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Growth and yield performance of carrot (*Daucus carota* L.) as influenced by plant population density under irrigation condition

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Abstract: Poor agronomic practices, such as inadequate plant density, can result in suboptimal carrot (*Daucus carota* L.) yield and quality in some regions. In 2020, a field experiment was conducted under irrigation conditions in Gerado, South Wollo administrative zone, Ethiopia, using the Nantes variety as a test crop, to investigate the impact of inter-row and intra-row spacing on carrot yield. The treatments involved three inter-row (row) spacing levels (10, 15, and 20 cm) and three intra-row (plant) spacing levels (5, 10, and 15 cm) in a randomized complete block design with three replications. Row and plant spacing significantly affected (P<0.05) total yield, plant height, leaf fresh weight, root length, root diameter, and root fresh weight. The highest marketable yield (490.4 q ha^{-1}) was achieved with a plant density of 20 x 5 cm. In contrast, the highest unmarketable yield (36.3 q ha^{-1}) was obtained with a spacing of 20 x 15 cm. Hence, a plant density of 20 x 5 cm is recommended for optimal marketable carrot yield in the study region and similar agroecologies, although further research across multiple locations and seasons is necessary to validate the results.

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1. Introduction

Carrot (*Daucus carota* L.) is a short duration vegetable crop. In terms of production areas and market value, it is among the top ten most economically significant vegetable crops in the world. Carrots are widely cultivated because they offer a low-cost source of vitamins (particularly Vitamin A), minerals, and fibre in the human diet (Nuez and Prohens, 2008). The taproot contains high amount of carotene (10 mg per 100 g), thiamine (0.04 mg per 100 g) and riboflavin (0.05 mg per 100 g). Additionally, it contains protein, fat, minerals and vitamin C. Due to these several uses, carrot consumption has increased from time to time (Tegen and Jembere, 2021).

In the world's main carrot-growing nations, yields of carrots can range from 30 to 100 t ha^{-1}. Carrot yields per unit area in the majority of developing nations like Ethiopia (whose average fresh carrot yield per ha is 5.6 t) continue to be below the global average (Kassa *et al.*, 2018). Numerous factors, such as poor production techniques, a lack of technical inputs, pests, and postharvest losses, are linked to low productivity (Tegen and Jembere, 2021; Tschirley *et al.*, 2004). Abiotic stress can also contribute to the decline in quantity and quality of horticultural products, such as carrot (Muhie *et al.*, 2021).

One of the key elements affecting marketable carrot root yield and root size is plant population density (Lana, 2012). In previous research investigations, it was reported that plant population of 450,000 and 300,000 is ideal for fresh market and processing carrots, respectively (Tegen and Jembere, 2021). In addition, it was also revealed that narrow spacing resulted in a higher marketable carrot root yield (Da Silva *et al.*, 2008; Shiberu and Tamiru, 2016). On the other hand, another group of researchers reported that crops planted with wider spacing produced the highest total yield. This discrepancy between the result findings of researchers came from the purpose of production of carrots (for fresh market or for industrial use), as each purpose has its own specific root size range (Kabir *et al.*, 2013; Lana and Carvalho, 2013). Researchers also looked into the possibility of producing baby carrots that are more suited for commercialization through the use of high population density cropping and early harvesting. Farmers typically sow carrots by broadcast at a rate of 4-5 kg/ha, although some of them prefer inter-row spacing ranging from 20 to 30 cm and intra-row spacing of 10 to 20 cm. Crops such as carrot (*Daucus carota*) and Chinese jute (*Abutilon theophrasti*) exhibit plasticity in their morphology and modular growth, making it challenging to determine a suitable unit for population density (Wang *et al.*, 2017; Ford and Sorrensen, 2018), a crucial variable that connects individuals to crops. Some authors have provided details on agronomic practices used in carrot production (Bender *et al.*, 2020; Reginaldo *et al.*, 2021). However, there is limited information available on the plant population density of irrigated carrots that can ensure an optimal marketable yield. Farmers in the study area use broadcasting method of sowing under rainfed production system. Recent research finding also recommended the need to investigate the effects of plant density on carrot (Biratu *et al.*, 2022). The objective of the current study was to identify the optimum population density by adjusting inter- and intra-row spacing for marketable root yield and root size of carrot under irrigation.

2. Materials and Methods

Descriptions of the study area

The experiment was conducted at Gerado, South Wollo administrative zone, Northeastern Amhara region, Ethiopia in 2020 cropping season under irrigation. The area is located at distance of 401km away from the capital to the Northeastern part of the country. Geographically, the study area is found at the intersection of 11°8′ N and 39°38′ E (Fig. 1). It falls within semi-arid climatic zone with an average monthly minimum and maximum temperature of 12.37°C and 26.27°C, respectively. The area receives an annual rainfall amount of 1291.3 mm/year with erratic nature. Due to this the area is characterized as moisture deficit unless there is supplementary irrigation. The soil type of the area is sandy-loam. It has three permanent rivers which have the potential to irrigate throughout the year.

Experimental design and treatments

The experiment included nine treatments involving three different inter-row distances (10, 15, and 20 cm), also referred to as row distance (Rd), and three different intra-row distances (5, 10, and 15 cm), also referred to as plant distance in the row (Pd). The experiment was arranged in a randomized complete block design with three replications following the procedures of Gomez and Gomez (2010). The treat-

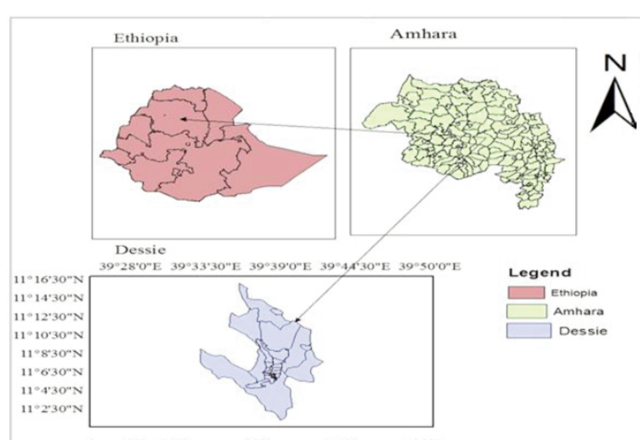

Fig. 1 - Map of the study area.

ments were assigned randomly to the experimental plots within a block.

Experimental materials and procedures

Carrot, cv. Nantes was used as a test crop for this experiment. This cultivar of carrot is well adapted in the study areas. The land was well prepared to a fine tillage to a depth of 30 cm following the conventional tillage practice, using oxen to plough. Thereafter, a field layout was prepared, and each treatment was assigned randomly to the experimental plots. Seeds were sown in raised beds with 20 cm height at a spacing based on treatment assigned to the plot. Carrot seeds were sown by drilling in 1.2 m x 1 m long rows in each plot. The complete amount of phosphorus (175 kg P_2O_5 ha^{-1}) was applied at once, while the nitrogen in the form of urea (150 kg ha^{-1}) was applied in two parts: half of the amount was applied during sowing, and the remaining half was manually top-dressed in the inter-row spaces during the mid-tillering crop stage, which occurred 35 days after emergence (DAE). Irrigation and other required cultural practices were applied equally to all plots. During the experimental periods, a successful crop was produced by applying furrow irrigation at seven days interval and consistently performing all recommended cultural practices. Weeds were manually removed and collected from the crop fields, while harvesting was carried out at crop maturity using a hand hoe.

Data collection

Phenological data. Data such as days to 50% emergence and days to 90% physiological maturity were recorded by counting the number of dates to the respective phenological parameters.

Growth parameters. Plant height, leaf number, leaf fresh weight, and canopy cover were recorded appropriately using five randomly selected plants. Canopy cover was determined as the perimeter of the plant at its widest horizontal plane. It typically assumes that there are a few minor gaps in the leaves and that an average crown perimeter will smooth out any uneven edges.

Yield parameters. Root length and root diameter were measured from five randomly selected plants using a calliper. The fresh weight of roots per plant was determined by measuring the weight of five randomly selected plants using a sensitive balance and the average value was calculated and used for analysis.

The yield of marketable roots was calculated per unit plot excluding border effects. The yield per unit area was converted to marketable yield per hectare. The unmarketable roots were identified based on cracked, branched, small size with diameter of approximately 1-1.5 cm and rotten. Then, the unmarketable roots were calculated per unit plot excluding border rows. The yield per unit area was converted to unmarketable yield per hectare.

Statistical analysis

The collected data underwent Analysis of Variance (ANOVA) using SAS 9.1, which was appropriate for the design of the experiment. The means of significant treatment effects were separated using the Least Significant Difference (LSD) test at a 5% level of significance.

3. Results and Discussion

Phenology

Plant density is considered as one of the most important factors affecting crop phenology (Shafi *et al.*, 2012; Khan *et al.*, 2017). In the present experiment, plant spacing did not significantly ($P≤0.05$) affect days to 50% emergence. This could be attributed to the fact that the viability of the seed, moisture availability, and air conditions are the essential elements required for germination, rather than spacing. Similarly, Tesfu and Charles (2010) found that neither sowing date nor planting density significantly affected the number of days required for 50% crop emergence.

In general, carrot plants grown with a narrower row distance tended to mature faster than those grown with wider spacing. The fastest time to reach maturity for carrot plants (73.3 days) was observed with a spacing of 10 x 5 cm, while the slowest time (134.3 days) was observed with a spacing of 20 x 15 cm, followed by a spacing of 20 x 10 cm (121.3 days) (Table 1). This suggests that row spacing has a more significant effect than plant spacing on maturity in this specific case study. Indeed, when the distance between rows was increased from 10 cm to 20 cm, the number of days to reach physiological maturity increased by 34 days. Other investigations have also found that plant density has a significant impact on the time it takes to reach 90% maturity (Da Silva *et al.*, 2008; Tegen *et al.*, 2021). Tesfu and Charles (2010) proposed that lower plant density may allow for more space and resources per plant, which could lead to extended vegetative growth and a longer time to reach maturity.

Growth and yield

The result of analysis of variance (ANOVA) showed that all growth and yield parameters of Nantes carrot were significantly affected ($P < 0.05$) by plant and row distances and their interaction (plant spacing).

Plant height

It is well known that growth parameters, such as plant height, can be influenced by plant population density (Abuzar *et al.*, 2011; Rahman *et al.*, 2011). Based on our results, the highest plant height of carrot (73.0 cm) was recorded from a spacing of 20 x 15 cm, followed by 15 x 15 cm spacing (60.0 cm). Conversely, the shortest plant height (17.3 cm) was recorded when carrots were sown with a spacing of 10 x 5 cm (Table 2).

Increasing the distance between rows from 10 cm to 20 cm resulted in a 26.7 cm increase in plant height. This may be due to the availability of essential resources necessary for growth and development, as well as the presence of adequate free space between plants to reduce competition in the higher spacing. These findings are consistent with previous research, such as Dawuda *et al.* (2011), who reported that taller plants were observed at higher spacing, and Kabir *et al.* (2013), who reported that taller plants were observed at a spacing of 30 x 20 cm compared to a spacing of 20 x 10 cm. According to Kabir *et al.* (2013), plants sown in higher spacing had enough space for vegetative growth and experienced less competition for nutrients compared to those sown in lower spacing treatments, such as 20 x 10 cm and 25 x 15 cm. When crops have to compete with their neighbouring plants for soil nutrients and sunlight, their health and growth can be negatively impacted. Poorly functioning plants will not attain their desired height or canopy and their roots will have to compete not only for nutrients and water but also for space. Furthermore, high planting density can inhibit photosynthesis.

Leaf number, leaf weight and canopy cover

Plant density have been reported to affect leaf number, canopy development, plant architecture, early ground cover and competitive ability of crops with weed (Bonaparte and Brawn, 1976; Deressegn and Telele, 2017; Hou *et al.*, 2019; Bernhard and Below, 2020). Moreover, leaf weight can be affected by the accumulation and the partitioning of synthesized food to non-photosynthetic parts (Halford, 2010; Osorio *et al.*, 2014).

The highest values of leaf count (21.0), leaf weight

Table 1 - Mean days to maturity of carrot as influenced by plant spacing

Row distance (cm)	Plant distance in the row (cm)			Mean
	5	10	15	
10	73.33 e	81.67 de	87.67 d	80.89 c
15	82.00 de	89.67 d	108.33 c	93.33 b
20	89.67 d	121.33 b	134.33 a	115.11 a
Mean	81.67 c	97.56 b	110.11 a	
CV (%) = 7.44%				

Mean values within rows and columns followed by different letter(s) are significantly different at 5% probability level.
CV= coefficient of variation.

Table 2 - Mean plant height (cm) of carrot as influenced by inter and intra row spacing

Row distance (cm)	Plant distance in the row (cm)			Mean
	5	10	15	
10	17.33 f	23.67 ef	31.33 de	24.11 c
15	21.17 ef	41.60 cd	60.00 b	40.92 b
20	27.33 ef	52.00 bc	73.00 a	50.78 a
Mean	21.94 c	39.09 b	54.78 a	
CV (%) = 17.81%				

Mean values within rows and columns followed by different letter(s) are significantly different at 5% probability level.
CV= coefficient of variation.

(15.0 g) and canopy spread (52.7 cm) were observed at the widest plant spacing (20 x 15 cm), while the lowest values (6.3, 9.1 g, and 14.3 cm, for leaf number, leaf weight and canopy cover, respectively) were found with the narrowest spacing of 10 x 5 cm (Table 3).

Table 3 - Mean leaf number, leaf weight and canopy cover of carrot (*Daucus carota* L.) plants as influenced by inter and intra row spacing

Distances (cm)	Leaf number (n)	Leaf weight (g)	Canopy cover (cm)
Row distance (Rd)			
10	8.22 c	11.23 c	27.89 c
15	12.44 b	12.51 b	33.89 b
20	15.33 a	14.15 a	39.67 a
Plant distance in the row (Pd)			
5	8.89 c	11.18 c	24.56 c
10	11.33 b	12.94 b	31.44 b
15	15.78 a	13.81 a	45.44 a
Plant spacing (Rd × Pd)			
10 × 5	6.33 g	9.06 e	14.33 f
10 × 10	8.00 gf	12.19 cd	31.33 de
10 × 15	10.33 def	12.57 cd	38.00 c
15 × 5	9.33 ef	12.57 cd	27.33 e
15 ×10	12.00 cd	12.36 cd	28.67 de
15 × 15	16.00 b	13.89 ab	45.67 b
20 × 5	11.00 de	12.19 bc	32.00 cde
20 × 10	14.00 bc	14.27 ab	34.33 cd
20 × 15	21.00 a	14.98 a	52.67 a
CV (%)	11.74%	5.74%	10.37%

Mean values within rows and columns followed by different letter(s) are significantly different at 5% probability level.
CV= coefficient of variation.

When the row distance was increased from 10 cm to 20 cm, it was observed that approximately seven additional leaves could develop, indicating that wider spacing can result in higher leaf area for maximum assimilate synthesis. This could be attributed to the greater free space available for plant growth between rows, which reduces competition for nutrients. This finding is consistent with previous studies by Dawuda *et al.* (2011) and Kabir *et al.* (2013), which reported that wider spacing can lead to more leaves and larger canopies, potentially intercepting more light for better growth and yield. Lower crop population density, as reported by Demisie and Tolessa (2018) and Van Delden *et al.* (2021), may allow foliage to receive maximum photosynthetically active radiation (PAR) and synthesize assimilates, ultimately contributing to greater leaf growth. An increase in canopy size is likely to enhance photosynthesis, leading to the production of more leaves, which has been supported by the findings of Appiah *et al.* (2017) and Tesfu and Charles (2010) in other plants. Similar findings have also been reported in carrot (Alam *et al.*, 2020) and radish (Sandipan and Rawat, 2020).

Root length, root diameter and root weight

The number of plants per unit area can influence the yield and quality of horticultural crops (Rodriguez *et al.*, 2007; Lencha and Buke, 2017; Demisie and Tolessa, 2018; Sinta and Garo, 2021; Tegen *et al.*, 2021). In the current investigation, the maximum root length (22.2 cm), root diameter (5.9 cm) and root weight (136.3 g) were recorded at spacing of 20 x 15 cm followed by 15 x 15 cm spacing (19.1 cm for root length, 5.2 cm for root diameter and 115.4 g for root weight). On the contrary, the lowest values (13.7 cm, 3.4 cm, and 64.2 g for root length, diameter and weight, respectively) were recorded when plants were cultured in rows spaced 10 cm apart with 5 cm between plants within rows (Table 4). Increasing plant spacing resulted in longer roots having larger diameter, thus in higher plant yield, potentially due

Table 4 - Mean root length, root diameter and root weight of carrot (*Daucus carota* L.) plants as influenced by inter and intra row spacing

Distances (cm)	Root length (cm)	Root diameter (cm)	Root weight (g)
Row distance (Rd)			
10	15.51 c	3.97 c	79.14 c
15	17.03 b	4.37 b	104.60 b
20	19.31 a	4.87 a	114.46 a
Plant distance in the row (Pd)			
5	15.34 c	3.68 c	85.26 c
10	17.36 b	4.43 b	98.03 b
15	19.06 a	5.09 a	114.92 a
Plant spacing (Rd × Pd)			
10 × 5	13.77 h	3.40 f	64.23 f
10 × 10	16.57 ef	4.33 cd	80.23 ef
10 × 15	16.20 f	4.18 d	92.98 de
15 × 5	14.73 g	3.63 ef	96.09 cde
15 ×10	17.23 de	4.30 cd	102.26 bcd
15 × 15	19.10 b	5.17 b	115.45 b
20 × 5	17.53 cd	4.02 de	95.45 de
20 × 10	18.23 c	4.65 c	111.62 bc
20 × 15	22.17 a	5.93 a	136.32 a
CV (%)	2.83%	5.87%	28.6%

Mean values within rows and columns followed by different letter(s) are significantly different at 5% probability level.
CV= coefficient of variation.

to the availability of sufficient resources for root growth and development, and reduced competition for available soil resources.

The results of our study are in line with previous research, which suggests that wider spacing of plants can lead to increased nutrient uptake and photosynthesis rates, resulting in improved areal and root growth as well as fresh root weight in carrot production (Kabir *et al.*, 2013; D'hooghe *et al.*, 2018; Appiah *et al.*, 2021). Kharsan *et al.* (2019) reported a gradual increase in root diameter with increasing spacing, observing a 1.4 cm increase in root diameter when plant spacing was increased from 5 cm to 15 cm. Similar results and arguments were reported more recently also by Tegen and Jembere (2021), Kwiatkowski *et al.* (2022) and Searight *et al.* (2022). It was suggested that plants sown with wider spacing had more room to develop their roots in the soil, leading to an increase in root diameter compared to those planted with lower spacing.

Marketable and unmaketable root yield (q ha^{-1})

According to Pant and Sah (2020) and Sandhu *et al.* (2021), the success of crop establishment, yield, and profitability are all affected by plant density. Poor plant stand is a major factor in reducing yield, and increasing planting density can further exacerbate this problem by decreasing the plant's net photosynthetic rate (Pn), stomatal conductance (Gc), and leaf chlorophyll content, ultimately leading to decreased yield (Zhang *et al.*, 2021).

The highest marketable yield (490.4 q ha^{-1}) was recorded at spacing of 20 x 5 cm followed by 15 x 5 cm spacing (359.5 q ha^{-1}), as the smallest root marketable yield (83.4 q ha^{-1}) was recorded at 20 x 15 cm spacing (Table 5). Thus, the highest marketable root yield of carrot per hectare was obtained with the smallest plant distance within the row and the largest distance between rows, while the carrot yield was the lowest when plants were grown using the largest intra- and inter-row spacings. This result is supported by Appiah *et al.* (2021), who observed that narrow spacing resulted in small and uneven root sizes which are rejected from the market. The reason for the lower marketable yield resulting from wider spacing can be indirectly attributed to the number of plants per unit area. Each plant has the chance to produce marketable root. Hence, the density of plants per unit area has a direct impact on the available number of roots, which ultimately affects the yield. Moreover, an increase in row spacing causes excessive branching and cracking of the roots, making them less desirable to consumers or in the market, as stated by Connors (2022) and Searight *et al.* (2022).

Table 5 - Marketable and unmarketable root yield of carrot (*Daucus carota* L.) as influenced by inter and intra row spacing

Distances (cm)	Marketable yield (qha^{-1})	Unmarketable yield (qha^{-1})
Row distance (Rd)		
10	166.98 c	5.85 c
15	225.67 b	9.66 b
20	286.10 a	16.97 a
Plant distance in the row (Pd)		
5	338.11 a	5.61 c
10	227.74 b	9.29 b
15	112.90 c	17.58 a
Plant spacing (Rd × Pd)		
10 × 5	164.42 def	2.70 d
10 × 10	185.98 cde	6.38 cd
10 × 15	150.55 def	8.47 cd
15 × 5	359.48 b	9.72 c
15 ×10	112.82 cd	11.29 bc
15 × 15	104.70 ef	17.99 b
20 × 5	490.43 a	4.40 cd
20 × 10	284.43 bc	10.21 bc
20 × 15	83.43 f	36.29 a
CV (%)	25.74%	32.89%

Mean values within rows and columns followed by different letter(s) are significantly different at 5% probability level.
CV= coefficient of variation.

According to Haque and Sakimin (2022), exceeding a certain planting density threshold can lead to decreased yield and quality due to inadequate resource supply, resulting in produce that is unsuitable for the market. In our experiment, larger planting distances of 20 x 15 cm and 15 x 15 cm resulted in the highest unmarketable yields of 36.3 q ha^{-1} and 17.9 q ha^{-1}, respectively. Conversely, reducing the distances to 10 x 5 cm minimized the unmarketable yield to just 2.7 q ha^{-1}, as shown in Table 5.

Dawuda *et al.* (2011) also reported maximum unmarketable yield from plants that were grown adopting wide spacing up to 30 × 5 cm. In agreement with the present finding, Adem Seid *et al.* (2019) reported a decline in unmarketable yield as plant spacing increased. It was suggested that percentage of root cracking might increase in the wider spacing due to more fluctuation of available soil moisture as absorbed by the plants. According to some authors (Merfield, 2006; Adem Seid *et al.*, 2019; Tegen and Jembere, 2021; Mahaffee *et al.*, 2023), the only disadvantages of high-density plantings include producing fewer jumbo carrots and lack of airflow through the field that can increase the incidence of foliar diseases, but this can be managed via integrated pest management. In a previous investigation on carrot cultivation, it has been reported that the yield of boxed sized root increases with plant density to a maximum and then decreases, being maximum yield achieved with higher plant density (Tegen and Jembere, 2021).

4. Conclusions

The growth and productivity of carrots are significantly affected by agronomic practices, with plant population being a vital management factor. Results from our experiment showed that spacing had a significant influence on all parameters except for days to emergence. The lowest sowing density with a spacing of 20 x 15 cm resulted in the highest values of plant height (73.0 cm), number of leaves (21.0 cm), diameter of root (3.4 cm), and length of root (22.2 cm). However, the highest root yield per hectare (490.4 q ha^{-1}) was recorded from a spacing of 20 x 5 cm, while the lowest yield (83.4 kg ha^{-1}) was from the widest spacing of 20 x 15 cm. Although wider spacing resulted in greater root length, leaf and root fresh weights, and plant height, it also led to maximum unmarketable yield, demonstrating the significance of plant distance on carrot productivity. Thus, our research suggests that the optimal plant density for maximum marketable yield of carrots in similar agroclimatic conditions and irrigated production systems is 5 cm intra-row spacing and 20 cm inter-row spacing. Going beyond this optimum level may cause branching, cracking, and unsuitability of the carrot roots for the market. However, it's important to note that these findings are from a single season and location, and further research across various locations and seasons is necessary for more reliable recommendations.

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