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Chili Yields, Nutrient Use, and Water Use Efficiency under Precision Fertigation at Different Plant Density and Drip Irrigation Lines

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Abstract

The study aimed to evaluate the effects of irrigation line number and plant density on the growth and yield of curly red chili pepper (*Capsicum annuum* L.) cv. Tangguh. The study was conducted from August 2023 to January 2024 at the Cikarawang Experimental Station of IPB University (6°32'56" S; 106°43'54" E; 240 m above sea level) on Ultisol characterized by severely low phosphorus (1.1 ppm) and high potassium content (66 ppm). A split-plot design within a randomized complete block design was employed, with irrigation line number (single or double drip lines per bed) as the main plot and four planting densities (26,666, 53,322, 80,000, and 106,666 plants.ha^{-1}) as subplots. Each treatment was replicated three times, resulting in 24 plots (each 1.5 m × 10 m). Fertilizers applied included Urea (45% N), SP-36 (36% P_2O_5), cattle manure, dolomite, biofertilizers (*Trichoderma* spp.), and PGPR. Irrigation and fertigation were managed using the Nutrigads automatic drip system. The data collected included plant growth, yield components, nutrient use efficiency, water use efficiency, and partial factor productivity for nitrogen (N) and phosphorus (P). The results showed that the irrigation line number had no significant effect on individual plant growth parameters. However, using double lines significantly increased total fruit yield per bed and hectare, indicating its contribution to overall productivity. Conversely, the double line system reduced water use efficiency (WUE = 2.07 kg.mm^{-1}) compared to the single line system (WUE = 3.64 kg.mm^{-1}; P<0.0001). Higher planting densities (up to 106,666 plants.ha^{-1}) enhanced total yield by promoting vertical growth but reduced individual plant performance, and had a positive effect on WUE, NUE, and PUE.

Keywords: crop spacing, drip layout, N-use efficiency, nutrient injection, red chili cultivar

Introduction

Price fluctuations in chili (*Capsicum annuum* L.) can trigger inflation and disrupt economic stability, positioning chili as a nationally strategic commodity. In 2022, Indonesia cultivated 49,713 ha of red chili, 95,564 ha of curly chili, and 189,267 ha of cayenne pepper, with respective outputs of 458,439.4, 1,017,381.8, and 1,544,440.9 tons (BPS, 2023). Despite these figures, supply inconsistencies and production inefficiencies persist, underscoring the need for technological innovation to meet year-round demand.

Drip irrigation, particularly when combined with fertigation, has emerged as a sustainable approach for enhancing water and nutrient use efficiency. It delivers inputs directly to the root zone, reducing losses through evaporation and runoff. However, the effectiveness of such systems is influenced by irrigation line configuration and plant spacing, yet their interaction in chili cultivation remains underexplored (Juhász et al., 2022).

The number of drip lines affects water distribution and root-zone moisture retention, particularly under high-density planting. While more lines can enhance uniformity, they may also lead to waterlogging or nutrient leaching. Conversely, plant density influences yield by affecting light interception and inter-plant competition. Inadequate irrigation in densely populated areas can exacerbate stress, resulting in reduced yields.

Fertigation enables precise nutrient delivery, aligning with growth stages to enhance uptake and productivity. Still, its success depends on optimizing both irrigation design and plant density (Lob et al., 2023). Achieving this balance is key to maximizing chili yield while ensuring resource-use efficiency.

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This study aims to determine the optimal combination of drip irrigation line quantity and plant density under precision fertigation to enhance yield, nutrient-use efficiency, and water-use efficiency in chili cultivation.

Materials and Methods

This study was conducted at the Cikarawang Experimental Station, Department of Agronomy and Horticulture, Faculty of Agriculture, IPB University (6°32'56" S; 106°43'54" E), situated at an altitude of 240 meters above sea level. The research area comprised 1000 m² of open dryland, classified as Ultisols with very low available phosphorus (1.1 ppm) and high available potassium (66 ppm). Irrigation was supplied using well water. The experimental period spanned from August 2023 to January 2024.

The materials used included curly red chili pepper (*Capsicum annuum* L.) of the Tangguh variety, totaling 3,960 seeds. Fertilizers applied were in the form of single-nutrient sources: Urea (45% N), SP-36 (36% P_2O_5), dolomite [$CaMg(CO_3)_2$], and cattle manure. Additional inputs included a starter solution (N: 14%; P: 12%; K: 14%), biological fertilizers containing Trichoderma hamatum WSY-03, biofungicides with active ingredients *Trichoderma koningii* and *T. harzianum*, PGPR comprising *Bacillus polymyxa* and *Pseudomonas fluorescens*, and biofungicide composed of *Cryptococcus terreu*s, *C. albidus*, and *Candida edax*. Organic fertilizer with 99.9% solubility contained 60% humic acid, 15% organic carbon, 1% total nitrogen, 5.46% total P_2O_5, 1.08% total K_2O, and a pH of 7.48. Supporting materials included polyethylene mulch (0.03 mm thick, 120 cm wide), 990 bamboo stakes (1.5 m in length), and 10 rolls of cotton twine (200 m per roll). Insecticides used contained profenofos and deltamethrin (0.5 $ml.L^{-1}$ each), while fungicides contained difenoconazole (0.25 $ml.L^{-1}$) and mancozeb (4–6 $g.L^{-1}$).

The equipment employed included an automatic irrigation and fertigation system (Nutrigads), comprising a head unit, Irrigation controller, fertigation controller, rain sensor, soil moisture sensor, and an LNK WiFi Module, along with other field tools. Additional supporting tools included seedling trays, electric sprayers, measuring tapes, and an analytical balance. Details regarding Nutrigads and Ferads systems can be accessed via IPB University's official website (https://ipb.link/nutrigads; https://ipb.link/nutriferads).

The experimental design followed a split-plot arrangement within a randomized complete block design, with three replications. The primary plot factor was the number of drip irrigation lines per bed (single vs. double). At the same time, the subplots consisted of four planting densities: 26,666 $plants.ha^{-1}$ (two rows, 50 cm spacing), 53,322 $plants.ha^{-1}$ (two rows, 25 cm spacing), 80,000 $plants.ha^{-1}$ (three rows, 25 cm spacing), and 106,666 $plants.ha^{-1}$ (four rows, 25 cm spacing). Each treatment was replicated three times, resulting in a total of 24 experimental plots (beds), each measuring 1.5 m × 15 m, with a bed width of 90 cm, ditch width of 60 cm, and bed height of 15 cm.

Planting configurations were as follows: treatment 1 (60 plants per bed, spacing 50 cm × 30 cm), treatment 2 (120 plants per bed, spacing 25 cm × 30 cm), and treatment 3 (180 plants per bed, spacing 25 cm × 25 cm, three rows) treatment 4 (240 plants per bed, spacing 25 cm × 25 cm, four rows). Four representative plants per plot were selected for observation.

The experimental procedures included seedling preparation, soil sampling, land preparation, bed formation, pre-plant fertilization, mulching, transplanting, maintenance, and harvesting. Seeds were germinated in trays for 30 days, having been pre-soaked in a biological fertilizer solution (10 $g.L^{-1}$) for two hours. Once seedlings had developed four leaves, foliar fertilizer (2–8 $g.L^{-1}$) was applied every four days until transplanting at the 6–8 leaf stage.

Soil samples were collected diagonally from 12 locations per plot, composited, air-dried, and analyzed at the Soil, Plant, and Fertilizer Testing Laboratory, IPB University. Analyses included soil pH and organic carbon, as well as available phosphorus (Lestari et al., 2021) and potassium (Lestari et al., 2020), using the Mehlich I method.

Land was tilled using a hand tractor and divided into 24 plots. Beds were constructed with dimensions of 90 cm in width, 60 cm in ditch width, and 15 cm in height. Preplant fertilizers (cattle manure, dolomite, 40% Urea, 100% SP-36, and biofungicide) were incorporated before laying mulch. Planting holes (7 cm diameter) were arranged in a zig-zag pattern.

Staking was performed two weeks after transplanting using a vertical system. Treatment 1 used one stake per plant, while treatments 2, 3, and 4 used 18 stakes per bed to support the twine. Irrigation was managed by Nutrigads, scheduled to run three times daily for 30 minutes. Fertilization was delivered through fertigation, following the recommended rate (see Table 1).

Pest and disease control involved biweekly pesticide applications. Pest activity was monitored using yellow

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sticky traps, while attractant pesticides with methyl eugenol were used to manage fruit flies. Weeding was done manually every week. Harvesting was performed once the fruits reached full red maturity.

The observed variables included plant height (cm), the number and weight of marketable and unmarketable fruits per plant and per plot, total fruit number and weight, and estimated yield per hectare (tons). Water use efficiency was determined according to the following formula:

WUE = total weight per ha/irrigation volume (m^3)

Nitrogen (NUE) or Phosphorus (PUE) use efficiency:
N/PUE = total weight per ha/NP rates per ha

Partial factor productivity of nitrogen (PPFN) = Dry matter yield $N_{1,2,3}$/Applied N fertilizer $_{1,2,3}$ X 100%

Factor productivity of phosphorus (PPFP) = Dry matter yield $N_{1,2,3}$/Applied N fertilizer $_{1,2,3}$ X 100%

Fruit harvesting was conducted at the red-ripe stage in 10 rounds, categorized into 13 weeks after transplanting (WAT) for early harvest (2 weeks), 15 WAT for mid-harvest (2 weeks), and 17 WAT for late harvest (3 weeks). The data were analyzed using analysis of variance (ANOVA), followed by Polynomial Regression using SAS software.

Results and Discussion

The experiment was conducted from September 21, 2024, to January 31, 2025. Thirty days after germination, chili seedlings were transplanted to the field, with replanting undertaken over the following week. Fertilization recommendations were generated using the Ferads application. The program suggested applications of 480 $kg.ha^{-1}$ urea, 650 $kg.ha^{-1}$ SP-36, and 270 $kg.ha^{-1}$ of organic material (base soil inorganic content)

During the experiment, total rainfall ranged from 216.7 mm to 325.8 mm, with an average temperature of 26.04°C and a relative humidity of 85.72% (Table 2). High rainfall in October–November 2024 (724.7 and 1365.9 mm, respectively) is likely to influence soil moisture beneath plastic mulch on inceptisol, particularly in the bed edge zones. This condition has the potential to alter aeration and nutrient distribution in the root zone, which may affect growth responses during the mid-growth phase. Therefore, the interpretation of results should consider the hydrological dynamics during this wet period.

Plant Height

As shown in Table 3, no significant differences in plant height were observed among planting densities from 1 to 9 weeks after transplanting (WAT), indicating that

Table 1. Fertilizer application based on Ferads recommendation*

No	Fertilizer application	Urea (kg)	SP36 (kg)
A.	Preplant (40%N, 100% P_2O_5)	26.32	84.06
B.	Drip application (60%, N), 15 times	39.50	-
1	Weeks 1	2.63	-
2	Weeks 2	2.63	-
3	Weeks 3	2.63	-
4	Weeks 4	2.63	-
5	Weeks 5	2.63	-
6	Weeks 6	2.63	-
7	Weeks 7	2.63	-
8	Weeks 8	2.63	-
9	Weeks 9	2.63	-
10	Weeks 10	2.63	-
11	Weeks 11	2.63	-
12	Weeks 12	2.63	-
13	Weeks 13	2.63	-
14	Weeks 14	2.63	-
15	Weeks 15	2.63	-
	Total	39.47	-

Notes: *for a 540 m^2 plant bed.

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early vegetative growth was not influenced by planting density. However, at 10 and 11 WAT, plant height was significantly affected by density (P<0.0001), with the tallest plants observed at the highest density (106,667 plants.ha^{-1}). This trend may be attributed to increased competition for light, which has prompted vertical growth. Such delayed responses are consistent with competition-driven elongation, a phenomenon well-documented in other crops, such as soybeans, where increased density enhances height but reduces stem diameter and branching. These growth patterns are also affected by canopy light interception and photosynthetic efficiency (Wang et al., 2023; Xu et al., 2024).

The interaction between irrigation line number and planting density significantly influenced plant height at 5, 6, and 7 WAT, with marginal significance at 9 WAT. However, no significant interaction was found for fruit number at 8 WAT, indicating that line number and planting density independently affect yield components. Significant interactions appearing at 5–7 WAP coincide with the rapid vegetative growth phase, when water demand rises sharply and root exploration becomes more extensive. Under these conditions, the spatial pattern of water distribution from different irrigation line configurations could interact with the increased canopy competition at higher plant densities, influencing stem elongation rates. However, these effects appear transient, possibly because plant height reaches a physiological plateau around 9–11 WAP, at which point the plant's genetic growth limit masks further interaction effects.

Table 2. Data on rainfall, temperature, and humidity in Cikarawang Field Station, Bogor

Parameter	Climatology data for 2024-2025				
	September	October	November	December	January
Rainfall (mm)	309.0	724.7	1365.9	342.2	190.4
Temperature (˚C)	26.8	27.2	26.4	25.9	26.5
Relative humidity (%)	87.0	83.7	90.0	90.9	88.8

Source: Educational and Research Meteorology Station, IPB University, September 2024- January 2025.

Table 3. Chili plant height at different irrigation line numbers and plant densities at 1 to 11 weeks after planting

Treatments	Plant height (cm) (weeks after planting)										
	1	2	3	4	5	6	7	8	9	10	11
Number of irrigation lines											
Single	18.8	24.4	31.8	40.0	48.2	57.1	64.1	70.6	76.2	76.4	79.0
Double	18.6	23.9	32.1	40.1	50.0	59.1	66.3	71.3	76.9	80.5	82.8
Sig	ns	ns	ns	ns	**	**	*	ns	ns	*	*
P value	0.80	0.37	0.72	0.85	0.00	0.00	0.03	0.43	0.40	0.04	0.05
Plant density (plants.ha^{-1})											
26,667	18.3	23.7	31.3	39.8	48.5	58.2	65.0	70.3	76.0	73.3	75.7
53,333	19.7	24.7	32.3	40.3	48.8	57.5	64.5	70.5	76.2	75.7	78.8
80,000	18.2	24.2	31.7	40.0	49.3	58.2	65.2	70.7	77.0	82.2	84.3
106,667	18.5	24.2	32.5	40.0	49.7	58.5	66.0	72.3	77.0	82.7	84.7
Sig	ns	ns	ns	ns	ns	ns	ns	ns	ns	L**	L**
P value	0.4	0.6	0.6	0.9	0.1	0.5	0.7	0.4	0.8	0.0	0.0
Interaction											
Sig	ns	ns	ns	ns	**	**	*	ns	*	ns	ns
P value	0.82	0.59	0.98	0.34	0.01	0.02	0.11	0.15	0.05	0.67	0.83
CV	8.26	5.47	5.22	2.63	1.70	1.99	3.37	3.18	2.78	5.37	5.32

Notes: Orthogonal polynomial contrast for the effect of line number and plant density, ns= not significant; L=linear, Q=quadratic; and *= significantly different at P≤0.05, and **= significantly different at P≤0.01.

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The weakness of the interaction may also be explained by the design of the irrigation system and the soil's hydraulic properties. If soil water redistribution between rows is efficient, the difference in water supply between single and double lines is minimized, reducing the scope for interaction with density.

Fruit Weight per Plant

The number of irrigation lines had no statistically significant effect on fruit weight per plant across all harvest stages (P>0.05; Table 4). While Line 1 showed slightly higher values than Line 2 at early (124.59 g vs. 121.25 g), mid (128.14 g vs. 121.30 g), and late harvests (24.05 g vs. 25.98 g), these differences were not significant. Total fruit weight per plant was similar between Line 1 (276.78 g) and Line 2 (268.52 g; P=0.70), indicating that irrigation line number does not influence per-plant productivity, aligning with findings from Sezen et al. (2007).

In contrast, plant density had a significant effect on fruit weight per plant. Higher densities (80,000–106,667 plants.ha^{-1}) produced lighter fruits, while lower densities resulted in heavier fruit. The heaviest fruits were observed at 53,333 plants.ha^{-1} (144.86 g), followed by 26,667 plants.ha^{-1} (122.84 g; P=0.042). This pattern was also evident during the late harvest, where fruit weights were highest at 26,667 plants.ha^{-1} (24.77 g) and lowest at 80,000 and 106,667 plants.ha^{-1} (20.88 g and 21.95 g, respectively), consistent with the results reported by Chen et al. (2024).

The highest total fruit weight per plant was recorded at 53,333 plants.ha^{-1} (313.72 g), followed by 26,667 plants.ha^{-1} (303.53 g), and the lowest at 106,667 plants.ha^{-1} (231.03 g). These outcomes exemplify the density-yield trade-off: while higher planting densities increase yield per hectare, they often reduce yield per individual plant (Fageria and Baligar, 2005). Moderate densities (approximately 53,333 plants.ha^{-1}) tend to strike a favorable balance between fruit size and land-use efficiency.

An interaction between irrigation line number and planting density was only significant during the early harvest (P=0.01), indicating that their combined influence is more pronounced at earlier stages. No significant interactions were observed during the mid, late, or total harvest stages (P>0.05), indicating that these factors had independent effects over time.

Table 4. The simple and interaction effects of the number of irrigation lines and plant densities on chili fruit weight per plant

Treatments	Fruit weight per plant at early harvest (g)	Fruit weight per plant at mid-harvest (g)	Fruit weight per plant at late harvest (g)	Total fruit weight per plant (g)
Number of irrigation lines				
Single	124.59	128.14	24.05	276.78
Double	121.25	121.30	25.98	268.52
Sig	ns	ns	ns	ns
P-value	0.68	0.52	0.85	0.70
Plant density (plants.ha^{-1})				
26,667	122.84	155.93	24.77	303.53
53,333	144.86	136.41	32.46	313.72
80,000	110.56	110.89	20.88	242.32
106,667	113.45	95.64	21.95	231.03
Sig	L*	ns	L*	L*
P-value	0.042	0.13	0.03	0.1
Interaction				
Sig	**	ns	ns	ns
P-value	0.01	0.58	0.49	0.49
CV	16.00	34.78	28.63	18.64

Notes: Orthogonal polynomial contrast for the effect of line number and plant density, ns= not significant; L=linear, Q=quadratic; and *= significantly different at P≤0.05, and **=significantly different at P≤0.01.

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Fruit Number per Plant

Irrigation line number did not significantly affect the number of fruits per plant at any harvest stage (P>0.05; Table 5). The single line produced slightly more fruit than the double lines during early (29.13 vs. 27.22), mid (36.07 vs. 32.55), and late harvests (8.93 vs. 9.03), but these differences were not statistically significant. Similarly, the total fruit count per plant was comparable between the double lines (74.13 vs. 68.79; P = 0.40), suggesting irrigation line number has minimal impact on per-plant productivity, in agreement with Sezen et al. (2007).

Plant density, on the other hand, significantly affected fruit number per plant during mid-harvest (P=0.0399) and for the total count (P=0.05). The highest mid-harvest count was found at 26,667 plants.ha^{-1} (43.37 fruits), which declined with increasing density. The highest overall count was at 26,667 plants.ha^{-1} (83.32), followed by 53,333 plants.ha^{-1} (73.91), and the lowest was at 106,667 plants.ha^{-1} (56.74). These results confirm that higher densities increase inter-plant competition for resources, thereby reducing per-plant fruit number (Xu et al., 2024).

By the late harvest, plant density had no significant effect on fruit count (P=0.70), although plants at lower densities still produced more fruits (9.18 vs. 8.21 fruits at 106,667 plants.ha^{-1}). No significant interaction was observed between the irrigation line and planting density (P>0.05), again suggesting an independent influence. Coefficients of variation (CV) ranged from 23.34% to 41.96%, indicating greater variability during early harvests and increased consistency by the end of the season.

Practically, lower planting densities (26,667–53,333 plants.ha^{-1} optimize per plant yield, while higher densities (80,000–106,667 plants.ha^{-1}) enhance total yield per ha. An intermediate density of 53,333 plants. ha^{-1} appears optimal in balancing these trade-offs.

Fruit Weight per Bed

The effects of irrigation line number and planting density on chili fruit weight per bed (kg.15 m^{2}) across harvest stages and in total are presented in Table 6. The irrigation line number had a significant borderline effect on the average total fruit weight per bed (P=0.05) and a marginal effect at mid-harvest (P=0.06). In contrast, no significant effects were observed at either the early (P>0.05) or late harvest stages (P=0.72).

Table 5. The simple and interaction effects of the number of irrigation lines and plant densities on chili fruit numbers per plant

Treatments	Fruit number per plant at early harvest	Fruit number per plant at mid-harvest	Fruit number per plant at late harvest	Total fruit number per plant
Number of irrigation lines				
Single	29.13	36.07	8.93	74.13
Double	27.22	32.55	9.03	68.79
Sig	ns	ns	ns	ns
P value	0.70	0.36	0.45	0.40
Plant density (plants.ha^{-1})				
26,667	30.76	43.37	9.18	83.32
53,333	33.58	36.67	10.01	80.26
80,000	26.67	30.35	8.51	65.53
106,667	21.67	26.86	8.21	56.74
Sig	ns	L**	ns	L*
P value	0.05	0.0399	0.7	0.05
Interaction				
Sig	ns	ns	ns	ns
P value	0.25	0.72	0.15	0.72
CV	41.96	26.66	29.61	23.34

Notes: Orthogonal polynomial contrast for the effect of line number and plant density, ns= not significant; L=linear, Q=quadratic; and *= significantly different at P≤0.05, and **= significantly different at P≤0.01.

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Although differences were not statistically significant at early and mid-harvest stages, beds irrigated with double lines produced heavier yields than those with a single line. Specifically, at early harvest, the single line produced 26.25 kg per bed, while double lines yielded 29.87 kg. During mid-harvest, the single line yielded 9.23 kg, and the double lines yielded 10.89 kg. At late harvest, differences were negligible (single line= 1.98 kg; Double lines= 1.86 kg). However, when total fruit weight per bed was considered, plots with double lines produced significantly more fruit (42.62 kg per bed) than those with single lines (37.46 kg), highlighting the importance of a consistent and uniform water supply in maximizing yield.

Planting density had a highly significant linear effect on early yield (P<0.05), with denser plantings producing more fruit per bed. This trend confirms that both the irrigation system and planting density independently influence yield.

From a practical standpoint, higher planting densities (80,000–106,667 plants.ha^{-1}) in combination with double irrigation lines offer the most significant potential for maximizing yield per unit area. In contrast, lower planting densities (26,667–53,333 plants.ha^{-1}) may enhance per-plant productivity but result in reduced total yield per bed. Therefore, farmers can tailor their planting strategies to meet their production goals and utilize their available land resources effectively.

Predicted Fruit Weight per Hectare

This study also assessed the combined effects of irrigation line number and planting density on total predicted yield per hectare, as well as on nutrient use efficiency (NUE) and water use efficiency (WUE), summarized in Table 7. The use of double lines resulted in significantly higher yields compared to a single line, producing 28.41 tons.ha^{-1}, versus 24.97 tons.ha^{-1}, respectively (P=0.05). A similar trend was observed for the total fruit number, with double lines producing 4,059,167 fruits.ha^{-1} compared to 3,567,500 fruits.ha^{-1} in single line (P=0.05). These findings align with those of Kapoor et al. (2022), who reported that optimal irrigation enhances fruit development and overall yield.

Interestingly, WUE was higher in the single line (3.64 kg.mm^{-1}) compared to the double lines (2.07 kg.mm^{-1}), with the difference being statistically significant (P=0.015). This suggests that while two irrigation lines improve fruit yield, they may reduce water use efficiency due to increased water application. The result supports the notion that WUE is influenced not

Table 6. The single and interaction effects of the number of irrigation lines and plant densities on chili fruit weight per 15 m^2 bed

Treatments	Fruit weight per bed at early harvest (kg)	Fruit weight per bed at mid-harvest (kg)	Fruit weight per bed at late harvest (kg)	Total fruit weight per bed (kg)
Number of irrigation lines				
Single	26.25	9.23	1.98	37.46
Double	29.87	10.89	1.86	42.62
Sig	ns	*	ns	*
P value	0.09	0.06	0.72	0.05
Plant density (plants.ha^{-1})				
26,667	16.41	6.82	1.55	24.78
53,333	25.75	11.41	2.10	39.26
80,000	28.95	10.14	2.14	41.23
106,667	41.14	11.87	1.89	54.90
Sig	L**	L*	ns	L**
P value	<.0001	0.003	0.6	<.0001
Interaction				
Sig	ns	ns	ns	ns
P value	0.98	0.85	0.16	0.83
CV	17.33	19.19	41.59	14.36

Notes: Orthogonal polynomial contrast for the effect of line number and plant density, ns= not significant; L=linear, Q=quadratic; and *= significantly different at P≤0.05, and **= significantly different at P≤0.01.

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only by irrigation quantity but also by plant density, as discussed by Stagnari et al. (2017).

Overall, increasing plant density from 80,000 to 106,667 plants.ha^{-1} led to higher yields and improved nutrient use efficiency. However, this also intensified intraspecific competition, which can limit the performance of individual plants. The limited interaction between irrigation lines and planting density suggests that these factors can be optimized independently, allowing for greater flexibility in farm management.

The findings of this study indicate that maximizing total yield per ha and enhancing land use efficiency are best achieved through the combination of double-line irrigation and high planting densities, ranging from 80,000 to 106,667 plants.ha^{-1}. This strategy significantly increases overall fruit production by optimizing the utilization of spatial resources. In contrast, the highest fruit weight per plant was observed under single-line irrigation at a moderate density of approximately 53,333 plants.ha^{-1}, where reduced interplant competition favors individual plant performance. While per plant yield remains an important agronomic consideration, especially under resource-limited or site-specific conditions, the overall results suggest that total productivity and input-use efficiency should be prioritized in large-scale production systems. Therefore, an integrated and adaptive management approach, tailoring irrigation layout and planting density according to specific land characteristics and resource availability, is recommended to balance productivity goals with sustainable resource use.

Conclusions

This study demonstrated that planting density significantly influenced the growth and yield of chili plants. At the same time, the effect of the irrigation line number was more apparent at the plot level than on individual plant performance. A high planting density of 106,667 plants.ha^{-1} increased total fruit yield per bed, although this benefit was offset by reduced productivity per plant due to resource competition. Although the number of irrigation lines did not significantly affect individual plant traits, the use of double lines resulted in a notably higher total fruit weight per bed, indicating its importance in enhancing overall productivity. However, this benefit came with a trade-off in water use efficiency (WUE), which was lower in two-line irrigation systems (2.07 kg.mm^{-1}) compared

Table 7. The single and interaction effects of the number of Irrigation lines and plant density for chili predicted fruit weight per ha, WUE, NUE, and PFP

Treatments	Fruit weight (tons.ha^{-1})	Fruit number. ha^{-1}	Water use efficiency (kg.mm^{-1})	N use efficiency (kg.kg^{-1})	P use efficiency (kg.kg^{-1})	N Partial factor productivity (kg.kg^{-1})	P partial factor productivity (kg.kg^{-1})
Line number							
Single	24.97	3,567,500	3.64	111.48	258.94	51.28	40.08
Double	28.41	4,059,167	2.07	126.84	294.63	58.34	45.61
Sig	*	*	**	ns	*	*	*
P value	0.05	0.05	<.0001	0.05	0.05	0.05	0.05
Plant density (plants.ha^{-1})							
26,667	16.52	2,360,000	1.70	73.74	171.30	33.92	26.52
53,333	26.17	3,738,333	2.82	116.81	271.34	53.73	42.00
80,000	27.49	3,926,667	2.97	122.70	285.01	56.44	44.12
106,667	36.60	5,228,333	3.93	163.37	379.49	75.15	58.75
Sig	L**	L**	L**	L**	L**	L**	L**
P value	<.0001	<.0001	<.0001	<.0001	0.0	<.0001	<.0001
Interaction							
Sig	ns	ns	ns	ns	ns	ns	ns
P value	0.83	0.83	0.015	0.67	0.83	0.83	0.83
CV	14.36	14.36	13.02	14.36	14.36	14.36	14.36

Notes: Orthogonal polynomial contrast for the effect of line number and plant density, ns= not significant; L=linear, Q=quadratic; and *= significantly different at P≤0.05, and **= significantly different at P≤0.01.

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to single-line systems (3.64 kg.mm^{-1}). Plant density also positively influenced WUE, as well as nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE), with the highest values achieved at 106,667 plants.ha^{-1}. These findings underscore the importance of adopting integrated crop management strategies that incorporate optimal planting density, irrigation practices, and fertilization to optimize both yield and resource use efficiency. High planting densities (80,000–106,667 plants.ha^{-1}) are ideal for maximizing total yield per hectare. In contrast, a moderate density of 53,333 plants.ha^{-1} is more effective for balancing individual plant performance with land-use efficiency. The use of double line irrigation increases total fruit production per bed but may reduce WUE, making single line irrigation more suitable in water-limited environments. Conversely, systems with ample nutrients and reliable irrigation benefit more from high-density planting combined with double-line irrigation. Sustainable and productive nitrogen and phosphorus use in chili cultivation can be achieved by adjusting fertilizer application rates according to plant population density, thereby optimizing the nitrogen and phosphorus use efficiency.

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