter (Table 4). The coefficients of variation and determination presented acceptable values, which confers robustness, validity, and reliability to the results obtained in this study (Tables 3 and 4).

### *3.1 Plant Height (PH)*

The application of the trellising system (TS) significantly and positively influenced plant growth, particularly at sowing densities of 40 and 80 kg ha$^{-1}$, at which plants reached mean heights of 98.00 ± 1.00 and 94.75 ± 1.38 cm, respectively. In contrast, in the absence of TS, plant height declined consistently across all evaluated densities. Notably, at 40 kg ha$^{-1}$, plant height was reduced to 61.33 ± 10.27 cm, suggesting that the lack of trellising restricted vertical growth, likely due to increased lodging incidence. At the lowest density of 27 kg ha$^{-1}$, differences between treatments were less pronounced, with mean heights of 66.67 ± 5.36 cm with TS and 70.67 ± 8.35 cm without TS. This pattern indicates that under low intraspecific competition, the effect of trellising on vertical growth becomes less pronounced (Figure 2).

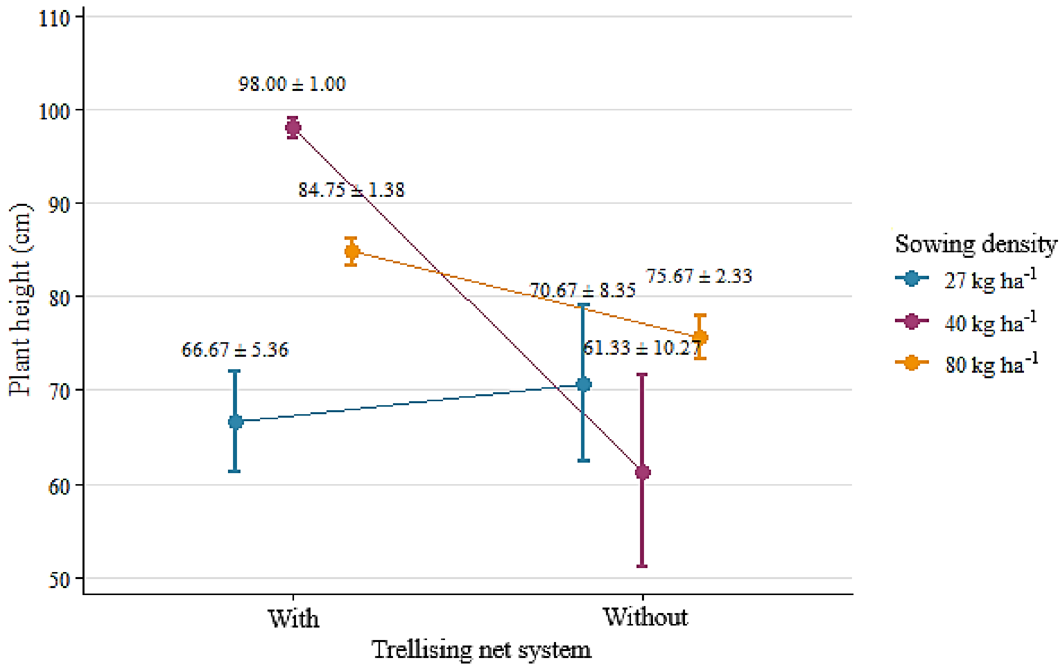


Figure 2. Interaction between the trellising net system and sowing density (TS × SD) over the plant height (PH)

Overall, the results demonstrate a significant interaction between sowing density and the trellising system. Trellising clearly enhances vertical growth, particularly at medium and high densities, by providing structural support and reducing competition for space and light. Previous studies have shown that increasing sowing density often leads to greater plant height, primarily due to intensified competition for light, which stimulates stem elongation (Wang et al., 2025).

Furthermore, Wu et al. (2023b) reported that sowing density, in combination with potassium availability, influences lodging resistance, lignin accumulation, and yield. These findings reinforce the interpretation that plants grown at higher densities require additional resources or structural support to maintain canopy integrity, thereby allowing them to achieve greater heights without structural failure.

*3.2 Number of Flowers per Plant (NFP)*

The analysis of variance (Table 3) indicated that the trellising system (TS) had a significant effect on the number of flowers per node (PNF). Treatments with TS exhibited a unimodal distribution characterized by pronounced positive skewness, with the highest probability density concentrated in the upper value range (13.2 ± 2.3 flowers on average). In contrast, treatments without TS presented flatter and more dispersed distributions, with a greater proportion of lower values (9.9 ± 2.4 on average) (Figure 3).

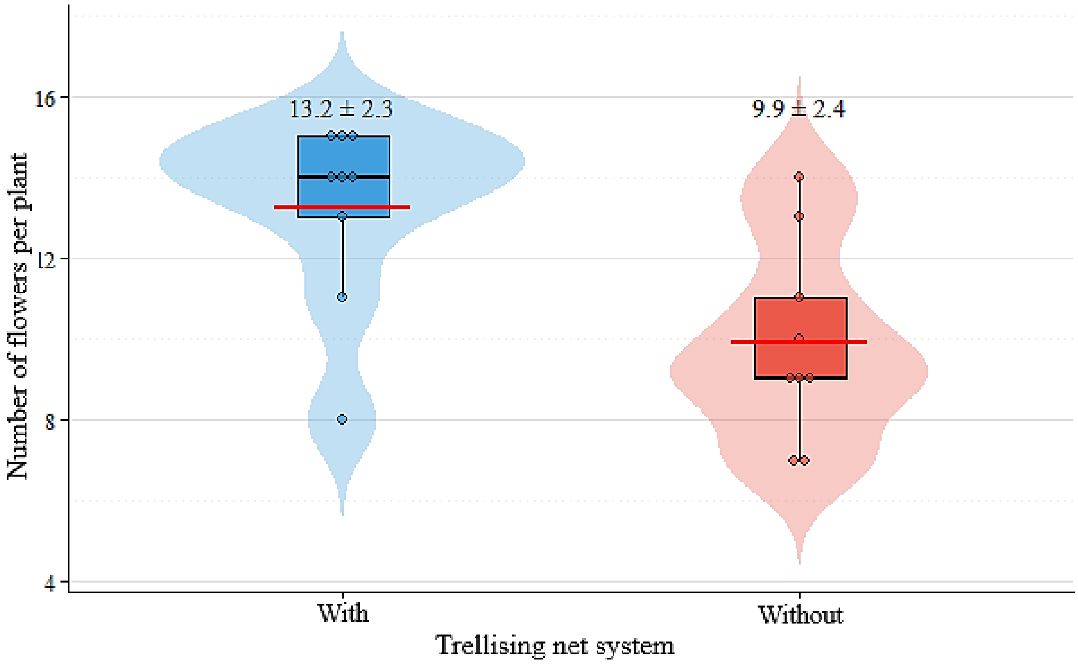


Figure 3. Effect of the trellising net system on the number of flowers per plant. Equal letters indicate non-significant differences (Tukey, $p > 0.05$)

Under TS conditions, the median shifted markedly toward higher values, indicating a substantial and more uniform enhancement in flowering. This distribution pattern suggests that TS not only increases the mean floral potential but also reduces phenotypic variability, thereby stabilizing trait expression under variable environmental conditions.

Although pea crops are well-adapted to cool temperatures and typically reach floral maturity around 90 days after sowing, their reproductive development is highly dependent on canopy architecture. Inadequate spatial arrangement that results in excessive canopy density and crowded foliage can induce physiological stress, leading to increased flower abortion.

This stress directly compromises critical reproductive processes, including fertilization and pod set, which rely on the proper functioning of male and female structures that are particularly sensitive to adverse environmental factors. Consistent with this, Tafesse et al. (2019) reported that reductions in final pod number and overall yield are often the result of the sequential abortion of buds, flowers, and young pods under such stress conditions.

In this context, the adoption of trellising systems represents a key agronomic strategy. By optimizing spatial arrangement, such systems enhance light interception and air circulation, while stabilizing the floral microenvironment. These improvements promote higher flower retention and more efficient pod set, ultimately supporting increased crop productivity (Zaki et al., 2017).

*3.3 Number of Pods per Plant (NPP)*

Although the analysis of variance did not indicate statistically significant main or interaction effects for the evaluated factors (Table 3), clear and biologically relevant trends were evident in the treatment means. Certain combinations of the trellising system (TS) and sowing density (SD) showed pronounced differences in the number of pods per plant (NPP), with variations reaching as much as 83.58% between the most contrasting treatments (T6 = 6.7 ± 0.6 pods plant$^{-1}$ and T2 = 12.3 ± 2.5 pods plant$^{-1}$) (Figure 4).

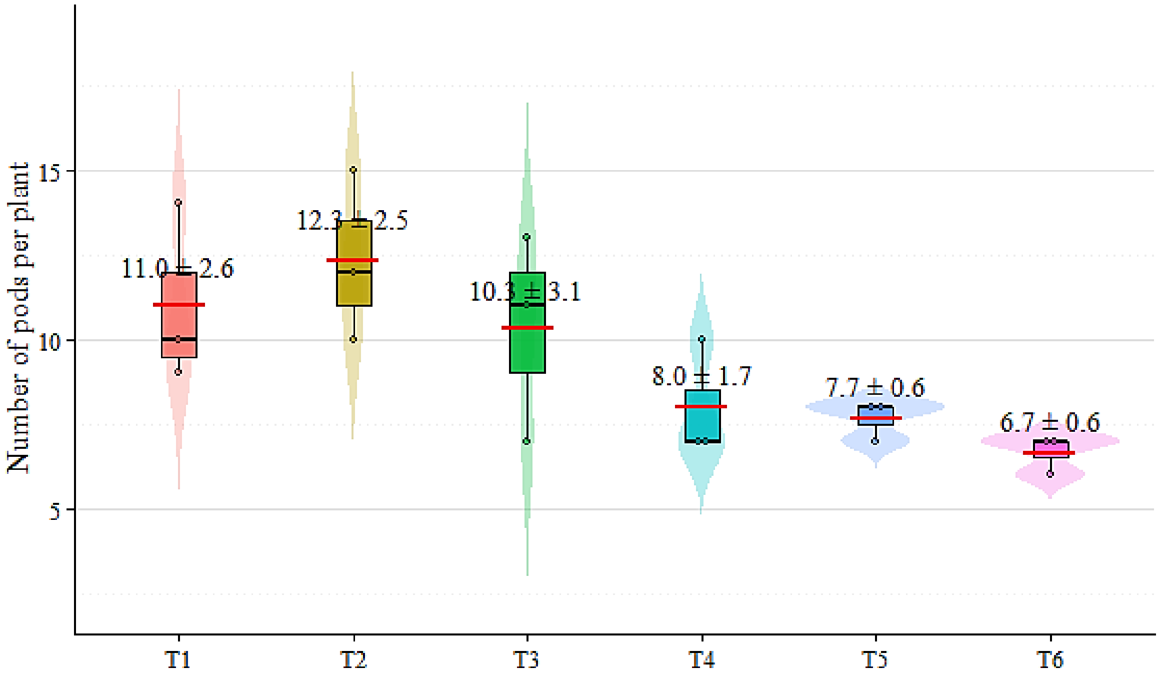


Figure 4. Means per treatment for the response variable number of pods per plant (NPP). T1: with trellising (80 kg ha$^{-1}$), T2: with trellising (40 kg ha$^{-1}$), T3: with trellising (27 kg ha$^{-1}$), T4: without trellising (80 kg ha$^{-1}$), T5: without trellising (40 kg ha$^{-1}$), T6: without trellising (27 kg ha$^{-1}$)

These results suggest that the studied factors may interact in a complex and non-linear manner. The magnitude of the observed effects may be biologically relevant, even if not statistically significant, possibly as a consequence of the limited sample size. Although differences did not reach the conventional significance threshold ($\alpha = 0.05$), the combination of TS and the evaluated SD levels in the pea crop resulted in the numerically highest values for the number of pods per plant (NPP; T1 = 11.0 ± 2.6 pods plant$^{-1}$), which may represent agronomic relevance under specific field conditions.

*3.4 Pod Length (PL)*

The TS strongly promoted PL across all sowing densities, whereas the absence of the trellis led to a significant reduction in PL, particularly at the highest density (Figure 5). Under trellising conditions, plants sown at 80 and 40 kg ha$^{-1}$ achieved the greatest PL values (7.8 ± 0.2 cm and 7.6 ± 0.5 cm, respectively), followed by those at the lowest density (27 kg ha$^{-1}$), with a mean PL of 6.4 ± 0.2 cm (Figure 5). This pattern suggests that the trellising system promotes more uniform and balanced pod development, likely through improved light interception, better air circulation, and reduced pod contact with the soil surface.

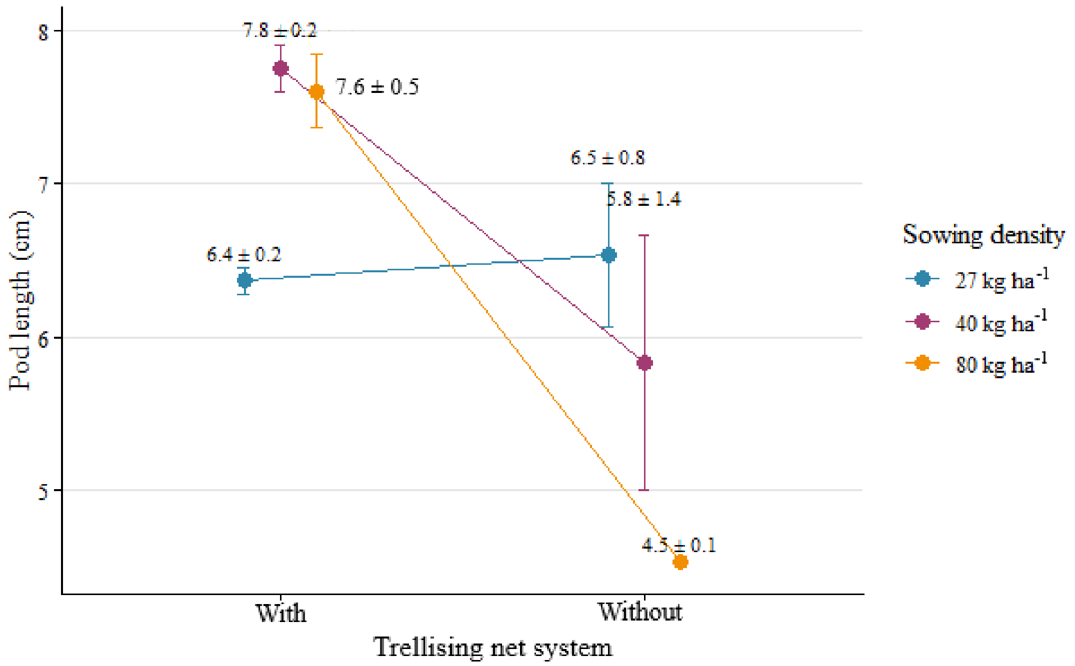


Figure 5. Interaction between the trellising net system and sowing density (TS × SD) on the pod length (PL) response variable

In contrast, when no trellising was employed, PL declined sharply, most notably at the highest density (80 kg ha$^{-1}$), where PL decreased to 4.3 ± 0.1 cm. This outcome indicates that, at high densities, the lack of structural support intensifies intra-plant competition for light, nutrients, and space, thereby restricting pod development. At an intermediate density (40 kg ha$^{-1}$) without trellising, PL was reduced to 5.8 ± 1.4 cm, while at the lowest density (27 kg ha$^{-1}$) it remained relatively stable, at 6.5 ± 0.8 cm, indicating a lower dependence on trellis support (Figure 5).

The results clearly demonstrate a significant interaction between the trellising system and sowing density, whereby the presence of TS alleviates negative competitive effects and mechanical stress on pod growth, while its absence limits pod elongation - especially under high-density conditions. These findings are consistent with previous research linking sowing density and plant size to pea yield components. For instance, Prusiński and Borowska (2022) observed that higher pea plant densities reduce pods per plant and modify morphological features.

Furthermore, at high sowing densities, increased competition for light and reduced interplant spacing drive stem elongation and increase the risk of lodging (i.e., plants falling over or becoming tangled) when support systems are not implemented. In this scenario, trellising - whether via mesh netting or stakes - maintains upright stem and pod architecture, improves light exposure of reproductive organs, and reduces pod contact with the soil.

These conditions favor enhanced pod filling and elongation, which helps to explain the marked decline in pod length observed at 80 kg ha$^{-1}$ in the absence of trellising. This result is in agreement with broader evidence of the interaction among sowing density, plant architecture, and yield components in peas and other legume crops (Sai Kachout et al., 2021).

*3.5 Pod Weight (PW)*

Pea plants grown with TS had an average pod weight of 7.3 ± 2.3 g, significantly higher than when the plants were grown without TS with 4.8 ± 2.4 g (Figure 6).

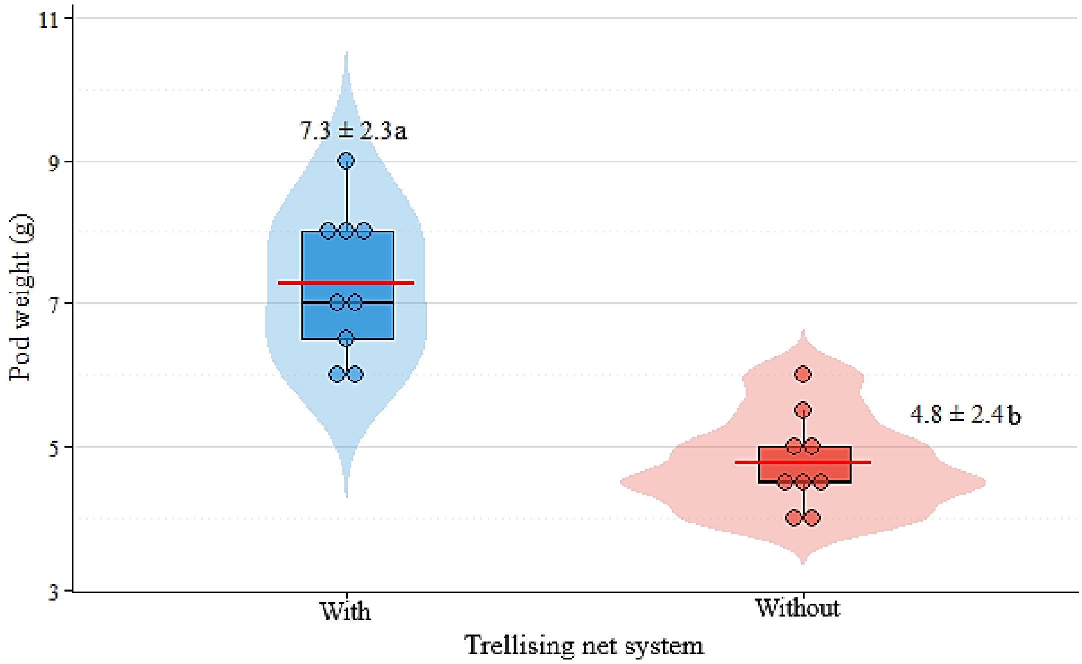


Figure 6. Effect of the trellising net system (TS) on the weight of the beaned sheath (PW). Equal letters indicate non-significant differences (Tukey, $p > 0.05$)

This difference demonstrates that the TS effectively promoted pod development and filling, thereby increasing individual pod weight. Such an effect can be attributed to improved distribution of solar radiation within the canopy, reduced intraspecific competition for resources, enhanced canopy aeration, and the prevention of direct contact between pods and the soil. Consequently, losses due to moisture accumulation and disease incidence are minimized, favoring more uniform and efficient pod filling.

The lower data dispersion observed under TS indicates greater uniformity in pod development, reflecting more balanced plant growth. Trellising often improves canopy structure, light interception, and harvestability in vine-type peas, which likely contributes to improved pod filling and size. In contrast, the no-trellis treatment exhibited greater variability, likely attributable to uneven solar radiation exposure, higher lodging incidence, or vine entanglement.

Thus, the results indicate that plant architecture management and lodging control directly influence pea yield components. By maintaining an upright canopy, the trellising system enhances light interception and radiation distribution and reduces pod-soil contact; these conditions favor pod filling and consequently increase individual pod weight (Prusiński & Borowska, 2022). Additionally, recent evidence indicates that lodging-resistant architecture and support systems contribute substantially to yield stability in pea crops (Chen et al., 2024).

Moreover, recent field studies and review papers in pea cultivation indicate that the positive impact of trellising is maximized only when crops are not limited by nutrient or water availability. For instance, in semi-leafless pea varieties under adequate nutrition and irrigation, support systems enhanced pod weight; however, when abiotic stress such as nutrient or water limitation is present, the beneficial effect of trellising may be substantially reduced (Janusauskaite, 2023; Carr et al., 2024).

### *3.6 Pea Weight per Pod (PWP)*

The outcomes demonstrate a consistent decline in PWP when plants were grown without trellising, regardless of sowing density. Under the TS, plants attained higher PWP values, with the maximum recorded at 6.9 ± 1.0 g at a density of 80 kg ha$^{-1}$, whereas the minimum value of 3.8 ± 0.3 g was observed under the same density in the absence of trellising (Figure 7).

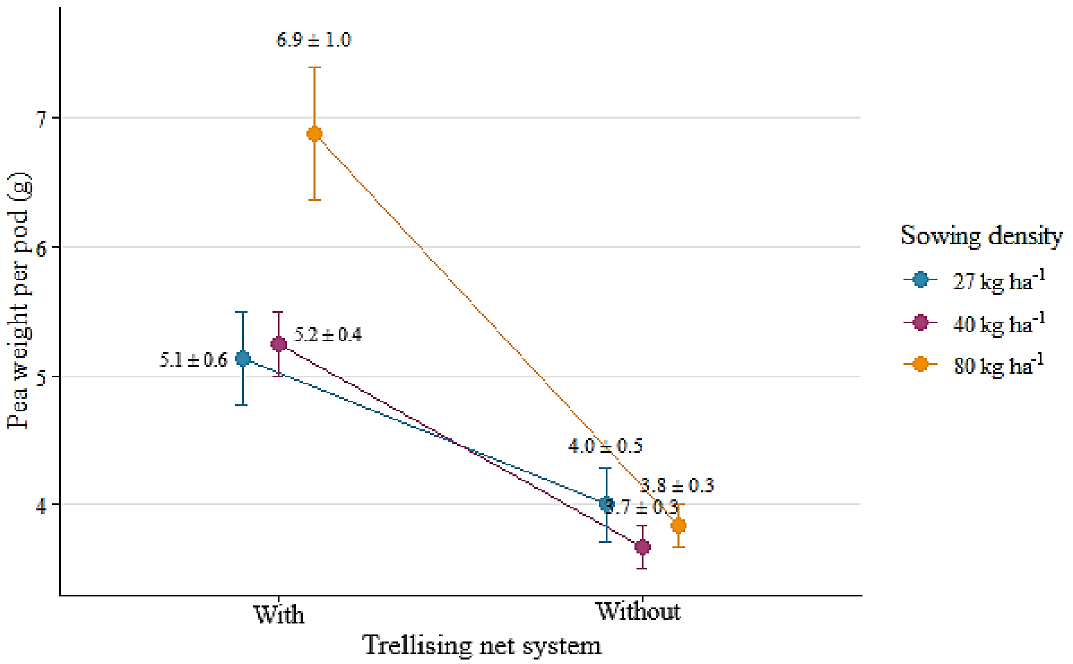


Figure 7. Interaction between the trellising net system and the sowing density (TS × SD) on the response variable pea weight per pod (PWP)

This pattern suggests a significant interaction between TS and SD, whereby the beneficial effect of trellising is amplified under higher sowing densities. At elevated densities, plants compete more intensely for light and space; in the absence of support, lodging and suboptimal canopy function reduce pea filling and, consequently, final PWP. Trellising alleviates these constraints by maintaining an upright canopy, improving aeration and light interception, and thereby promoting the translocation of photoassimilates to the peas.

The marked reduction in PWP without trellising, even at moderate densities, highlights the role of physical support as a critical growth-limiting factor. This effect becomes especially severe at the highest sowing density (3.8 ± 0.3 g at 80 kg ha$^{-1}$ without trellising), indicating a synergistic negative interaction. This response can be explained by the fact that under high density, plants adopt a shade-avoidance strategy favoring stem elongation at the expense of structural strength and assimilate partitioning to pods (Carriedo et al., 2016; Munz & Reiser, 2020). Without trellising, the resulting elongated and weak stems are highly susceptible to lodging.

The reduction in PWP in non-trellised plots is directly associated with the physiological consequences of lodging. Once plants collapse, net photosynthetic rates decline sharply, not only due to reduced light interception but also because of basal leaf senescence and deterioration caused by a humid and poorly aerated microenvironment (Liu et al., 2020). In contrast, the trellised treatment showed a much more gradual decline in PWP with increasing density, confirming that support systems allow more efficient exploitation of higher sowing densities by maintaining greater individual pod productivity.

*3.7 Number of peas per pod (PNPP)*

The results show that the TS resulted in an average of 5.8 ± 1.1 peas pod$^{-1}$, a value significantly higher than that recorded in the absence of TS, which was 4.0 ± 1.0 peas pod$^{-1}$ (Figure 8). From an agronomic point of view, this result indicates that TS enhances pod exposure to solar radiation, optimizes canopy aeration and photosynthetic efficiency, and reduces mechanical stress associated with pod-soil contact, thereby promoting greater pea development and more effective grain filling.

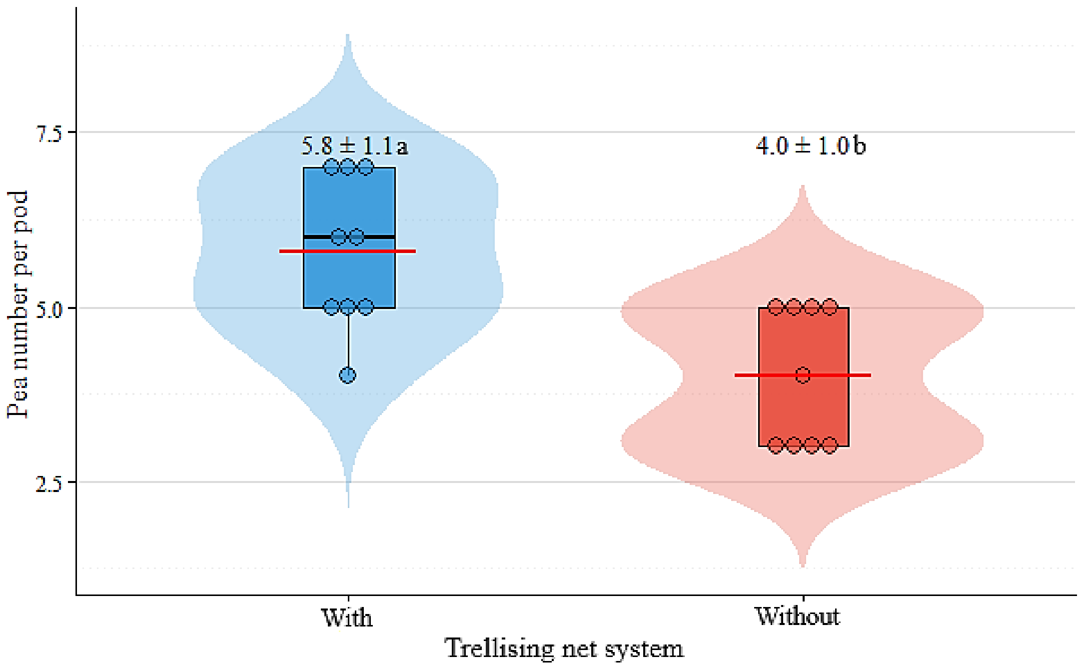


Figure 8. Effect of the trellising net system (TS) on the number of peas per pod (PNPP). Equal letters indicate non-significant differences (Tukey, p > 0.05)

The observed improvements in pea productivity can be attributed to several interrelated physiological and structural mechanisms facilitated by the trellising system. Firstly, vertical plant orientation improves solar radiation interception and expands the effective photosynthetically active leaf area, thereby enhancing photosynthetic efficiency and increasing the production of photoassimilates required for pod formation and seed filling. Secondly, the upright growth habit reduces internal canopy shading and enhances ventilation, which can lower flower abscission rates and favor effective pollination and fruit set. Finally, by minimizing plant-soil contact, trellising reduces mechanical damage and the incidence of foliar diseases, such as *Erysiphe pisi*, which can negatively impact reproductive capacity.

These findings are consistent with previous agronomic studies demonstrating the positive effects of canopy management and support structures on yield components in legumes and climbing crops (Checa et al., 2020; Karavidas et al., 2022; Prusiński & Borowska, 2022). Thus, the implementation of a trellising system positively affected reproductive structures, leading to greater productivity per pod compared with crops grown without structural support.

*3.8 Pea Diameter (PD)*

The results show that at a sowing density (SD) of 27 kg ha$^{-1}$, the largest mean pea diameter of 8.7 ± 0.5 mm was recorded, which was statistically similar to that observed at an SD of 80 kg ha$^{-1}$ (8.2 ± 0.8 mm), but significantly greater than the pea diameter of 7.5 ± 1.4 mm recorded at an SD of 40 kg ha$^{-1}$ (Figure 9).

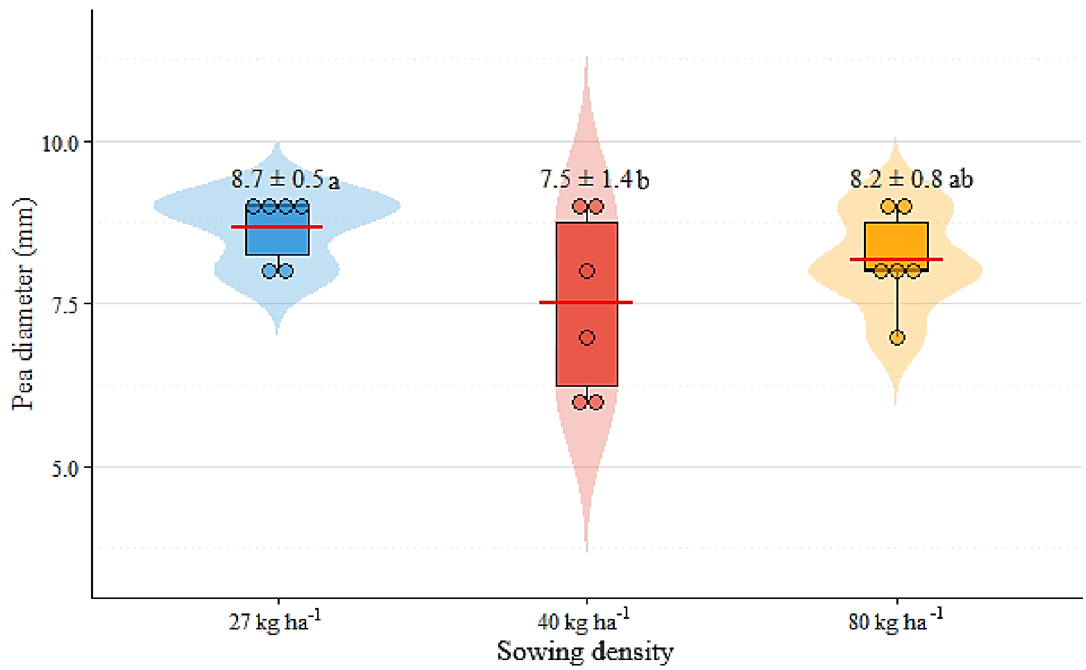


Figure 9. Effect of sowing density (SD) on pea diameter (PD). Equal letters indicate non-significant differences (Tukey, p > 0.05)

The observed reduction in pea diameter at intermediate sowing densities, compared to lower densities, can be attributed to greater intraspecific competition for essential resources such as light, water, and nutrients. This competition restricts the availability of photoassimilates required for pod filling. Notably, plants sown at lower densities benefit from increased root expansion and aerial space, facilitating more efficient resource acquisition and, consequently, larger pea size (Riascos Delgado & Checa Coral, 2018). Consistent with these observations, Prusiński and Borowska (2022) reported that sowing density significantly affects structural yield components, including the number of pods per plant, number of peas per pod, and individual pea weight.

Furthermore, the greater variability observed at the intermediate density (40 kg $ha^{-1}$), as indicated by the higher standard deviation, suggests heterogeneity in trait expression within this density level. Under these conditions, some plants outcompeted neighboring individuals, resulting in a mixture of larger and smaller peas. This variability highlights the complex interplay between plant density and individual plant performance. While lower sowing densities favor the development of larger peas due to reduced competition, they may also reduce the total number of pods and overall yield per unit area.

Therefore, optimizing sowing density requires a balance between individual pea size and total productivity, depending on the target market, whether for fresh consumption or dry processing. Field experiments conducted across multiple seasons and environments have demonstrated that the density maximizing yield per area does not necessarily coincide with the density producing the largest peas per plant. Consequently, if market demand prioritizes larger pea size, a moderately low sowing density, combined with adequate nutrient supply and irrigation, may be recommended.

Conversely, to maximize yield per hectare, higher sowing densities are generally preferable, as the increased plant population can offset reductions in individual pea size (Duque-Zapata et al., 2019; Ghodsi et al., 2022; Wu et al., 2023). Thus, sowing density exerts a decisive influence on pea diameter, with lower densities favoring larger peas due to reduced intraspecific competition. The optimal sowing density should therefore align with commercial objectives, balancing yield maximization and desired pea size and quality (Janusauskaite, 2023; Ordoñez-Flores et al., 2019).

*3.9 Pod Weight per Plant (PWPP)*

The results show that under ST conditions, an average PWPP of 69.3 ± 16.8 g $plant^{-1}$ was recorded, a value significantly higher than that observed in plants grown without ST, which reached 44.6 ± 10.6 g $plant^{-1}$ (Figure 10). This finding indicates that ST enhances light interception, improves canopy aeration, and provides structural support, thereby reducing losses associated with mechanical damage and disease incidence (Richard et al., 2013), which ultimately results in greater biomass accumulation and more efficient pod filling.

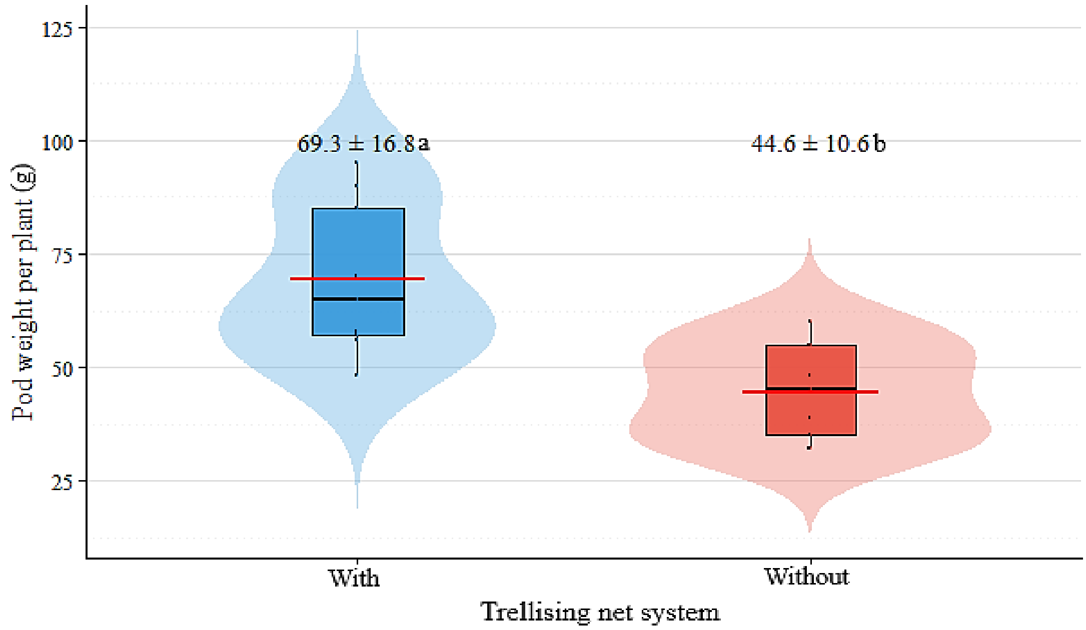


Figure 10. Effect of the trellising net system (TS) on pod weight per plant (PWPP). Equal letters indicate non-significant differences (Tukey, $p > 0.05$)

The highest mean PWPP of 64.0 ± 6.8 g plant$^{-1}$ was recorded at a sowing density of 27 kg ha$^{-1}$, significantly exceeding the values observed at densities of 40 kg ha$^{-1}$ (56.2 ± 20.3 g plant$^{-1}$) and 80 kg ha$^{-1}$ (50.5 ± 19.3 g plant$^{-1}$) (Figure 11). This trend can be attributed to increased intraspecific competition for resources - including water, light, and nutrients - at higher densities, which constrains individual plant growth and limits effective pod development and filling.

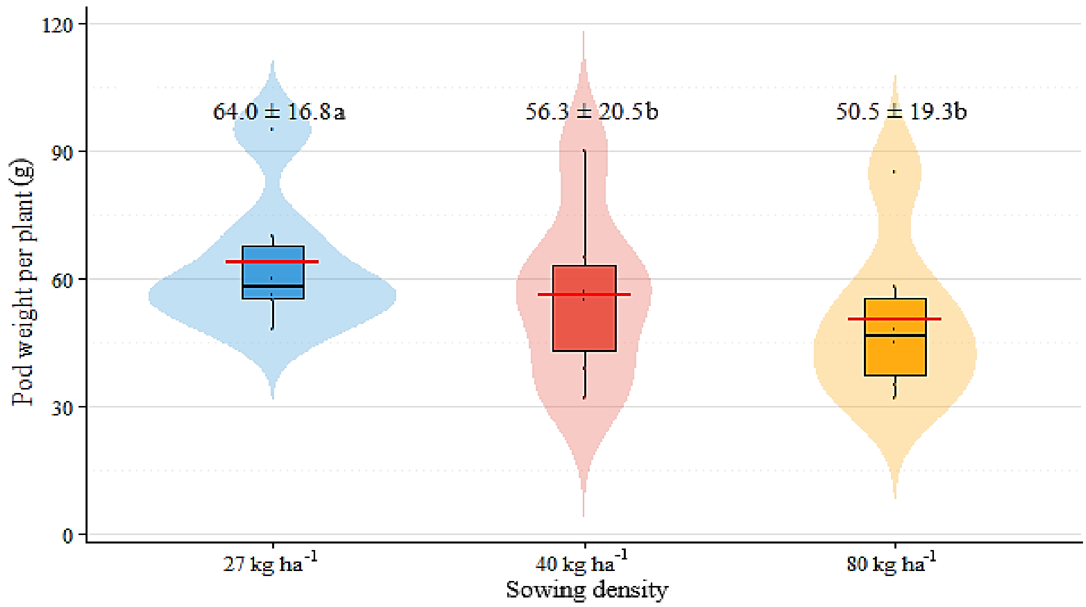


Figure 11. Effect of sowing density (SD) on pod weight per plant (PWPP). Equal letters indicate non-significant differences (Tukey, $p > 0.05$)

The results clearly demonstrate that the trellising net system (TS) had a significant and positive effect on pod weight per plant (PWPP). In contrast, increasing sowing density (SD) exhibited an inverse effect, reducing PWPP as intraspecific competition intensified. Specifically, PWPP declined progressively from 64.0 g at 27 kg $ha^{-1}$ to 56.2 g at 40 kg $ha^{-1}$, and further to 50.5 g at 80 kg $ha^{-1}$. This consistent pattern suggests that higher plant populations lead to increased competition for resources such as light and nutrients, thereby limiting the capacity of individual plants to develop heavier pods.

The primary mechanism underlying this pattern appears to be that the use of physical supports enhances canopy architecture and photosynthetic efficiency by optimizing light interception and improving ventilation. Trellising promotes a more favorable plant structure, reducing self-shading and facilitating the allocation of photoassimilates to reproductive organs (Checa et al., 2020).

Moreover, trellising minimizes mechanical stress and disease pressure by preventing direct contact between plants and the soil. For example, trellising systems in climbing legumes have been shown to increase yields by reducing pathogen incidence and improving the canopy microclimate (Karavidas et al., 2022). In pea crops, enhancements in the canopy microenvironment have been directly associated with greater dry matter accumulation and pod biomass (Ghodsi et al., 2022).

With respect to SD, the present findings are consistent with those of Prusiński and Borowska (2022), who reported that high sowing densities reduce average pod weight and the number of peas per plant, despite increasing plant population per unit area. Similarly, Janusauskaite (2023) concluded that low to moderate densities favor improved pea filling and higher pod weight, due to a more favorable source-sink balance, in agreement with earlier studies (Burbano Erazo et al., 2018; Prusiński & Borowska, 2022).

From an agronomic standpoint, these results indicate that combining a trellising net system with low to intermediate sowing densities represents an effective management strategy to enhance pod weight per plant and improve yield quality in pea cultivation. This integrated approach supports vertical growth and optimal leaf exposure, while simultaneously reducing disease incidence and improving harvest efficiency (Checa et al., 2020; Karavidas et al., 2022).

*3.10 Pod Yield (PY)*

The results show a tendency to increase PY with ST compared to without ST, regardless of the SD used. The highest PY value ($8.0 \pm 2.4$ t $ha^{-1}$) was recorded with ST at the SD of 80 kg $ha^{-1}$ (Figure 12).

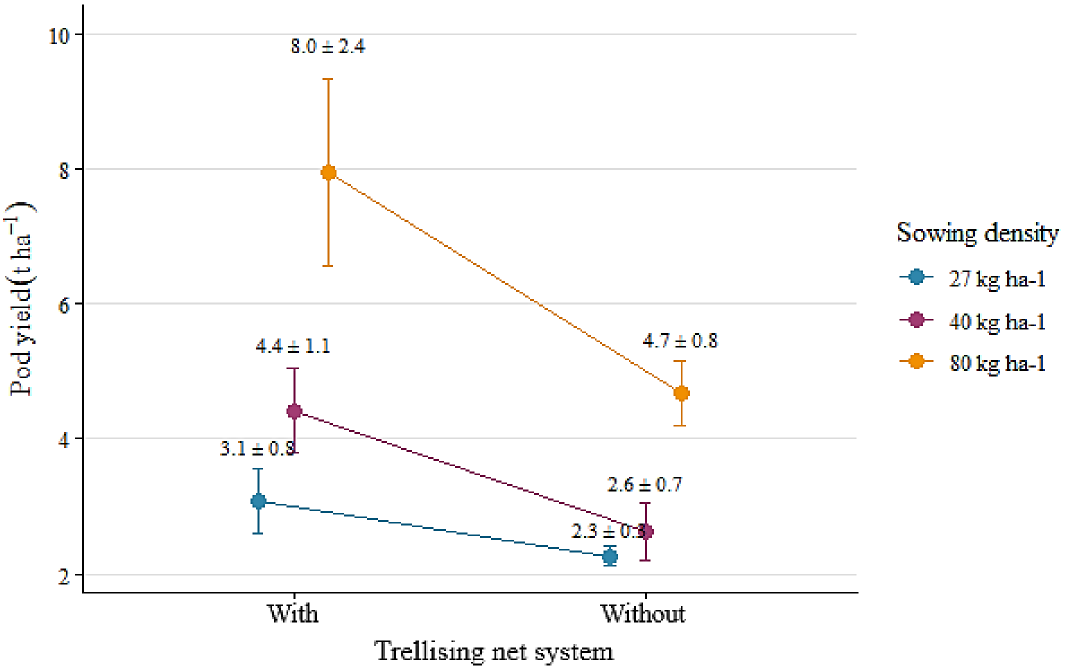


Figure 12. Interaction between the trellising net system and sowing density (TS × SD) on the pod yield response variable (PY)

The results confirmed a significant interaction between the TS and SD, whereby the beneficial effect of TS became increasingly pronounced at higher densities. Under high-density conditions, plants experience intense competition for light and space; in the absence of TS, this competition induces lodging and limits effective photosynthesis, thereby reducing yield. Conversely, the implementation of TS maintains plants in an upright growth habit, improves canopy aeration and light interception, enhances the translocation of photoassimilates to pods, and ultimately increases yield (Shen et al., 2022; Smitchger et al., 2020).

It should also be noted that the lack of TS consistently reduced yield across all sowing densities, indicating that without physical support, pod physiological development is constrained, particularly under high plant populations. These findings are consistent with recent studies highlighting the importance of integrated agronomic management of plant architecture and resource-use efficiency (Prusiński & Borowska, 2022; Tran et al., 2022). For example, Prusiński and Borowska (2022) demonstrated that variations in planting density and row spacing significantly affect yield components in pea crops.

Furthermore, trellising has been shown to increase both pod number and seed number per pod in pea production systems (Alarcón Alvarez et al., 2024). Checa et al. (2017) reported superior performance under high rainfall conditions when trellising was implemented, citing improved production quality and higher economic returns. In contrast, Carr et al. (2024) emphasized that although lower densities reduce intraspecific competition, they often result in lower yields per unit area. Thus, the use of trellising allows a more efficient exploitation of sowing density, thereby maximizing overall productivity. This highlights the importance of incorporating trellising as a key agronomic practice in intensive pea production systems.

*3.11 Presence and Incidence of Diseases*

In all evaluated treatments, foliar disease symptoms were detected, with *Erysiphe pisi* (powdery mildew) identified as the predominant pathogen. Disease incidence was substantially higher in the non-trellised treatments, particularly in T4 (no trellising, sowing density = 80 kg ha$^{-1}$), which recorded the highest incidence at 12.0%. This was followed by T5 (7.0%) and T6 (7.3%), both also lacking trellising but established at lower sowing densities. In contrast, treatments T1 (3.3%), T2 (2.6%), and T3 (3.0%) - all conducted under trellising conditions - showed markedly lower disease incidence (Figure 13).

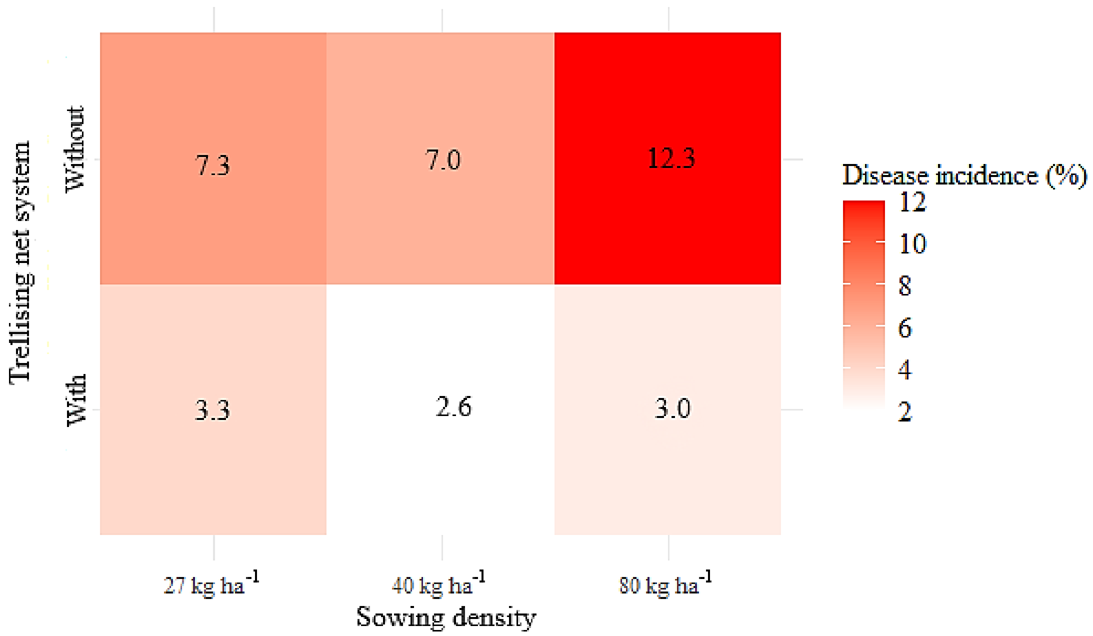


Figure 13. Effect of sowing density and trellising net system on the incidence of diseases in peas

These findings demonstrate that implementing a trellising system significantly reduces powdery mildew incidence in pea cultivation. This protective effect is likely attributable to improved canopy aeration and enhanced light penetration provided by trellising. In the absence of trellising, particularly under high sowing densities, a more humid microenvironment with restricted airflow is established, which favors foliar pathogen development.

This relationship is corroborated by previous studies highlighting canopy structure and microclimate as key determinants in the epidemiology of diseases such as *Ascochyta* blight and downy mildew in peas (Villegas-Fernández et al., 2021; Lee et al., 2023). Likewise, recent research has demonstrated that trellising systems enhance aeration and solar radiation penetration, lower canopy relative humidity, and consequently reduce disease incidence (Alarcón Alvarez et al., 2024).

## 4. Conclusions

The study demonstrates a strong and agronomically meaningful interaction between trellising systems and sowing density in pea production.

The use of a trellising net combined with a high sowing density (80 kg·ha$^{-1}$) resulted in the highest green pod yield (8.0 t·ha$^{-1}$), exceeding non-trellised treatments by more than 30%. Trellising substantially improved canopy architecture and light interception, mitigated lodging, increased the number of grains per pod and average pod weight, and significantly reduced powdery mildew incidence by enhancing aeration and lowering canopy humidity.

High sowing density increased yield at the area level through population compensation, but intensified intraspecific competition, leading to a reduction in pods per plant; therefore, yield gains at 80 kg·ha$^{-1}$ are contingent upon the effective conversion of canopy-level advantages into individual plant productivity. For practical field application, trellising should be integrated into a comprehensive management strategy that ensures balanced nutrition, adequate water availability, uniform plant establishment, and proactive disease monitoring.

While the results identify the combination of trellising and high sowing density as an effective strategy to maximize yield and improve crop health under the conditions evaluated, further validation across different cultivars, growing seasons, and environments, as well as an economic assessment of trellising costs relative to yield benefits, is recommended prior to large-scale adoption.

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**Authors Contributions**

Ing. I.M. Gutiérrez Limachi, Dr. A. Santivañez Aguilar, and Ing. M.A. Varias Álvarez conceived and designed the study. Data analysis was led by Ing. Gutiérrez, Ing. Varias, Ing. P.D. Garvizu, and Dr. E. Miranda Lemes. Experimental work was performed by a team of engineers including V. Mujica Belmonte, C.H. Guerrero Cocasapa, O.O. Meneces Arias, M.R. Uyando Torrico, Y.M. Pozo Rocha, and M. Orellana Huarachi. Dr. Santivañez Aguilar supervised the project and acquired funding with Dr. W.J. Martinez. All authors reviewed the manuscript and approved the final version. Contributions are assigned as described; no equal authorship is declared.

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**Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Informed consent**

Obtained.

**Ethics approval**

The Publication Ethics Committee of the Macrothink Institute.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

**Provenance and peer review**

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**Data availability statement**

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

**Data sharing statement**

No additional data are available.

**Open access**



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