Research Article

Habtamu Tegen*, Mnuyelet Jembere

Influences of spacing on yield and root size of carrot (*Daucus carota* L.) under ridge-furrow production

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Abstract: Although there is adequate information on the influence of plant population on root yield and size of carrot on flat and raised bed for rain fed production system, information on ridge-furrow bed preparation method is limited for irrigation production system. Therefore, in this study, field experiments were conducted for 2 years to determine the appropriate spacing of carrot on ridge-furrow carrot production practice under irrigation. Root yield increased significantly as the population increased. On the contrary, root size significantly decreased as population increased. The result of combined analysis over season and locations indicated that the narrowest spacing of 10 cm × 4 cm rows on the ridge and between plants, respectively, which accommodates 1,250,000 plants ha^{-1} gave significantly highest marketable carrot root yield of 26 t ha^{-1} followed by 22.6 t ha^{-1} with spacing of 20 cm × 4 cm which accommodates 1,000,000 plants ha^{-1}, but it produced the smallest individual root weight of 83 g which is mostly preferred for household consumption unlike jumbo roots. Therefore, in terms of root sizes and marketable yield, the current study identified that spacing of 10 cm × 4 cm is optimum on ridge-furrow carrot production practices.

Keywords: ridge-furrow, inter row spacing, intra row spacing, plant population, root yield

*** Corresponding author: Habtamu Tegen,** Directorate of Crop Research, Adet Agricultural Research Center, P. O. Box 08, Bahir Dar, Ethiopia, e-mail: habitt2006@yahoo.com
Mnuyelet Jembere: Directorate of Crop Research, Adet Agricultural Research Center, P. O. Box 08, Bahir Dar, Ethiopia

1 Introduction

Carrot (*Daucus carota* L.) is a short duration crop and it is among the top ten most economically important vegetable crops in the world in terms of areas of production and market value [1,2]. The main reason for widespread production of carrot is because it is a cheap source of vitamin A in the diets of many cultures. It is also a good source of other vitamins, minerals, and fiber [3]. It contains high amount of carotene (10 mg per 100 g), thiamin (0.04 mg per 100 g), and riboflavin (0.05 mg per 100 g). It also serves as a source of carbohydrate, protein, fat, minerals, vitamin C, and calories [4]; thus, it can play a great role in preventing night blindness due to sever deficiency of vitamin A in children, which is a problem of public health in developing countries. Due to these multiple functions, the worldwide consumption of carrot has increased over the years [5,6].

Carrot yields can range from 30 to 100 t ha^{-1} in major carrot growing countries of the world [7]. In most developing countries, carrot yields per unit area still remain below the world average. For example, the average productivity of carrot was only 3.5 t ha^{-1} in Ethiopia as compared to 36.5 t ha^{-1} of world average [6]. Low productivity is associated with so many factors including lack of improved production practices, unavailability of technological inputs, pests, and postharvest losses [7].

Plant population density is one of the main factors which influence root yield and root size of carrot [8]. According to Kelley and Phatak [3], the ideal plant populations should be in the range of 450,000 per ha for fresh market carrots and 300,000 per ha for processing carrots. Many research reports revealed different population densities to enhance the yield of carrot in different production practices. For instance higher carrot root yield was produced with the narrow spacing [9–11]. On the contrary Kabir et al. [12] reported that maximum yield was obtained from the plants grown at widest spacing. The difference may arise from the objective of the intended use of carrot since each use has its own certain root size range [13]. Simões et al. [2] confirmed that the use of high population density cropping and early harvesting may lead to production of baby carrots that are more acceptable for commercialization. Although, some authors have reported some information on the optimum population density on different bed preparation methods (flat and raised) for carrot production, information on ridge-furrow bed preparation method is very limited. In the study areas, flat and raised bed preparation method is used for rain fed carrot production to facilitate drainage [14,15]. But this method of bed preparation is usually not suitable for carrot production under irrigation condition to manage the irrigation water applied through furrow irrigation method [15]. Adopting onion production system through ridge-furrow bed preparation method is vital for carrot production under irrigation condition. Therefore, the objective of the current study is to identify optimum population density by adjusting inter and intra row spacing for root yield and root size of carrot on ridge-furrow bed preparation method under irrigation condition in Western Amhara of Ethiopia.

2 Materials and methods

2.1 Description of the study areas

The experiment was conducted in Ethiopia at Woramit and Ribb research sites of Adet Agricultural Research Center in 2015 and 2016 under irrigation production system from January to April. Site description of each location is provided below. Environmental conditions in terms of maximum and minimum temperatures (°C) and relative humidity (RH; %) of the locations during the experimental period are described in Figure 1.

2.1.1 Woramit

Woramit is located at 11°38′ N and 37°10′ E and at an altitude of 1,800 m above sea level. It has warm and humid climate with distinct dry and wet seasons. The mean daily maximum temperature is 29.5°C in April, while the mean daily minimum temperature is 6.2°C in January. The area receives a mean annual rainfall of 800–1,250 mm and is characterized as mild altitude agroecology. The soil is nitosol. The soil is moderately acidic (pH 6.4) and consists of sand (13%), silt (33%), and clay (54%). It has 3.9 and 0.16% organic matter content and total nitrogen content, respectively. Available phosphorus content is 6.3 mg kg^{-1} [16,17].

2.1.2 Ribb

Ribb is located in Fogera district of North-West part of Ethiopia. It is located at 11°44′ to 12°03′ N and 37°25′ to 37°58′ E at 1,774 m above sea level. It receives 1,400 mm mean annual rainfall. The mean daily maximum and minimum temperatures are 30 and 11.5°C, respectively. The area is characterized as mid altitude agroecology. The soil is fluvisol (an alluvial deposit). The soil has high available phosphorus (36.71 ppm) and very low to

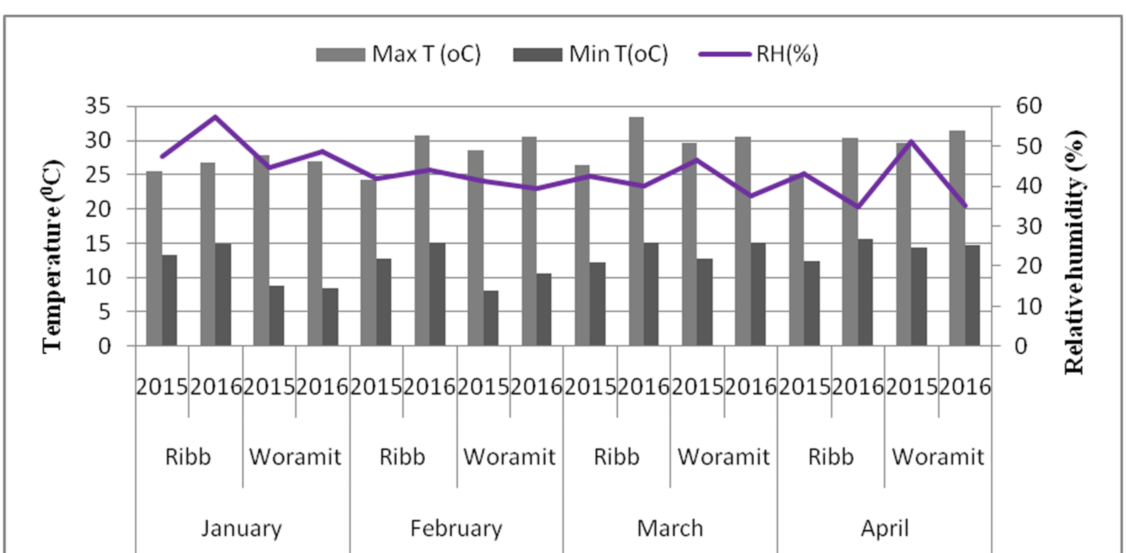

Figure 1: Environmental conditions of the study areas during the experimental years.

low total nitrogen contents (0.003%). The cation exchange capacity of the soil is high (33.00 cmol kg^{-1}). The soil is strongly acidic with high exchangeable acidity and high exchangeable Al^{3+} content [18].

2.2 Experimental materials, treatments, and design

Carrot variety "*Nantes*" was used for the study. The experiment consisted of three inter row spacing on the ridge (10, 20, and 30 cm) and three intra row spacing (4, 7, and 10 cm) which were arranged in 3 × 3 factorial combination in randomized complete block design with three replications combined over locations and years.

2.3 Experimental procedure

Seeds were sown by hand drilling on ridge in double row manner on 12 m^2 gross plot size (3 m × 4 m). 9, 7, and 5 double rows per plot were maintained for the row spacing on ridges of 10, 20, and 30 cm, respectively. For each treatment combination, 30 cm furrow width was also maintained for irrigation water application. Theoretically it accommodates 1,250,000; 1,000,000; 750,000; 716,666; 573,333; 500,000; 430,000; 375,000, and 300,000 plant population per hectare. Nitrogen (46 kg ha^{-1}) and phosphorus (P_2O_5; 69 kg ha^{-1}) in the form of urea and di-ammonium phosphate (DAP) fertilizers, respectively, were applied for each treatment. The entire DAP was applied at the time of planting, while urea was applied in two splits, first half (50%) at the time of planting and second half (50%) at 30 days after sowing [19]. Thinning was performed 30 days after sowing to maintain 125, 100, 75, 72, 57, 50, 43, 38, and 30 plants per m^2 according to the treatments. Irrigation water was applied with the furrow irrigation method with 7 days interval by adopting onion production of the area [19]. First weeding, along with thinning, and ridge maintenance were applied at 30 days after sowing, while the second and third were done at 45 and 60 days after sowing, respectively [15].

2.4 Data collection

Days to physiological maturity: It was determined as the actual number of days from sowing to the time at which more than 90% of the plants in a plot were mature by using distractive sampling taken from border rows.

Root length (cm): It was measured by using caliper placed at the point of the leaf detached to tip of the matured root.

Root diameter (cm): It was measured by using caliper placed at the widest point in the middle portion of the matured root.

Average root weight (g): Randomly selected marketable roots were measured by using digital balance, which were produced from central rows of each plot.

Root (cortex) to core ratio: It was determined by cutting carrot roots at the widest (middle) point. Then, core was measured from center to beginning of flesh part of each carrot root, while root (cortex) was measured from the beginning of flesh part to skin of each carrot root. The value of root (cortex) divided by core gave root to core ratio.

Carrot root yield: Marketable root yield was determined as the total weight of roots free from soft rot, and free from damage caused by growth cracks, sunburn, pithiness, woodiness, oil spray, dry rot, other diseases, insects, or other means, and the length of each carrot is not less than 7.62 cm which accommodates both processing and fresh types of carrots per net plot area and converted to t ha^{-1} [20]. Unmarketable root yield was determined as total weight of roots with soft rot and damage-caused growth cracks, sunburn, pithiness, woodiness, oil spray, dry rot, other diseases, insects, or other means, and the length of each carrot is less than 7.62 cm which do not fulfill the requirements of both processing and fresh types of carrots per net plot area and converted to t ha^{-1} [20]. Total root yield was determined as sum of marketable and unmarketable roots in t ha^{-1}.

2.5 Statistical analysis

The analysis of variance (ANOVA) was conducted for each location and season using PROC GLM procedure [21] version 9.0 to see the effect of inter and intra row spacing. After Bartlett's homogeneity test, the combined ANOVA over location and season was conducted using PROC MIXED procedure. Inter and intra row spacing were considered as fixed effects, while location and season were considered as random effects. Whenever the ANOVA result was significant ($P \leq 0.05$), the mean separation was performed using Fisher's LSD for the main effects and Duncan's multiple range test for the interaction effects.

3 Results and discussion

3.1 Days to maturity

The combined ANOVA over location and season showed that days of 90% maturity were significantly ($P \leq 0.05$) influenced by inter and intra row spacing, season and location, two way interaction of intra row vs location and intra row vs season. Horticultural root maturity was also significantly ($P \leq 0.05$) influenced by three and four way interaction of intra row vs location vs season and inter vs intra vs location vs season, respectively, as indicated in Table 1. Although the observed maturity date difference among treatments does not have a vital role in supply for early market to fetch premium price, plants grown with widest inter row spacing on the ridge (30 cm) and intra row spacing (10 cm) matured lately as presented in Table 2. Regarding the growing environment, plants grown in 10 cm intra row spacing on the ridge matured lately by 7 days and 5 days as compared to plants grown in 4 cm at Ribb and Woramit condition, respectively, as illustrated in Table 4. The observed early maturity on highest plant population might be due to the narrowest intra row spacing (4 cm) convincingly by the presence of high resource competition such as plant nutrient, water, and sunlight. Splittstoesser [22] stated that adequate space ensures less competition for sunlight, water, and fertilizers. In this regard, Manimurugan et al. [23] confirmed that earliness in days to 50% flowering was observed in high plant density.

3.2 Root (cortex) to core ratio

The combined ANOVA showed that root to core ratio of carrot was significantly ($P \leq 0.05$) influenced by main effect of spacing, location and season, two way interaction of inter vs intra row spacing, intra row vs location, and intra row vs season as indicated in Table 1. Significantly highest root to core ratio (1.36) was obtained on carrot roots produced in combination of wider inter and intra row spacing of 30 cm × 10 cm followed by 20 cm × 10 cm as presented in Table 3. In line with the current findings, Pandey et al. [24] reported that carrot varieties cultivated with 30 cm × 10 cm spacing produced a root to core ratio value of 1.22. Significantly ($P \leq 0.05$) highest root to core ratio was produced at Ribb in 2016 as shown in Table 2. As illustrated in Table 4, carrots produced with all possible intra row spacing at Ribb gave higher root to core ratio as compared to carrots produced with all possible intra row spacing at Woramit conditions. The reason behind is that

Table 1: Combined ANOVA mean squares of treatments' effects on yield, yield components, and days to maturity of carrot over years and locations

Source of variation	df	Mean squares							
		HRM (day)	RL (cm)	RD (cm)	RW (g)	R:C	MRY (t ha^{-1})	UMRY (t ha^{-1})	TRY (t ha^{-1})
Inter	2	106.71**	9.02**	2.25**	762.28**	0.05**	154,366,150**	1,636,887**	175,640,503**
Intra	2	302.86**	23.90**	1.35*	3,511.64**	0.10**	163,562,709**	1,117,833**	182,900,144**
Location	1	29.03**	2.76^{ns}	195.39**	201.47**	19.46**	221,179,812**	45,685,579**	65,820,840**
Season	1	37.92**	10.39**	242.18**	8,782.43**	19.46**	695,712,048**	146,344,116**	203,892,032**
Replication (location vs season)	8	6.27^{ns}	0.43^{ns}	0.13^{ns}	100.17**	0.02^{ns}	8,001,952^{ns}	300,993**	5,585,498^{ns}
Inter vs intra	4	4.61^{ns}	0.67^{ns}	0.13^{ns}	141.97**	0.06**	9,286,784*	553,369**	10,750,268**
Inter vs location	2	1.64^{ns}	0.20^{ns}	0.44^{ns}	18.55^{ns}	0.01^{ns}	38,836,607**	415,560**	34,314,320**
Inter vs year	2	6.01^{ns}	0.38^{ns}	0.63^{ns}	100.68^{ns}	0.01^{ns}	43,221,660**	2,056,331**	31,851,298**
Intra vs location	2	38.01**	0.21^{ns}	0.09^{ns}	201.02**	0.035*	40,954,677**	332,167**	34,822,931**
Intra vs season	2	33.71**	0.21^{ns}	0.06^{ns}	225.93**	0.035*	1,266,299^{ns}	1,257,137**	3,910,125^{ns}
Location vs season	1	0.59^{ns}	2.44^{ns}	872.63**	11,644.33**	0.00^{ns}	132,347,508**	28,496,019**	38,020,448**
Inter vs location vs season	2	1.53^{ns}	0.58^{ns}	2.14*	63.06^{ns}	0.00^{ns}	2,542,012^{ns}	634,916**	802,735^{ns}
Intra vs location vs season	2	26.01**	0.76^{ns}	0.21^{ns}	0.80^{ns}	0.00^{ns}	45,772,136**	315,542**	53,688,425**
Inter vs intra vs location	4	11.15**	0.76^{ns}	0.07^{ns}	58.92^{ns}	0.01^{ns}	4,278,443^{ns}	128,966*	5,614,410*
Inter vs intra vs season	4	8.28*	0.76^{ns}	0.08^{ns}	172.64**	0.01^{ns}	3,584,438^{ns}	355,402**	4,300,345*
Inter vs intra vs location vs season	4	0.28^{ns}	0.76^{ns}	0.24^{ns}	94.21*	0.00^{ns}	5,147,670*	76,544^{ns}	4,817,455*
Error	70	2.02	0.66	0.28	29.66	0.01	1,595,112	38,354	1,660,549

*, **, and ns – significant ($P < 0.05$), highly significant ($P < 0.01$), and non-significant, respectively. HRM – horticultural root maturity; RL – root length; RD – root diameter; RW – individual root weight; R:C – root to core ratio; MRY – marketable root yield; UMRY – unmarketable root yield; TRY – total root yield.

Table 2: Main effects of spacing, location, and year on yield, yield components, and days to maturity of carrot

	RL (cm)	RD (cm)	RW (g)	R:C	HRM (day)	MRY (t ha^{-1})	UMRY (t ha^{-1})	TRY (t ha^{-1})
Inter row spacing (cm)								
10	14.1^{b}	5.5^{b}	91.1^{c}	1.3^{b}	102^{c}	22.5^{a}	1.8^{a}	24.3^{a}
20	14.7^{a}	5.6^{b}	96.4^{b}	1.3^{b}	104^{b}	20.6^{b}	1.4^{c}	22.0^{b}
30	15.1^{a}	6.0^{a}	100.3^{a}	1.4^{a}	105^{a}	18.4^{c}	1.5^{b}	19.9^{c}
SE(±)	0.47	0.30	3.10	0.05	0.80	0.70	0.10	0.80
Sig	**	**	**	**	**	**	**	**
Intra row spacing (cm)								
4	13.9^{c}	5.5^{b}	87.1^{c}	1.2^{c}	101^{c}	22.9^{a}	1.7^{a}	24.6^{a}
7	14.6^{b}	5.7^{ab}	94.1^{b}	1.3^{b}	104^{b}	19.7^{b}	1.7^{a}	21.4^{b}
10	15.5^{a}	5.8^{a}	106.6^{a}	1.4^{a}	106^{a}	18.8^{c}	1.4^{b}	20.2^{c}
SE(±)	0.46	0.30	3.07^{a}	0.05	0.80	0.7	0.1	0.8
Sig	**	*	**	**	**	**	**	**
Location								
Ribb	14.8	7.0^{a}	97.3^{a}	1.7^{a}	103^{b}	21.9^{a}	0.9^{b}	22.8^{a}
Woramit	14.5	4.3^{b}	94.6^{b}	0.9^{b}	104^{a}	19.1^{b}	2.2^{a}	21.2^{b}
SE(±)	0.31	0.21	2.09	0.04	0.55	0.5	0.08	0.5
Sig	ns	**	**	**	**	**	**	**
Season								
2015	14.3^{b}	4.2^{b}	86.9^{b}	0.9^{b}	104^{a}	17.9^{b}	2.7^{b}	20.7^{b}
2016	15.0^{a}	7.2^{a}	105.0^{a}	1.7^{a}	103^{b}	23.0^{a}	4.2^{a}	23.4^{a}
SE(±)	0.31	0.21	2.09	0.04	0.54	0.4	0.07	0.49
Sig	**	**	**	**	**	**	**	**
CV%	5.58	9.41	5.67	7.14	1.37	6.17	12.36	5.84

*, **, and ns – significant ($P < 0.05$), highly significant ($P < 0.01$), and non-significant, respectively. Means with common letter within the column do not differ significantly ($P \geq 0.05$). HRM – horticultural root maturity; RL – root length; RD – root diameter; RW – individual root weight; R:C – root to core ratio; MRY – marketable root yield; UMRY – unmarketable root yield; TRY – total root yield.

Table 3: Inter and intra row interaction effects on yield and yield component of carrot as combined over locations and years

Treatment inter × intra rows	RW (g)	R:C	MRY (t ha^{-1})	UMRY (t ha^{-1})	TRY (t ha^{-1})
10 × 4	83.0^{e}	1.3^{bc}	26.0^{a}	1.9^{ab}	28.0^{a}
10 × 7	90.9^{d}	1.2^{c}	21.4^{bc}	2.1^{a}	23.5^{b}
10 × 10	99.5^{bc}	1.3^{bc}	20.0^{cd}	1.4^{de}	21.4^{c}
20 × 4	87.8^{de}	1.2^{c}	22.6^{b}	1.4^{de}	24.0^{b}
20 × 7	92.8^{cd}	1.3^{bc}	19.9^{cd}	1.3^{e}	21.2^{c}
20 × 10	105.9^{b}	1.4^{ab}	19.3^{de}	1.5^{cde}	20.7^{cd}
30 × 4	90.6^{d}	1.3^{bc}	20.0^{cd}	1.7^{bc}	21.7^{c}
30 × 7	98.7^{c}	1.3^{cb}	17.8^{ef}	1.7^{cd}	19.5^{de}
30 × 10	114.4^{a}	1.4^{a}	17.2^{f}	1.2^{e}	18.4^{e}
SE(±)	7.11	0.12	1.65	0.26	1.68
Significance	**	**	**	**	**
CV%	5.67	7.14	6.16	12.36	5.84

** – highly significant ($P < 0.01$). Means with common letter within the column do not differ significantly ($P \geq 0.05$). RW – individual root weight; R:C – root to core ratio; MRY – marketable root yield; UMRY – unmarketable root yield; TRY – total root yield.

carrot roots produced at Woramit condition had bigger root diameter. According to Northolt et al. [25], thicker carrot roots had a relatively smaller root (cortex) and larger core. In nitosol condition at Woramit, carrot plants subjected to develop shorter root length but large root diameter compared in alluvial deposit soil at Ribb. In alluvial deposit soil, roots can easily penetrate the soil to develop larger root length but relatively shorter diameter. According to Johansen et al. [26], with relatively compacted soil layers at nitosols, roots will be concentrated more in the upper layers of the soil with larger root diameters.

3.3 Root length

The combined ANOVA showed that carrot root length was significantly ($P \leq 0.05$) influenced by inter and intra row spacing and season as indicated in Table 1. Root length increased as the corresponding spacing increased in the

Table 4: Interaction effects of spacing by location on yield, yield components, and days to maturity of carrot as combined over years

Trait	RW (g)		R:C		HRM (day)		MRY (t ha^{-1})		UMRY (t ha^{-1})		TRY (t ha^{-1})	
	Ribb	**Wor.**	**Ribb**	**Wor.**	**Ribb**	**Wor.**	**Ribb**	**Wor.**	**Ribb**	**Wor.**	**Ribb**	**Wor.**
Inter												
10	89.75	92.51	1.70	0.89	101	102	24.8^{a}	20.2^{bc}	1.0^{c}	2.6^{a}	25.9^{a}	22.7^{bc}
20	94.36	98.51	1.71	0.87	103	105	22.3^{ab}	18.9^{c}	0.82^{c}	2.0^{b}	23.1^{b}	20.9^{bcd}
30	99.66	100.94	1.80	0.92	105	106	18.7^{c}	18.1^{c}	0.93^{c}	2.1^{b}	19.6^{d}	20.2^{cd}
SE(±)	10.88		0.11		3.23		2.65		0.36		2.77	
Sig	ns		ns		ns		**		**		**	
CV%	11.68		8.99		3.21		13.36		23.64		12.96	
Intra												
4	84.00^{c}	90.27^{bc}	1.76^{ab}	0.93^{c}	99^{d}	102^{c}	25.2^{a}	20.6^{bc}	1.0^{c}	2.4^{a}	26.2^{a}	22.9^{b}
7	91.83^{b}	96.39^{b}	1.65^{b}	0.86^{c}	105^{ab}	104^{bc}	21.5^{b}	18.0^{c}	0.96^{c}	2.4^{a}	22.4^{bc}	20.4^{bc}
10	107.95^{a}	105.32^{a}	1.81^{a}	0.89^{c}	106^{a}	107^{a}	19.1^{b}	18.6^{c}	0.84^{c}	1.9^{b}	19.9^{c}	20.5^{bc}
SE(±)	7.64		0.11		2.18		2.61		0.41		2.7	
Sig	**		**		**		**		**		**	
CV%	8.21		8.29		2.16		13.12		26.55		12.39	

** and ns – highly significant ($P < 0.01$) and non-significant, respectively. Means with common letter within the column do not differ significantly ($P \geq 0.05$). RW – individual root weight; R:C – root to core ratio; HRM – horticultural root maturity; MRY – marketable root yield; UMRY – unmarketable root yield; TRY – total root yield.

current study as shown in Table 2. The widely spaced plants produced longer roots than the closely spaced plants [27]. According to Lana and Carvalho [13], root length should be as long as 6.0 cm for carrot processing. Similarly, Kabir et al. [12] reported that the largest root (11.02 cm) was recorded from the plants grown at the wider spacing of 30 cm × 20 cm inter and intra row spacing of carrot. The authors also explained that plants grown at the wider spacing received more nutrients and rate of photosynthesis for vegetative and root growth. Thompson [28] also concluded that plant density can influence carrot root shape.

3.4 Root diameter

The combined ANOVA showed that carrot root diameter was significantly ($P \leq 0.05$) influenced by all the main effects of inter and intra row spacing, season, location, two way interaction of location vs season, and three way interaction of inter vs location vs season as indicated in Table 1. Root diameter values ranging from 4.0 to 6.0 cm were obtained in the current study. According to Szczepanek et al. [29], small roots (<1.9 cm in diameter), medium roots (1.9–3.8 cm in diameter) as well as large roots (3.8–5.0 cm in diameter) are the standard size distribution. Therefore, the root diameter values recorded in the current study falls in large root category. The highest root diameter value was obtained when plants were grown with widest inter row spacing of 30 cm on the ridge and intra row spacing of 10 cm at Woramit growing condition in 2016 as compared to Ribb growing condition in 2015 as presented in Table 2. Similarly, McCollum et al. [30] obtained maximum root diameter at the inter and intra row spacing of 30 cm × 20 cm. Generally, greater than Salter et al. [31] root size standard (2.0 to 3.0 cm diameter) for canning purpose, Sanders [1] root size standard (1.9 to 3.2 cm in diameter) for fresh market purpose, and Lana [8] carrot size standard (2.5 cm in diameter) for dual purpose were obtained in the current study with all sources of variations such as inter and intra row spacing, locations, and season (Table 2). According to Simões et al. [2], with the inter and intra row spacing of 20 cm × 4 cm for 64–78 days growing period produced carrot roots up to 2.3 cm in diameter on one meter width raised bed. As indicated in Table 2, the current study also identified that significantly higher root length was produced under Ribb growing condition, whereas significantly higher root diameter was produced under Woramit growing condition. The soil at the Ribb experimental site is fluvisol (an alluvial deposit) which is light to roots to easily penetrate as compared to nitosol at Woramit condition. With relatively compacted soil layers, roots will be concentrated more in the upper layers of the soil [26].

3.5 Average root weight

The combined ANOVA showed that average carrot root weight was significantly ($P \leq 0.05$) influenced by all sources of variations except two way interaction of inter vs location and inter vs season as indicated in Table 1. As indicated in Table 3, the highest root weight value of 114 g followed by 106 g per plant were obtained from plants grown with the spacing combination of 30 cm × 10 cm and 20 cm × 10 cm, respectively, while the smallest root weight value (83 g) was obtained from plants grown with the combination of 10 cm × 4 cm inter and intra row spacing. Similar to the current result, maximum root weight of 312 g was obtained by the wider spacing of 30 cm × 15 cm in Ambo conditions of Ethiopia [9]. The present study also showed that root weight values increased as inter and intra row spacing increased. This trait is also influenced by growing location and season. Table 2 shows that significantly higher root weight value was obtained when plants were grown at Woramit condition compared to Ribb in terms of location as well as season of 2016 compared to 2015. This might be due to the prevailing growing condition in terms of temperature and RH condition observed at Woramit location and in 2016 growing season. As indicated in Figure 1, relatively higher temperature and lower RH condition were observed throughout the growing season. The current study confirmed that narrowest spacing of 10 cm × 4 cm gave larger proportion of small roots which is mostly the preference of household consumption (Table 3). The present result is in line with Lana [8] who reported that decreasing line spacing from 16.6 to 10.0 cm was important to assure larger proportion of superior quality thinner roots. Dawuda et al. [11] also reported that the wider spacing of 30 cm × 5 cm promoted vegetative growth and increased root length of carrot, but planting at closer spacing of 20 cm × 5 cm resulted in higher total and marketable yields and also increased income and profit.

3.6 Carrot root yield

The combined ANOVA showed that marketable root yield was significantly ($P \leq 0.05$) influenced by all sources of variations except two way interaction of intra spacing vs season. Similarly unmarketable root yield was significantly ($P \leq 0.05$) influenced by all sources of variations (Table 1). The combined mean in Table 3 shows that significantly ($P < 0.05$) highest marketable root yield of 26 t ha^{-1} was produced when plants were grown with the combination of the lowest inter and intra row spacing of 10 cm × 4 cm. While the lowest root yield of 17 t ha^{-1} was produced with plants grown with the combination of the largest inter and intra row spacing of 30 cm × 10 cm. Similarly, combined mean shows that significantly ($P < 0.05$) highest unmarketable root yield (1.9 t ha^{-1}) was produced with plants grown with the combination of the lowest inter and intra row spacing of 10 cm × 4 cm followed by treatment combination of 10 cm × 7 cm. Similar to the current study, Shiberu and Tamiru [9] found higher carrot root yield of 55 t ha^{-1} with the lowest intra row spacing of 5 cm. Taivalmaa and Talvitie [10] also reported that the highest yields were recorded from carrots sown in double rows on a narrow ridge. Dawuda et al. [11] also reported that planting at closer spacing of 20 cm × 5 cm resulted in higher total and marketable yields and also increased income and profit. In contrast with the present findings, Kabir et al. [12] reported that maximum fresh root yield was obtained from the plants grown at widest spacing of 30 cm × 20 cm with hybrid (F1) variety. According to Mack [32], total root yields as well as roots less than 25 and 25–38 mm diameter were increased as row spacing were decreased from 60 to 15 cm. The lowest commercial yields were found with the widest spacing between plants, while the smallest spacing between plants (4 cm) had yields of 45.9 Mg ha^{-1} [33]. The total and marketable yields were larger in flat land and narrow ridge than in the broad and compacted broad ridges [34]. The Brasília Nina carrot

Table 5: Interaction effects of spacing and season on the root yield of carrot as combined over locations

Trait	MRY (t ha^{-1})		UMRY (t ha^{-1})		TRY (t ha^{-1})	
	2015	2016	2015	2016	2015	2016
Inter						
10	18.8^{cd}	26.2^{a}	3.2^{a}	0.39^{c}	22.1^{bc}	26.5^{a}
20	18.1^{cd}	23.1^{b}	2.4^{b}	0.44^{c}	20.5^{c}	23.5^{b}
30	16.9^{d}	19.8^{c}	2.6^{c}	0.43^{c}	19.5^{c}	20.3^{c}
SE(±)	2.65		0.36		2.77	
Sig	**		**		**	
CV%	13.36		23.64		12.96	
Intra						
4	20.2	25.5	3.0^{a}	0.43^{c}	23.2	26.0
7	17.4	22.0	2.9^{a}	0.40^{c}	20.4	22.4
10	16.2	21.5	2.3^{b}	0.23^{c}	18.5	21.9
SE(±)	2.61		0.40		2.65	
Sig	ns		**		ns	
CV%	13.12		26.55		12.39	

** and ns – highly significant ($P < 0.01$) and non-significant, respectively. Means with common letter within the column do not differ significantly ($P \geq 0.05$). MRY – marketable root yield; UMRY – unmarketable root yield; TRY – total root yield.

Table 6: Interaction effects of spacing, locations, and season on the root yield of carrot

Traits	Location	MRY (t ha^{-1})		UMRY (t ha^{-1})		TRY (t ha^{-1})	
		2015	2016	2015	2016	2015	2016
Inter row (cm)							
10	Ribb	22.5^{bcd}	27.2^{a}	1.816^{c}	0.272^{d}	24.3^{abc}	27.4^{a}
	Woramit	15.2^{e}	25.1^{ab}	4.671^{a}	0.506^{d}	19.8^{cd}	25.7^{ab}
20	Ribb	20.6^{cd}	23.9^{abc}	1.397^{c}	0.259^{d}	22.0^{bcd}	24.1^{abc}
	Woramit	15.6^{e}	22.2^{bcd}	3.319^{b}	0.614^{d}	19.0^{d}	22.8^{bcd}
30	Ribb	18.4^{de}	18.9^{de}	1.537^{c}	0.317^{d}	19.9^{cd}	19.3^{d}
	Woramit	15.4^{e}	20.7^{cd}	3.745^{b}	0.549^{d}	19.2^{d}	21.3^{bcd}
CV%		13.36		23.64		12.96	
Intra row (cm)							
4	Ribb	22.9^{bcd}	27.5^{a}	1.687^{c}	0.322^{d}	24.6^{ab}	27.8^{a}
	Woramit	17.6^{efg}	23.6^{abc}	4.208^{a}	0.530^{d}	21.8^{bcd}	24.1^{abc}
7	Ribb	19.7^{b-e}	23.2^{bc}	1.684^{c}	0.231^{d}	21.4^{bcd}	23.4^{bcd}
	Woramit	15.1f^{g}	20.9^{b-e}	4.250^{a}	0.571^{d}	19.3^{de}	21.5^{bcd}
10	Ribb	18.8^{def}	19.3^{cde}	1.380^{c}	0.295^{d}	20.2^{cde}	19.6^{de}
	Woramit	13.5^{g}	23.6^{ab}	3.277^{b}	0.567^{d}	16.8^{e}	24.2^{abc}
Sig		**		*		**	
SE(±)		4.25		0.66		2.46	
CV%		13.12		26.55		12.39	

* and ** – significant ($P < 0.05$) and highly significant ($P < 0.01$), respectively. Means with common letter within the column do not differ significantly ($P \geq 0.05$). MRY – marketable root yield; UMRY – unmarketable root yield; TRY – total root yield.

cultivar showed high performance in root yield and quality, mainly in the 15 cm spacing between rows in an agroecological system [35].

Unlike unmarketable yield, the significantly higher marketable yield was obtained at Ribb as compared to Woramit and in 2016 as compared to 2015 in terms of two-way interaction of inter and intra row spacing by location (Table 4) and in terms of two-way interaction of inter and intra row spacing by season (Table 5). Generally, the overall higher marketable yield was obtained at Ribb in 2016 as compared to at Woramit in 2015 in terms of three-way interaction of inter and intra row spacing by location by season (Table 6). The observed yield difference might be due to the fluctuation of temperature and RH condition particularly minimum temperature and RH that occurred at locations and growing years. As indicated in Figure 1, there was a fluctuation of temperature and RH condition at Woramit compared to Ribb and in 2015 as compared to 2016 condition. Higher and lower temperatures reduce the rate of growth and adversely affect the physical quality of the roots [12]. Growth and yield pattern of carrots are affected by varietal performance and change in climatic conditions [36].

At both location and season, increased plant density due to inter and intra row spacing resulted in an increase in the production of marketable and total yield. On the other hand, increased plant density due to the incremental of inter and intra row spacing resulted in decrease in the production of unmarketable root yield as demonstrated in Tables 4 and 5. According to Kelley and Phatak [3], 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. The author also confirmed that the incidence of disease may be managed by other integrated pest management practice. According to Salter et al. [31], the yield of canning-size root yield increased with plant density to a maximum and then declined, the maximum yield being achieved at a higher density.

4 Conclusion

The findings of the research indicated that the performance of carrot in terms of yield and root size was better at Ribb location as compared to Woramit. Although there was an interaction between spacing and location, the overall trend of the spacing was quite similar from location to location. Therefore, each location does not need a location-specific recommendation. The narrowest spacing of 10 cm × 4 cm which accommodates 1,250,000 plants ha^{-1} gave the significantly highest marketable carrot root yield of 26 t ha^{-1} followed by 22.6 t ha^{-1} with the spacing of 20 cm × 4 cm which accommodates the plant population of 1,000,000 plants ha^{-1}. The widest spacing of 30 cm × 10 cm which accommodates 300,000 plants ha^{-1} produced the largest individual root weight per plant of 114 g with the yield penalty of 9 t ha^{-1}. Although the narrowest inter and intra row spacing produced the smallest individual root weight of 83 g compared to other treatment combinations, it fell under the large size carrot category. This size category is mostly preferred for household consumption, unlike jumbo roots. Therefore, it is concluded that the spacing of 10 cm × 4 cm was identified as optimum inter and intra row spacing under the ridge-furrow practice of irrigated carrot production.

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