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Interaction between sowing date and mulching is important for better growth and productivity of carrot in a weather-vulnerable area of Ethiopia

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Abstract: Inadequate agronomic practices and unfavorable weather conditions often hinder carrot cultivation. Therefore, this experiment evaluated the effects of sowing date and mulching on the growth and yield of carrots during the 2023/2024 main cropping season at Kersole, Legambo District. The experiment involved three sowing dates (early, mid, and late in July) and four mulching materials (no mulch, sawdust, straw, and dried grass), utilizing a Randomized Completely Block Design (RCBD) with three replications. Except main effects of sowing date, and interaction effects on days to 50% emergence and root diameter, all other parameters were significantly (*P*≤0.05) affected. Early sowing combined with either sawdust or dried grass mulch resulted in the highest marketable root yields respectively. Late sowing without mulch and with dried grass mulch showed the lowest marketable root yield and minimum weed density respectively. Early sowing with sawdust mulch also provided the highest net benefit, while early sowing with dried grass mulch exhibited the highest marginal rate of return. Therefore, early sowing with dried grass mulch can be recommended for carrot cultivation in study areas and similar agroecologies. However, for optimal results, it is necessary to carry out the experiment using several mulching materials and various sowing dates across seasons and locations.

1. Introduction

Carrot (*Daucus carota* L.) is a commonly important root crop of the *Apiaceae* family, widely distributed worldwide. Carrots are herbaceous dicotyledonous plants that grow upright, reaching a height of 20-50 cm when mature. The fleshy taproot is its primary edible part, which typically

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exhibits a straight, conical, and cylindrical shape. It was originally wild in different parts of Asia and Europe. It was primarily domesticated in rich Afghanistan, considered the first center of origin, and Turkey is believed to be the second center of origin. From these centers of diversity, carrots gradually spread across Europe, the Mediterranean, and numerous countries in Asia. Over time, it was cultivated and introduced to local wild varieties across the globe (Stolarczyk and Janick, 2018). Carrot roots are highly valued for their abundance of carotenoids, which serve as precursors to vitamin A (Tabor and Yesuf, 2012). Additionally, carrots contain flavonoids, vitamins, and minerals, making them a nutritious crop that contributes to overall health and well-being (Zeleke and Derso, 2015). China is the leading global producer, with Europe emerging as the rapidly advancing carrot market. Notably, North America, particularly the USA and Canada, boasts the most significant shares in the carrot markets. As of 2020, the world consumed 46.3 million metric tonnes of turnips and carrots globally, according to FAOSTAT 2021 data.

Ethiopia has a relatively low production compared to the global average. Its production has not been adequately exploited as it faces several constraints such as limited research activities on the topic, unfavorable weather conditions, and poor agronomic practices such as unplanned sowing dates, lack of mulching practices, and improper weeding. In the study area, the quality of carrot roots is also compromised due to suboptimal agronomic practices, thus discouraging farmers from engaging in carrot production. Typically, farmers in the study area sow carrots on bare beds without applying mulches. Similarly, they often sow carrots in late July, thus leading to poor seed germination, inadequate growth, and development as well as exposure to severe winter conditions (soil moisture deficit and lack of rainfall) towards the end of summer. The research by Mengistu (2009) reveals that the pre-termination of rainfall, occurring during critical developmental stages of the crop, especially the root initiation stage, results in both quantitative and qualitative reductions in yield. Farmers relying on subsistence agriculture within Legambo District have faced recurrent droughts and famines resulting from severe weather occurrences associated with climate change, such as erratic rainfall, frost threats, and hailstorm flooding (Cafer and Rikoon, 2017).

Within subsistence agriculture, the occurrences and regularities of climate extremes and variabilities pose significant challenges comparable to average annual shifts. The magnitude and implications of climate variability are not adequately examined in Ethiopia. For subsistence agriculture, occurrences and frequencies of climate extremes and variabilities are equally affecting as of mean annual changes. However, despite its climatic constraints, the region still holds promise as a viable location for cultivating carrots, especially through strategic adjustments in sowing dates and the application of mulching techniques. The importance of adjusting the cropping schedule is appropriate to adapt a weather and climate variations in the particular region (Desta *et al.*, 2020). The timing of sowing is essential as it aligns with favorable climatic conditions and has been demonstrated to impact the growth and yield of carrots (Gagopale, 2019). Moreover, the use of mulch helps to regulate temperature extremes (Rajasekar *et al.*, 2020). Furthermore, cultivators must consider the appropriate sowing date and mulching as one of the most significant factors to maximize productivity and quality, minimize weed occurrence, and maintain soil health. Consequently, this study was conducted to evaluate the effect of sowing date and mulching on the growth and yield of carrots in Kersole, Legambo district.

2. Materials and Methods

Description of the study area

The experiment was conducted at Kersole Kebele, Legambo district of agriculture and temperate fruit nursery site, South Wollo Zone, Ethiopia in the 2023/2024 main cropping season (from July to November). The site is located at 10°51' N and 39°11' E (Fig. 1) with an altitude of 2800 meters above sea level (m a.s.l.). The area is situated 501 kilometers north of Addis Ababa and 372 kilometers east of

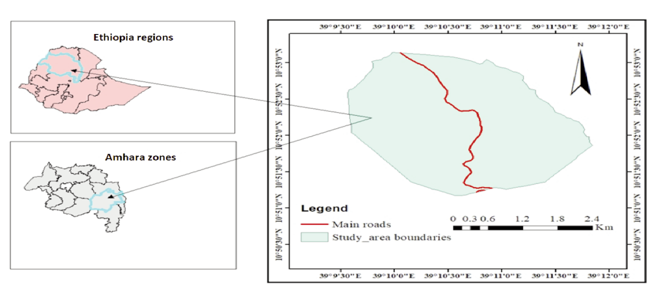

Fig. 1 - Map of the study area.

Bahir Dar. The area experiences an annual rainfall ranging from 700 to 1300 millimeters. The site has an average minimum temperature of 3°C and an average maximum temperature of 18°C. The predominant soil type in the area is clay soil, characterized by a pH of 5.57 (Regassa *et al.*, 2023) (Fig. 2). The region is predominantly characterized by its rolling terrain, (Regassa *et al.*, 2023). Approximately 68.54% of the district features a temperate (Dega) agroecology, with the next largest portion comprising alpine (Wurch) landscapes at 29.53%. A small percentage of 1.93% and 0.0016% of the district area is covered by subtropical (Woinadega) and tropical (Qolla) agroecology, respectively.

Treatments and experimental design

The experiment contained two factors (sowing date x mulching material). Sowing dates comprised three levels (Early - July = 10th July (S1); Mid - July = 20th July (S2) and Late - July = 30th July (S3)). Four levels of mulching materials were: no mulch (M0), sawdust (M1), straw (M2) (Fig. 3), and dried grass (M3). The experiment arrangement used a Randomized Completely Block Design (RCBD) in three replicates. The whole experimental area was 218.3 m^2 (29.5 m x 7.4 m) in length and width respectively. This area was divided into three blocks, and each block was further subdivided into 12 plots. As a result, there were a total of 36 unit plots. The treatments were assigned randomly within each plot of the block. Each unit plot had a net size of 3.6 m^2 (2 m x 1.8 m) which consisted of 9 rows and 40 plants per row. The distance between adjacent blocks was 1.0 meters, while the distance between plots within a block was 0.5 meters.

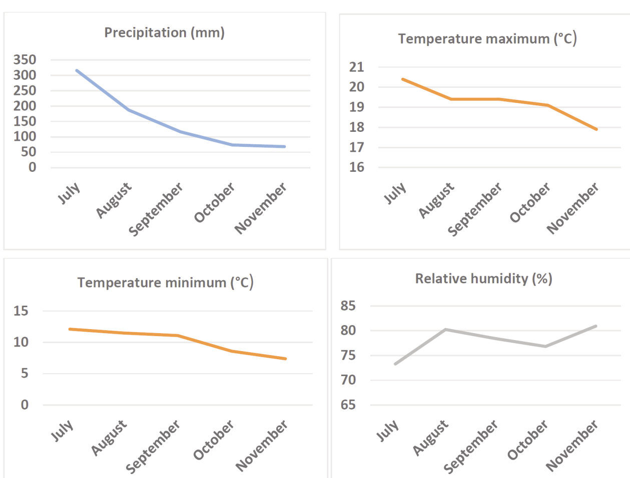

Fig. 2 - Monthly average weather data of the study area during the experimentation period (2023/2024). Source: https://power. larc.nasa.gov/data-access-viewer/

Experimental materials and procedures

'Nantes' variety of carrots was used for the experiment. The seeds of this particular variety were sourced and acquired from the Debrezeit Agricultural Research Center. Farmers are highly interested in this variety of carrots for their good adaptation, high marketing demand, and better root quality in the study area. The experimental field was readied using traditional tillage methods and cultivated using oxen to loosen the soil, catering to the deep and well-drained soil requirements favored by carrots. The soil was molded into raised beds to enhance drainage, promote extensive root growth, ensure uniformity, and minimize soil compaction. After this, a field layout was implemented, and each treatment was assigned randomly to the experimental plots. Seeds were sown as per each sowing date time on a 20 cm height raised bed with 20 cm x 5 cm spacing between rows

Fig. 3 - Pictures of mulch during a field trial.

and plants respectively. The straw and dried grass mulch were cut into small pieces approximately 5-10 cm by machete, following the method outlined by Olfati *et al*. (2008). After sowing the seeds on each particular sowing date, mulching materials were applied at about a rate of 4 t ha^{-1} sawdust and 6 t ha^{-1} straw and dried grass. Fully rate of phosphorus (175 kg P_2O_5 ha^1) was applied at the time of each sowing date, while the nitrogen in the form of urea (150 kg ha^1) was applied in a split way: half of the rate was applied at the time of each sowing date, and the remaining half was topdressed in the spaces during the active vegetative crop stage, which occurred 5 weeks after emergence (WAE). Weeds were lifted manually and removed from the crop fields, while harvesting was done at maturity by using a hand cultivator.

Data collection

Days to 50% emergence and 90% physiological maturity were obtained by counting the number of days to days when 50% of the seeds emerged and 90% of the plants attained physiologically matured, respectively. Carrot plants were physiologically matured when their lower leaves turned yellow and roots were at the harvestable size with their crown attaining a diameter ranging from 2-3.8 cm as described by UNECE (2018).

At physiological maturity stage, the plant height and number of leaves per plant were obtained from ten randomly selected plants from each unit experiment. The height of ten randomly selected plants from the ground level to the end of the uppermost parts was measured using a ruler.

After harvesting, the root length and diameter of ten randomly selected marketable carrot roots from each unit experiment was recorded using a digital caliper. The root diameter was obtained approximately two centimeters below the root collar (at middle) according to Zelalem (2019). Then the root fresh weight was recorded by weighing ten randomly selected marketable carrot roots from each net plot area and each replication after harvesting using a sensitive balance and the mean values were computed for further analysis. However, marketable carrot roots were those that were free from mechanical damage, disease, insect pest attack, undersized (<50 g), and cracks. The weight of those roots obtained from the designated plot was measured in kilograms using a scale balance and the yield was expressed as a ton per hectare. Carrot roots that were diseased, insect pest-damaged, cracked, branched, and undersized (<50 g) were considered unmarketable roots and their weight was measured in kilograms using a scale balance and their yield was also expressed as a ton per hectare.

Weed density was assessed determining the number of weeds in each plot during the second and fourth weeks after sowing. Samples were collected from a designated area measuring 0.25 square meters (0.5 m x 0.5 m) at two randomly selected points within each plot. The mean values were computed for further analysis and expressed as a quantity per square meter.

Data analysis

All the collected data were subjected to analysis of variance (ANOVA) using the statistical procedures described by Gomez and Gomez (1984) with the help of R-software version 4.2 and package Agricolae (R institute, 2022). The mean separation was conducted using the Least Significant Difference (LSD) at 5% of the required probability level. A simple correlation analysis was conducted to determine the relationship between growth and yield parameters of carrots as influenced by sowing date and mulching. Moreover, Partial budget analysis was conducted to evaluate the economic feasibility of sowing date and mulching, following the procedures below described by CIMMYT (1988). In brief:

Total root yield (TRY): The average yield of each treatment, measured in tons per hectare.

Adjusted total root yield (AjTRY): The average yield was decreased by 10% to accommodate the tendency for experimental yields to exceed what farmers could attain using identical treatments. In economic assessments, farmer yields are typically adjusted to be 10% lower than research findings to align with practical expectations.

$$\text{Adjusted total root yield (AjTRY)} = \text{TRY} \times (1 - 0.1)$$

Gross field benefit (GFB): Determined by multiplying the farm/ field gate price received by farmers for the carrots when sold by the adjusted marketable yield.

$$\text{Gross field benefit (GFB)} = \text{AjTRY} \times \text{price of carrot at farm gate}$$

Total variable costs (TVC): The expenses for mulch, the application cost of mulch, and labor costs for weeding varied across the treatments. The costs of additional inputs and production practices like land preparation, sowing, fertilizing, and harvesting were either consistent or negligible across the treatments.

Net benefit (NB): Obtained by deducting the total variable costs for inputs (TVC) from the gross field benefit (GFB).

Net benefit (NB) = Gross field benefit (GFB) - Total variable costs (TVC)

Marginal rate of return (MRR%): Calculated as the division of the change in net benefit by the change in total variable cost.

Marginal rate of return (MRR%) = [Change in net benefit (ΔNB)]/[Change in total variable cost(ΔTVC)] x 100

3. Results

Phenological parameters

The analysis of variance (ANOVA) showed that except for the effects of sowing date on days to 50% emergence, days to 90% maturity were significantly affected ($P \leq 0.05$) by sowing date, mulching, and their interactions (sowing date with mulching materials). In the case of mulching materials, sawdust mulch (M1) resulted in a minimum of 13.00 days, while bare soil (M0) led to a maximum of 15.00 days for 50% emergence. A maximum (101.66 days) number of days to achieve 90% maturity was observed from late sowing in July with growing carrots on bare soil (S3M0). Whereas, the minimum (97.00 days) number of days to 90% maturity was recorded from early sowing in July with sawdust mulch (S1M1) (Table 1).

Table 1 - Effects of sowing date and mulching on days to 50% emergency (DE) and 90% maturity (DM) Asian economic status

Factors	DE (no.)	DM (no.)
Sowing dates (S)		
S1	13.83 a	99.50 c
S2	13.91 a	100.25 b
S3	14.00 a	101.00 a
Mulching (M)		
M0	15.00 a	101.55 a
M1	13.00 c	98.44 d
M2	13.88 b	100.77 b
M3	13.77 b	100.22 c
Interaction (S X M)		
S1M0	15.00 a	101.33 a
S1M1	13.00 c	97.00 d
S1M2	13.66 b	100.00 b
S1M3	13.66 b	99.66 b
S2M0	15.00 a	101.66 a
S2M1	13.00 c	98.33 c
S2M2	14.00 b	101.00 a
S2M3	13.66 b	100.00 b
S3M0	15.00 a	101.66 a
S3M1	13.00 c	100.00 b
S3M2	14.00 b	101.33 a
S3M3	14.00 b	101.00 a
LSD (0.05)	0.25	0.84
CV (%)	1.87%	0.49%

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

Growth and yield parameters

ANOVA revealed that all the growth and yield parameters were significantly ($P \leq 0.05$) affected by sowing date, mulching, and their interactions. However, root diameter was not significantly influenced by the interaction effects of sowing date and mulching. The maximum plant height (23.94 cm), and number of leaves (9.80) were observed from early sowing with sawdust mulch (S1M1). Conversely, minimum plant height (18.65 cm) and leaf numbers (6.80) were obtained from late sowing without mulch (S3M0) (Table 2). The maximum root length (17.43 cm), and root fresh weight (106.78 g) were observed from early sowing with sawdust mulch (S1M1). While, minimum root length (14.00 cm) and root fresh weight (54.87 g) were obtained from late sowing without mulch (S3M0). Moreover, root diameter showed a linear decrease as the sowing date was delayed in which the maximum (2.67 cm) and minimum root diameter (2.39 cm) were recorded from growing carrots on sawdust mulch (M1) and without mulch (M0) respectively (Table 2).

On the other hand, early sowing with sawdust mulch (S1M1) resulted in the highest marketable root yield (26.19 t ha^{-1}) and the minimum (0.71 t ha^{-1}) unmarketable root yield. Following closely, the early sowing with dried grass mulch (S1M3) recorded a marketable root yield of 23.57 t ha^{-1}. In contrast, late sowing without mulch (S3M0) resulted in the lowest marketable root yield of 13.19 t ha^{-1} and the maximum (2.12 t ha^{-1}) unmarketable root yield. Furthermore, marketable root yield showed a linear decrease as the sowing date was delayed. Conversely,

Table 2 - Effects of sowing date and mulching on plant height, number of leaves, root length, root diameter, and root fresh weight

Factors	Plant height (cm)	Leaves (No.)	Root lenghts (cm)	Roort diameter (cm)	Root fresh weight
Sowing dates (S)					
S1	21.94 a	8.20 a	16.14 a	2.68 a	80.65 a
S2	21.06 b	7.82 b	15.41 b	2.51 b	65.82 b
S3	20.30 c	7.49 c	14.86 c	2.45 b	60.40 c
Mulching (M)					
M0	19.63 d	7.23 c	14.75 c	2.39 c	60.87 c
M1	22.49 a	8.76 a	16.32 a	2.67 a	80.55 a
M2	20.89 c	7.50 b	15.35 b	2.53 b	66.13 b
M3	21.38 b	7.79 b	15.46 b	2.61 ab	68.28 b
Interaction (S X M)					
S1M0	20.25 ef	7.45 c	15.47 c	2.50 cde	63.98 cd
S1M1	23.94 a	9.80 a	17.43 a	2.86 a	106.78 a
S1M2	21.68 bc	7.65 c	15.76 bc	2.64 bc	73.45 b
S1M3	21.88 bc	7.90 bc	15.90 b	2.74 ab	78.37 b
S2M0	19.99 f	7.45 c	14.78 e	2.35 ef	63.77 cd
S2M1	22.39 b	8.35 b	16.02 b	2.62 bcd	67.62 c
S2M2	20.34 ef	7.60 c	15.39 cd	2.48 def	65.29 cd
S2M3	21.53 c	7.90 bc	15.44 c	2.60 bcd	66.61 c
S3M0	18.65 g	6.80 d	14.00 f	2.32 f	54.87 e
S3M1	21.15 cd	8.15 b	15.51 c	2.54 cd	67.24 c
S3M2	20.66 def	7.45 c	14.92 e	2.47 def	59.66 de
S3M3	20.74 de	7.58 c	15.04 de	2.49 cde	59.84 de
LSD (0.05)	0.74	0.49	0.38	0.09	5.57
CV (%)	2.09%	3.75%	1.46%	3.72%	4.93%

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

unmarketable root yield showed a gradual increase as the date of sowing was delayed (Table 3).

Weed density

ANOVA revealed that sowing date, mulching, and their interactions significantly affected weed density ($P \leq 0.01$). The density of weeds showed a progressive decrease as the date of sowing was delayed in which the maximum (109.36 n m^{-2}) and minimum (68.00 n m^{-2}) densities of weeds were recorded from early (S1) and late (S3) sowing in July respectively. Whereas, in the cases of mulching maximum (179.87 n m^{-2}) and minimum (35.62 n m^{-2}) densities of weeds were recorded from growing carrots on bare soil and dried grass mulch (M3) applications respectively (Table 3).

Correlation

The correlation analysis using Pearson correlation coefficients (*r*) was performed to assess the relationship between the growth and yield parameters of carrots, considering the effects of sowing date and mulching. The results showed a significant positive correlation among all the growth parameters of the carrots, indicating a direct relationship where the effect of one parameter depends on another. However, the growth parameters, namely plant height and leaf number, exhibited a negative correlation with weed densities (WD). Accordingly, the total yield of carrots positively correlated with plant height (r = 0.77**), number of leaves per plant (r = 0.61**), root length (r = 0.75**), root diameter (r = 0.69**), root fresh weight (r = 0.64**), and marketable root yield (r = 0.6**). Furthermore, except for the unmarketable root yield (URY), all the yield parameters were negatively correlated with weed densities (Table 4).

Partial budget analysis

The minimum (375 USD ha^{-1}) and maximum

Table 3 - Effects of sowing date and mulching on marketable root yield (MRY), unmarketable root yield (URY), and weed density (WD)

Factors	MRY (t ha^{-1})	URY (t ha^{-1})	WD (n m^{-2})
Sowing dates (S)			
S1	23.40 a	0.96 b	109.36 a
S2	21.65 b	1.48 a	86.01 b
S3	19.16 c	1.56 a	68.00 c
Mulching (M)			
M0	17.60 c	1.75 a	179.87 a
M1	23.74 a	0.99 d	46.42 c
M2	21.79 b	1.36 b	89.25 b
M3	22.49 ab	1.23 c	35.62 d
Interaction (S X M)			
S1M0	20.57 cd	1.31 de	231.03 a
S1M1	26.19 a	0.71 i	61.35 f
S1M2	23.31 b	0.97 gh	93.03 d
S1M3	23.57 b	0.85 hi	52.02 g
S2M0	19.04 d	1.82 b	172.50 b
S2M1	23.25 b	1.07 fg	45.63 g
S2M2	22.1 bc	1.62 c	90.40 de
S2M3	22.23 bc	1.44 cd	35.51 h
S3M0	13.19 e	2.12 a	136.10 c
S3M1	21.79 bc	1.20 ef	32.3 h
S3M2	19.97 cd	1.49 cd	84.3 e
S3M3	21.69 bc	1.42 d	19.33 i
LSD (0.05)	2.45	0.19	8.12
CV (%)	6.76%	8.76%	5.46%

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

(863.33 USD ha^{-1}) total variable cost (TVC) was obtained from early sowing in July with no mulching (S1M0) and late sowing in July with sawdust mulching (S3M1) respectively and all the remaining treatments were confined between these two ranges (Table 5). According to the results of the partial budget analysis, early sowing with sawdust mulch (S1M1) yielded the highest net benefits of 11266.67 USD per hectare with a remarkable marginal rate of return (799.4%). Following closely was early sowing in July with dried grass mulch (S1M3), which had a net benefit of 10555.67 USD per hectare and the highest marginal rate of return (12,199.7%). On the other hand, late sowing in July with no mulching (S3M0) resulted in the lowest net benefit of 6489.5 USD per hectare and an unacceptable marginal rate of return (MRR%) (Table 5).

4. Discussion and Conclusions

Phenological parameters

Despite the sowing date, mulching regulates important seed emergence factors. In line with a study conducted by Mengistu and Yamoah (2010), most carrot varieties exhibited a typical emergence period ranging from 10 to 15 days. Mulching regulates essential factors for seed germination and emergence, including soil moisture, temperature, and air conditions. This optimized environment created by mulching can contribute to faster and

Table 4 - Correlation analysis of growth and yield parameters of carrot as influenced by sowing date and mulch

Par	DE	DM	PH	NL	RL	RD	RFW	MRY	URY	TRY	WD
DE	1	0.77 **	-0.76 **	-0.66 **	-0.67 **	-0.65 **	-0.54 **	-0.72 **	0.66 **	-0.70 **	0.77 **
DM		1	-0.85 **	-0.86 **	-0.84 **	-0.73 **	-0.79 **	-0.60 **	0.74 **	-0.56 **	0.49 **
PH			1	0.84 **	0.88 **	0.85 **	0.81 **	0.80 **	-0.85 **	0.77 **	-0.50 **
NL				1	0.86 **	0.70 **	0.83 **	0.64 **	-0.70 **	0.61 **	-0.40 *
RL					1	0.82 **	0.85 **	0.78 **	-0.86 **	0.75 **	-0.32 NS
RD						1	0.73 **	0.72 **	-0.79 **	0.69 **	-0.4 2*
RFW							1	0.67 **	-0.72 **	0.64 **	-0.23 NS
MRY								1	-0.77 **	0.60 **	-0.42 *
URY									1	-0.72 **	0.40 *
TRY										1	-0.41 *
WD											1

Par = parameters, DE = days to 50% emergence, DM = days to 90% maturity, PH = plant height, NL = number of leaves, RL = root length, RD = root diameter, RFW = root fresh weight, MRY = marketable root yield, URY = unmarketable root yield, TRY = total root yield, WD = weed densities, ** = highly significant (p ≤ 0.01), * = significant (p ≤ 0.05), NS = not significant.

Table 5 - Partial budget and marginal rate of return (MRR) analysis for a response of carrot to sowing date and mulching

Treatment combinations	Total root yields (Kg ha^{-1})	Adjustable total root yield (Kg ha^{-1})	Growth field benefit (USD)	Total variable cost (USD)	Net benefit (USD)	Marginal rate return (%)	Rank
S_1M_0	21880	19692	9846	375	9471	--	
S_2M_0	20860	18774	9387	387.5	8999.5	D	
S_3M_0	15310	13779	6889.5	400	6489.5	D	
S_1M_3	24420	21978	10989	433.33	10555.67	12199.7	1
S_2M_3	23670	21303	10651.5	445.83	10205.67	D	
S_3M_3	23110	20799	10399.5	458.33	9941.16	D	
S_1M_2	24280	21852	10926	541.66	10384.33	531.8	3
S_2M_2	23720	21348	10674	554.16	10119.83	D	
S_3M_2	21470	19323	9661.5	566.66	9094.83	D	
S_1M_1	26900	24210	12105	838.33	11266.67	799.4	2
S_2M_1	24320	21888	10944	850.83	10093.17	D	
S_3M_1	22990	20691	10345.5	863.33	9482.16	D	

D = dominated, selling price of carrot at farm gate = 0.5 USD kg^{-1}, labor cost = 2.5 USD Man per day.

more efficient seed emergence. The moisture content should be sufficient for the seeds to absorb water and germinate. Low soil moisture content delays or inhibits seed germination in the field, reduces uniformity of seedling performance, and total stand establishment, and ultimately reduces the yield of carrots (Muhie *et al.*, 2024). The delayed maturity observed in late sowing (S3) could be attributed to unfavorable weather conditions typically experienced towards the end of summer (August). Insufficient rainfall during the critical growth stages such as root development may adversely affect plant phenology. Throughout the vegetative growth stages of the late sowing date, minimum temperatures were received. This might have requested a prolonged time to reach 90% maturity. In contrast, the vegetative growth periods (July and August) associated with early sowing in July benefited from sufficient rainfall and relatively favorable temperatures (Fig. 2). Indeed, this promoted better vegetative growth, which is vital for achieving early 90% maturity. Sandler *et al*. (2015), support the current finding, that a proper sowing date could help to minimize damage from cold, moisture deficit, weeds, pests, and diseases. Similarly, the accelerated maturity of carrot roots might be associated with the easy uptake of nutrients as the available water helps the plant to dissolve the nutrients and move through transpiration pull which in turn helps carrot roots to mature early (Muhie *et al.*, 2024). In contrast to growing carrots without mulch, the practice of mulching generally enhanced the likelihood of achieving early maturity. Mulching achieved this by providing organic matter, effectively regulating soil temperature and moisture levels. In agreement with this experiment, Singh and Jaysawal (2021) observed that sawdust mulching has a significant influence on the harvesting period (maturity).

Growth and yield parameters

The higher plant height and leave numbers observed from the early sowing in July (S1) could be attributed to maximum rainfall and temperature in July and August (Fig. 2). Moreover, they contributed to improving various vegetative aspects, including plant height and leaf number. Additionally, carrots require a sufficient amount of water for proper growth and development consequently, these conditions play a crucial role in accelerating the crop's physiological processes. Considering the combined effect of precipitation and temperature, carrot farmers must plan their planting and cultivation schedules accordingly. Sowing during periods of adequate rainfall can improve the chances of successful growth. This result is consistent with Kabir *et al*. (2013), who observed that all environmental conditions, especially temperature, facilitated vegetative growth. Furthermore, researchers have observed that early sowing may result in maximal photosynthesis and a longer growth period than late sowing, which encountered harsh winter months immediately following sowing and thus diminished growth (Lavanya *et al*., 2017). However, mulching offers vital soil microclimate elements such as moisture, temperature, nutrients, aeration, and weed control, which can enhance crop growth and development.

Acharyya *et al*. (2020) verified this result, sawdust mulch maintains ideal soil temperature, which promotes vegetative development and overall crop yields to a satisfactory level. Based on the trends shown in figure 2, the fluctuations in precipitation and temperature can impact the enhancement of root growth (root length, diameter, and weight) throughout the entire growing season. Crops that were sown early have a greater opportunity to experience relatively optimal temperatures and precipitation throughout their entire growing periods, consequently, this favorable condition of early sowing can result in increased leaf production and canopies, which have the potential to capture more sunlight. This can contribute to improved root growth and ultimately lead to higher crop yields. On the other hand, the root developmental periods of late sowing in July (September and October) were characterized by lower maximum (19.1°C) and minimum (8.6°C) temperatures (Fig. 2). These were below the physiological range of temperatures (15-20°C), and might potentially hinder root growth by disrupting the normal physiological processes of crops. This experimental result is supported by the findings of different researchers, who reported that carrots are a temperature-sensitive root crop and their root growth was developed under suitable environmental conditions (Kabir *et al*., 2013).

The observed maximum root length, root diameter, and root weight in the sawdust mulch could be attributed to several factors such as mulch contributes to the improvement of soil structure and aeration, this creates a favorable environment for root development, allowing roots to penetrate the soil more easily and access nutrients effectively. In addition, the mulch layer helps to maintain the temperature of the soil by providing insulation, which can mitigate extreme temperature fluctuations. This stable soil temperature promotes optimal root growth and function. Furthermore, mulch supports beneficial microbial flora in the soil. These contribute to nutrient cycling and availability, promoting nutrient uptake by roots and enhancing root growth. Whereas, the cultivation of carrots on bare soil encounters unfavorable soil conditions, leading to the production of carrots with poor root quality. Findings of this experiment align with, Shahadot (2021), indicating that the application of sawdust mulch is likely associated with the provision of consistent moisture and nutrients to the root zone. This favorable supply of moisture and nutrients promotes rapid cell division and cell elongation, ultimately leading to the production of long and thicker roots. In addition, consistent findings of the maximum fresh weight of roots were reported in multiple studies using sawdust mulch, including those conducted by Ladumor *et al*. (2020), Acharyya *et al*. (2020), and Paunović *et al*. (2020).

Figure 2 reveals a decrease in precipitation levels from July to November. Carrots require a sufficient amount of water for proper growth and development. Inadequate rainfall during critical stages, such as root development, can lead to stunted growth and reduced yields. The success of crop establishment, yield, and profitability could be attributed to the favorable precipitation and temperature observed during the vegetative growing periods (July and August) of early-sown crops. An optimal environment for the crops, promotes healthy growth and development, ultimately leading to higher yields and increased profitability. Furthermore, improved vegetative performance, characterized by increased net photosynthetic rate, stomatal conductance, and leaf chlorophyll content, plays a vital role in enhancing root quality. Conversely, late-sown crops faced challenges due to inadequate rainfall and lower temperatures experienced during the vegetative growing periods (August and September) (Fig. 2), thus unfavorable conditions during critical growth stages might have negatively impacted crop performance, leading to potential yield reductions.

Mulching offers a comprehensive supply of essential resources, thereby enhancing the quality of roots for the market. This study is in line with, Hasan *et al*. (2018), who reported that the use of mulch resulted in the highest marketable root yield. The maximum unmarketable root yield observed in bare soil could be attributed to fluctuating soil moisture, temperature, and inadequate soil aeration. These contribute to the development of poor-quality roots, characterized by branching, cracking, forking, under-sizing, underweight, and green shoulder roots. Whereas, minimum non-marketable root yield observed in carrot cultivation with sawdust mulch could be attributed to the regulating effect of mulching on fluctuating soil conditions, especially moisture and temperatures. By maintaining more stable soil conditions, mulching reduces the occurrence of root branching and cracking, resulting in roots that are highly desirable to both consumers and the market. Furthermore, mulching contributes to the production of fewer green shoulder roots by protecting the soil against cracking and direct exposure to light. Green shoulder roots, which have a bitter taste, negatively impact root appearance and quality, unsuitable for consumption and market. The present experimental result is consistent with Paunović *et al*. (2020) who revealed that various mulching materials such as sawdust affected the availability of nutrients to the plants. The application of sawdust mulch reduces the loss of phosphorous due to excessive precipitation, thus leading to an increase in the production of quality roots (Sarolia and Bhardwaj, 2012).

Weed density

The reason for the density of weeds showing a progressive decrease as the date of sowing was delayed could be, that at the onset of summer (July), there was a higher amount of rainfall and a faster rate of temperature rise compared to the end of summer (Fig. 2). Consequently, these conditions contribute to the proliferation of weeds, resulting in higher weed growth and densities. The availability of water resources encourages weed species to flourish and compete with desired plants for resources. The result is consistent with Singh *et al*. (2019), who found that weed emergence is comparatively weaker during the latter part of summer and early autumn compared to the early summer and spring periods. The reason for minimum weed density within dried grass mulch might be attributed to its slow decomposition rate, which has the potential to suppress weed growth and promote positive plant growth supported by Hayati *et al*. (2023). Among the different mulch materials studied, the straw mulch was the least effective in terms of weed suppression potential. This can be attributed to the loose nature of straw mulch, which does not provide tight coverage of the soil. As a result, straw mulch does not offer effective weed control efficacy when compared to dried grass and sawdust mulch. Furthermore, the current investigation aligns with Ossom *et al*. (2019), who suggested that mulches effectively inhibit weed growth by blocking the penetration of light or excluding specific wavelengths of light required for weed germination and growth. Additionally, Biswas and Das (2019) reported that straw mulch decomposes rapidly, leading to a short duration of weed control efficiency.

Correlation

This finding suggests that both the application of sowing date and mulching positively impacted the yield of carrots by influencing important yield components of the crop. As a result, the yield of carrots was increased. This could be attributed to the fact that increased weed presence leads to a reduction in crop growth and yield. Weeds compete with the crop for essential resources such as nutrients, water, space, and light, as supported by the findings of Manthy *et al*. (2020). In general, there was a positive correlation between the total yield of carrots and the growth parameters. Enhanced vegetative growth such as plant height and leaf performance, contributed to the production of higher quantities of photoassimilates, consequently leading to increased root yield. This concept is supported by the findings of Acharyya *et al.* (2020), who reported that the use of organic mulching promotes improved vegetative growth, ultimately resulting in increased root yield.

Partial budget analysis

From the economic point of view, all treatments with a marginal rate of return higher than the minimum rate of return are considered advantageous and economically viable. The results indicated that the most economically productive treatment combination, offering the highest marginal rate of return, was early sowing with dried grass mulch (S1M3), making it an ideal choice for small-scale farmers. Additionally, for resourceful cultivators or investors, the application of early sowing in July with sawdust mulch (S1M1) proved to be profitable despite its higher cost, resulting in the highest net benefit among all the treatments.

In the study area, characterized by a temperate climate, farmers typically cultivate carrots on bare beds and frequently sow carrots in late July, attributed to severe winter conditions, such as soil moisture deficit due to insufficient rainfall, at the end of summer. This leads to suboptimal yield and, as a result, farmers are discouraged from engaging in carrot cultivation. For this reason, this study focused on implementing management practices such as proper sowing dates and mulching to minimize adverse effects on root yield and suppress weed growth. The result showed that sowing date and mulching had a significant influence on almost all parameters except for days to 50% emergence. Early sowing with sawdust mulch resulted in the maximum plant height, number of leaves, root length, root fresh weight, and marketable root yield. Additionally, early sowing with no mulch (S1M0) resulted in the maximum weed density. While late sowing with dried grass mulch (S3M3) had a minimum weed density. The correlation analysis showed that the growth parameters and the majority of the yield parameters of carrots exhibited positive correlations with both marketable and total root yields. Based on the partial budget analysis, early sowing in July with sawdust mulch (S1M1) resulted in the highest net benefit. However, the highest marginal rate of return was recorded from early sowing in July with dried grass mulch (S1M3). This research evidences that early sowing with sawdust mulch resulted in the highest marketable root yield and net benefit, despite the associated higher costs. For resource-full producers, it can be recommended as the second-best alternative. However, for the economical production of carrots, a temporary recommendation is to utilize an early sowing in July with dried grass mulch. This particular combination exhibited the highest marginal rate of return, making it the most desirable agronomic management practice for small-scale farmers in the study area. However, this investigation specifically emphasizes agronomic practices. In addition, it is a one-time experiment. Therefore, it is necessary to carry out the experiment using several mulching materials under various sowing dates and locations. This comprehensive approach will lead to efficient results and sound recommendations.

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