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Impact of planting density and nitrogen on the productivity of warm-climate onion in the Mexican pacific

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ABSTRACT

Objective: To evaluate three population density and nitrogen supply in onion.

Design/methodology/approach: An experiment was developed in the dry tropics of Mexico. Seedlings were produced in nursery and transplanted on 0.9 m planting beds. In addition to crop management with drip irrigation, nitrogen nutrition was planned according to the rational form of supply. Density/nitrogen factors were evaluated in factorial design 3^2. Developmental, productive and qualitative bulb variables were recorded and statistically analyzed.

Results: The interaction of factors was varied, but in the productive, only the density factor was consistent; bulb weight excelled in the low density (14.8 plants m^2) but did not lead to the highest yield, on the other hand, the highest density together with N supply, presented the highest yield per area of 2.14 and 2.17 kg m^2.

Limitations on study/implications: Onions are favored by the Mexican population as they are among the most consumed vegetables due to their bulbs, and they are attributed with various health benefits. Approximately 52 thousand hectares are harvested in the country and Michoacan participates with 8.3% of production. However, yields are lower than their potential, due to the lack of adaptation to current environmental conditions. This leads to consider the exploration of alternative locations and the implementation of strategies to improve yields, where nutrition and spacing are key factors.

Findings/conclusions: The density of 26.9 plants m^2 with N addition produced the highest yield.

Keywords: *Allium cepa* L., bulb, plant spacing, nitrogen fertilization, productivity.

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INTRODUCTION

Onion is one of the main vegetables in the basic food basket in Mexico, making it popular among the country's population of over 100 million people (INEGI, 2020), with a *per capita* consumption of 8.6 kg (SIAP, 2023). Both the fresh shoots or leaves and the bulbs of this vegetable are consumed (Brewster, 2008). Additionally, onions are attributed with various health benefits, such as anticancer properties, platelet aggregation inhibition and anticoagulant effects, as well as antiasthmatic and antibiotic properties (Griffiths *et al.*, 2002).

Globally, Mexico ranks 10^{th} out of 58 onion-producing countries by established area (FAOSTAT, 2022). In 25 of 32 states, 52,024 hectares were harvested, with Michoacán contributing 8.3% of the national production (SIAP, 2023). However, as a temperate climate vegetable, onion yields do not reach their cultivation potential due to environmental issues, which have affected agricultural areas by creating challenges related to adaptation to current conditions. This leads to considering the exploration of alternative locations, where actions in agronomic components, such as planting density and nutrition, especially nitrogen, are implemented to mitigate adversities (Siliquini *et al.*, 2015; Russo, 2008). Regarding population density, the implementation of various planting patterns directly influences bulb size (Brewster, 2008). As planting density per area increases, yield also rises; however, this can reach a limit, as yield tends to decrease when density exceeds the supported level, due to competition for light, nutrients, and available water in the soil (Siliquini *et al.*, 2015). This imbalance is often exploited to produce specific onion sizes. High densities, between 1,000 and 2,000 plants m^2, favor the production of small bulbs for seed-material. Densities between 50 and 100 plants m^2 produce bulbs with diameters between 5 and 7 cm for fresh consumption. In contrast, densities between 25 and 50 plants m^2 produce larger bulbs (Brewster, 2008). Several studies highlight positive effects on onion production through the use of different densities.

By simply increasing the row spacing from 5 to 10 cm, bulb diameter and stem diameter increased by 17% and 15%, respectively (Yemane *et al.*, 2014). Additionally, with a density of 45 plants m^2 on 1.2 m wide planting beds, significant increases in vegetative growth, bulb yield, and bulb quality were observed compared to 0.6 m wide beds at the same density (Abou *et al.*, 2017).

Conversely, yields of 47,540 kg ha^{-1} were associated with a density of 200 plants m^2. However, the preference for smaller bulbs, with a weight of 60 g, is achieved at a lower density of 66.67 plants m^2 (Walle *et al.*, 2018). Thus, managing planting densities is crucial, as long as the level of competition is not reached when plants grow too close together (Siliquini *et al.*, 2015).

Regarding nutrition, meeting the needs of onions efficiently is challenging due to their particular shallow root system (Brewster, 2008). Although various criteria are used to nourish them, little attention is given to soil and foliar analysis, and the different phenological stages are not considered (Bonza-Espinoza *et al.*, 2016). Since onions require nutrients, fertilization is necessary to improve yield, although soil fertility is the foundation for planning the application rates, with the expectation of a response from the crop (Przygocka-Cyna *et al.*, 2020). Thus, nitrogen demand is met by combining soil N with N from fertilizers to ensure optimal growth (Messele, 2016). Since onions are considered an intensive crop, they require high amounts of N (Casella *et al.*, 2022), with 65% of the N concentrated in the bulbs and 35% in the leaves (Geisseler *et al.*, 2022). Since N (NH_4-N or NO_3-N), which is anionic in nature, is easily lost due to its inability to be retained by clay particles, there is a risk of reduced yield. Nitrogen application rates generally range from 50 to 200 kg ha^{-1}, but it should be noted that very low or very high doses can alter or delay the formation and maturation of leaves and bulbs (Tae *et al.*, 2003).

This occurs when nitrogen is applied during the bulb growth phase, between 60 and 75 days after planting, depending on the genotype (Amaya & Méndez, 2013). Therefore, it is necessary to split nitrogen applications between 60 and 80 kg ha^{-1} before planting, and a similar amount when the plants reach about 10 cm in height (Brewster, 2008). Given the need to generate information addressing population density management and nitrogen nutrition in onions, the objective of this study was to evaluate the effect of three population densities and two nitrogen application methods on onions under dry tropical environmental conditions.

MATERIALS AND METHODS

In the Dry Tropics of Michoacán, Mexico, an experiment was conducted at the Valle de Apatzingán Experimental Station of the National Institute of Forestry, Agricultural, and Livestock Research in Antúnez, Michoacán, Mexico (19° 00’ 34” N and 102° 13’ 44” W), at an elevation of 338 m above sea level. According to García (2004), the predominant climate corresponds to Bs_1, supporting representative species of low deciduous forest, and the soil is classified as pelic vertisol (INEGI, 2016). The climatic variation behaved as specified in Table 1.

In a 3 m^2 seedbed with sandy loam soil, onion seedlings of the Cojumatlán® variety were produced. The preparation involved tilling the soil and applying 90% wettable sulfur at a rate of 10 g m^2. Small furrows were then drawn with a spacing of 15 cm, where onion seeds were sown in a “drill” method, covered with soil, and irrigated by gravity until field capacity was achieved. The seedbed was then covered with black plastic for four days to promote germination. Afterward, it was uncovered, and watering continued until the emergence of the epicotyls. Afterward, the seedlings were watered daily, and ammonium sulfate fertilizer was applied by broadcasting on two occasions. Once the seedlings reached a bulb size similar to that of a cotton swab, after six weeks, they were transplanted. Simultaneously, the experimental area was prepared through tillage, and planting beds were formed with a width of 0.9 m. Additionally, a soil sample was analyzed to determine the status of the main physical and chemical variables, yielding the following results: organic matter 1.43%, pH 7.90, inorganic nitrogen 19.4 mg kg^{-1}, phosphorus 15.5 mg kg^{-1}, potassium 448 mg kg^{-1}, and cation exchange capacity 65.6 mol kg^{-1}.

The management of the experiments was based on cultural practices specific to the crop and phytosanitary management recommended by INIFAP (2015). Additionally, some strategies were based on the guidelines proposed by Khosa and Lee (2018), except for nutrition, which was one of the factors to be tested; these were supplied with nitrogen

Table 1. Climatic variation during the experiment, autumn-winter cycle.

Climate variables	Mean value (September-February)
Maximum Temperature (°C)	34.41
Minimum Temperature (°C)	17.25
Average Temperature (°C)	26.01
Precipitation (mm)	25.61
Evaporation (mm)	4.13

fertilizer sourced from ammonium sulfate (21% N). Irrigation was by drip with daily intervals, consisting of the placement of two irrigation tapes over the planting beds. The emitters, spaced 0.2 m apart, released a flow rate of 0.7 L h^{-1}. The irrigation time varied according to demand, but generally lasted between 2 and 3 h. The crop cycle was approximately 16 weeks.

Using a factorial experimental design, the density factor was evaluated with three treatments, and the nitrogen factor (supply) with two treatments, which together formed six treatments with four replicates. The density factor was set up on beds of 0.9 m with densities of 14.8 (D1), 22.2 (D2), and 29.6 (D3) plants m^2 in two, three, and four rows, respectively. The nitrogen factor consisted of two treatments based on the formula 140-0-0 (N-P-K) kg ha^{-1}, supplied in two parts (N1; before transplanting and 30 days after transplanting) and supplied in one part (N2; 30 days after transplanting), respectively.

At 110 days after transplanting, corresponding to the maturity stage, the development variables were evaluated. Plant height was measured with a tape measure from the base of the soil to the tip of the longest leaf. Stem diameter was measured with a caliper 2.0 cm above soil level.

The number of leaves was recorded by counting the number of leaves produced per plant. At harvest stage, 120 days after transplanting, productive variables such as bulb weight were recorded by weighing the bulbs using a digital scale (Denver Instrument Company Model AA-160); bulb size was measured by the polar and equatorial circumferences with a tape measure; and yield was calculated based on the average bulb weight and the density of plants per area. The qualitative characteristics of the bulbs were obtained from 10 physiologically mature bulbs per treatment. pH was measured by cutting the bulb tissue into pieces and grinding it in a mortar with distilled water; once mixed, the juice was collected in a beaker, and pH values were recorded using a portable pH meter (Hanna® model pHep). Soluble solids were measured using a handheld refractometer (Atago® model HSR-500), where a drop of onion tissue extract was placed on the base of the refractometer and the reading was recorded. The moisture content of the bulbs was obtained by taking 100 g of cut tissue from the bulbs per treatment, which were placed in labeled expanded polystyrene plates and maintained at room temperature for 20 days; the percentage of moisture was calculated based on the difference between initial and final weight.

The obtained data were processed using analysis of variance under a factorial design, and means were compared using Tukey's test ($P=0.05$). The statistical software used was SAS (2002).

RESULTS AND DISCUSSION

In the development variables, both quantitative and qualitative bulb analyses, the responses were diverse (Table 2). As observed, the development variables did not show changes due to the D*N interaction, and the factor N also did not show changes when considered separately; only the factor D exhibited differences. The treatment D3 increased plant height by 16% and the number of leaves by 12% compared to treatments D1 and D2. However, regarding stem diameter, treatments D1 and D2 were 8% superior to treatment D3 (Table 2).

As for the productive variables, no differences were observed due to the D*N interaction. However, when considering the factors D and N separately, differences were only observed in the polar and equatorial diameters of the bulbs in factor D, with increases of 13% and 10%, respectively, in treatment D2 compared to treatments D1 and D3 (Table 2). For the variables of fruit weight and yield per area, differences were observed due to factors D and N, where treatment D1 and treatment N2 increased fruit weight by 11% and 7%, respectively, compared to the other treatments in each factor. In contrast, treatment D3 and N2 increased yield per area by 32% and 6%, respectively, compared to the rest of the treatments combined (Table 2). Regarding the qualitative bulb variables, no significant changes were detected due to the D*N effect in the variables pH, soluble solids, and dry matter. Similarly, the analysis of the separate effects of factors D and N on the qualitative bulb variables showed no differences (Table 2).

On the other hand, the variance analyses of the combined treatments for the development variables showed statistical differences. The greatest plant height was achieved with the D3-N2 treatment, followed by the D3-N1 treatment, both of which exceeded the others by 16% (Table 3). With a height of 52.3 cm, the D3 (29.6 plants m^2) - N2 (N in one application) treatment aligns with the findings of Seifu *et al.* (2015), who evaluated six nitrogen doses (ranging from 0 to 138 kg ha^{-1}) and four row spacings (ranging from 7.5 to 15 cm). They obtained the greatest plant height (53.69 cm) with a spacing of 15 cm between rows and 138 kg N ha^{-1}, which is consistent with the present findings.

Regarding the stem diameter variable, significant differences were observed, with the highlighted treatments being D1-N2, D2-N2, and D1-N1, which collectively exceeded the treatments at density 3 (29.6 plants m^2) by 10% in both levels of nitrogen supply. However, these treatments integrated at density 3 reflected the highest number of leaves. Similar studies also did not report significant effects on this variable (Seifu *et al.*, 2015; Alemu *et al.*, 2022). In contrast, Amaya and Méndez (2012) reported stem diameters of 1.42 cm, but with low doses of 60 kg ha^{-1} N after 104 days, and they also found no effect on this

Table 2. Analysis of density (D) and nitrogen (N) factors and their interaction on development, productive, and qualitative variables in onion. Antúnez, Michoacán, Mexico.

Variables	D	D1	D2	D3	N	N1	N2	D*N
PH (cm)	**	42.21 b	42.98 b	50.98 a	NS	45.17	45.61	NS
SD (cm)	**	1.36 a	1.30 a	1.22 b	NS	1.27	1.31	NS
NL (No.)	**	7.87 b	8.30 b	9.15 a	NS	8.36	8.51	NS
PD (cm)	**	11.32 b	12.72 a	10.80 b	NS	11.44	11.79	NS
ED (cm)	**	7.95 ab	8.38 a	7.12 b	NS	7.70	7.93	NS
BW (g)	**	83.91 a	76.82 b	73.18 b	**	75.3 b	80.65 a	NS
YA (kg)	***	1.23 c	1.70 b	2.15 a	**	1.64 b	1.75 a	NS
pH	NS	6.55	6.54	6.48	NS	6.49	6.55	NS
SS (°Brix)	NS	5.51	5.30	5.58	NS	5.53	5.40	NS
DM (%)	NS	11.33	11.08	11.26	NS	11.22	11.23	NS

PH (plant height); SD (stem diameter); NL (number of leaves); PD (polar diameter), ED (equatorial diameter); BW (bulb weight); YA (yield per area); pH (Hydrogen potential); SS (soluble solids); DM (dry matter); NS=Not Significant; *P≤0.05; **P≤0.01; ***P≤0.0001.

Table 3. Analysis of plant height, stem diameter, and leaf count variables in onion, affected by plant density and nitrogen. Antúnez, Michoacán, Mexico.

Density (D) / Nitrogen (N)	Height (cm)	Diameter (cm)	Leaves (No.)
D1-N1	43.00 bc	1.35 ab	7.77 b
D1-N2	41.42 c	1.37 a	7.97 ab
D2-N1	42.85 bc	1.25 bc	8.25 ab
D2-N2	43.12 bc	1.35 ab	8.35 ab
D3-N1	49.67 ab	1.22 c	9.07 ab
D3-N2	52.3 a	1.22 c	9.22 a
C.V.	7.28	4.04	6.90
Significance	**	**	**

C.V.=Coefficient of variation; **P≤0.01; ***P≤0.0001.

variable from the supply of other nutrients. The above indicates that stem diameter is not a prominent trait in response to nutrient supplies, as would be desirable in other species; in fact, onions with thinner stems are preferred.

The analysis of variance for the variable "leaves per plant" showed significant differences. The density of 26.9 plants m^2 (D3) and the single N application (N2) resulted in an average of 9.22 leaves (Table 3). It is important to note that the combination of plant density and nitrogen supply influences this variable. However, nitrogen application, either alone or in combination, also promotes leaf emission, as reported by Singh *et al.* (2017). They achieved 11.96 leaves per plant using the fertilizer formula 120-60-80 (N-P-K) kg ha^{-1} combined with *Azospirillum*. This result is similar to the findings of the present study, although only in trend.

Similarly, the variance analyses detected significant differences in the combined treatments of productive variables (Table 4). For the polar and equatorial diameter variables, the D2-N2 treatment exceeded the average of the D3 treatment in both nitrogen levels by 18% and 16%, respectively. Since bulb size depends on density and nitrogen nutrition, the densities of 14.8 and 22.2 plants per m^2, along with nitrogen, presented the

Table 4. Analysis of bulb size, weight, and yield variables in onion, by the effect of density and nitrogen. Antúnez, Michoacán, Mexico.

Density (D) / Nitrogen (N)	Polar diameter (cm)	Equatorial diameter (cm)	Weight (g)	Yield (kg m^2)
D1-N1	11.02 b	7.97 ab	80.90 ab	1.19 c
D1-N2	11.62 ab	7.92 ab	86.92 a	1.28 c
D2-N1	12.35 ab	8.32 ab	72.32 b	1.60 b
D2-N2	13.10 a	8.45 a	81.32 ab	1.80 b
D3-N1	10.95 b	6.82 b	72.67 b	2.14 a
D3-N2	10.65 b	7.42 ab	73.70 b	2.17 a
C.V.	7.10	8.64	5.83	5.82
Significance	**	*	**	***

C.V.=Coefficient of variation; *P≤0.05; **P≤0.01; ***P≤0.0001.

largest bulb sizes, ranging from 11.02 to 13.10 cm in polar diameter and 7.92 to 8.45 cm in equatorial diameter, respectively, compared to treatments with higher density (Table 4). Therefore, having more plants per area may have reduced bulb size. Some studies reported similar behavior. Singh *et al.* (2017) highlighted the influence of N on bulb size, showing that both N alone or in combination increased bulb length and diameter by 5.13 cm and 5.85 cm, respectively. Similarly, Russo (2008) evaluated two onion varieties with three different densities and two N doses. He found that increasing the density to 102,000 plants ha^{-1} produced more bulbs, but of smaller size in short-day onions. This response was similar to the results obtained in this study, where higher density led to smaller bulbs. In fact, Siliquini *et al.* (2015) concluded that bulb size decreases as plant density increases due to competition for resources.

On the other hand, the bulb weight variable showed significant differences, with treatment D1 standing out, achieving 86.2 g, surpassing the other treatments by 12%. However, this was not reflected in the yield variable, as the most outstanding treatments corresponded to density D3 at both nitrogen levels, which together exceeded the other treatments by 32% (Table 4). It is important to highlight that for the bulb weight and yield variables, the outstanding treatments were not necessarily those with the largest bulb size. The highest bulb weight corresponded to the treatment with the lowest density of 14.8 plants m^2, with a value exceeding 80 g per bulb. However, the highest yield was achieved with the density of 29.6 plants m^2, with a value exceeding 2 kg m^2 (Table 4). In contrast, the lower density affected bulb weight, while the higher density impacted yield. Additionally, treatments with the addition of nitrogen improved yield. Various reports suggest improvements in bulb production through adjustments in density and nitrogen. Seifu *et al.* (2015) evaluated six nitrogen doses and four row spacings. The highest yield was achieved with 15 cm spacing combined with 138 kg ha^{-1} of nitrogen; similarly, Simon *et al.* (2014) reported a yield of 2.72 t ha^{-1} with 69 kg ha^{-1} of nitrogen and 46 kg ha^{-1} of P_2O_5, which is comparable to the yield reported in this study. In their case, the lower nitrogen supply was compensated by the addition of phosphorus. On the other hand, Kahsay *et al.* (2014) tested three different spacings and four onion varieties. They found that the average bulb weight increased from 49.86 to 81.31 g when the spacing between rows was increased from 5 to 10 cm, achieving a yield of 36.14 t ha^{-1}, which is similar to the results obtained in this study. This aligns with the findings of Gebretsadik and Dechassa (2018), who evaluated nitrogen supply from 0 to 150 kg ha^{-1} and plant spacing from 4 to 10 cm. The highest yield of 26.72 t ha^{-1} was achieved with a nitrogen dose of 100 kg ha^{-1} and a spacing of 6×20 cm (833,300 plants ha^{-1}), which aligns with previous reports. Similarly, Walle *et al.* (2018) tested six densities ranging from 25 to 200 plants m^2 and two onion varieties, finding that the highest density (200 plants m^2) produced yields of 47,540 kg ha^{-1}. However, they noted a preference for bulbs weighing around 60 g, which were best produced at a density of 66.67 plants m^2.

Regarding the integrated treatments of the qualitative variables, the variance analyses did not show differences in pH, soluble solids, and dry matter, although their average values corresponded to 6.52, 5.46, and 11.22%, respectively (Table 5). This behavior is consistent with that reported by Walle *et al.* (2018), who tested six densities and two onion

Table 5. Analysis of qualitative variables pH, soluble solids, and dry matter in onion bulbs, by the effect of density and nitrogen. Antúnez, Michoacán, Mexico.

Density (D) / Nitrogen (N)	pH	Soluble solids (°Brix)	Dry matter (%)
D1-N1	6.67	5.57	11.20
D1-N2	6.43	5.45	11.47
D2-N1	6.40	5.27	11.07
D2-N2	6.68	5.32	11.10
D3-N1	6.42	5.75	11.40
D3-N2	6.55	5.42	11.12
C.V.	3.98	5.84	6.20
Significance	NS	NS	NS

C.V.=Coefficient of variation; NS=Not Significant.

varieties. They found no differences in the variable soluble solids, either by separate factors or by the cultivar/density interaction. This aligns with what has been reported for this variable; however, the supply of elements influences biomass production (Przygocka-Cyna *et al.*, 2020). This was also found by Singh *et al.* (2017), who tested a chemical formula and biofertilizers and found that the combination of the dose 120-60-80 (N-P-K) kg ha^{-1} with *Azospirillum* generated 4,510 kg ha^{-1} of dry matter from bulbs, which corresponds to 10% dry matter. This is similar to what was found in the present study. However, the choice of varieties also influences different purposes; for example, for tissue dehydration, the materials should contain between 17% and 20% dry matter, compared to 10% to 12% for the production of bulbs for fresh consumption (Brewster, 2008), which corresponds to the dry matter content found.

In onion cultivation management, various strategies are necessary to improve yields. However, the choice of onion cultivar, nitrogen supply, and planting distances are crucial as they influence outcomes (Awad *et al.*, 2022; Mahmood and Khan, 2007; Gamiely *et al.*, 1991). Thus, the results obtained provided insights for enhancing the production system or, if necessary, discarding practices that may be detrimental.

CONCLUSIONS

The interaction of factors and the independent factors were significant in the productive variables, primarily due to the effect of planting density. The higher density of 29.6 plants m^2 favored plant height, reaching 49.67 cm and 52.3 cm, as well as the number of leaves with 9.07 and 9.22 leaves, but did not influence stem diameter, which corresponded to the lower density of 14.8 plants m^2. Even with nitrogen supply, the highest density of 26.9 plants m^2 reduced bulb size. In contrast, the lowest density produced the highest bulb weights of 80.9 g and 86.92 g, while the highest yield per area of 2.14 and 2.17 kg m^2 corresponded to the treatment with the highest density of 26.9 plants m^2 along with nitrogen supply. The qualitative characteristics of the bulbs were not statistically influenced by the treatments tested.

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