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Yield and yield components of coriander under different sowing dates and seed rates in tropical environment

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Abstract: Coriander makes use of favorable environmental conditions when it is sown at optimum time and rate. However, this information is very limited in the southeastern mid-highlands of Ethiopia. Field experiments were, therefore, conducted between 2011 and 2014 at three different research stations to determine optimum sowing dates and rates. The experiment had split plot design in randomized complete block with three replications, in which sowing dates and seed rates were the main and sub-plot treatments, respectively. The four sowing date treatments were June 20, July 10, July 30 and August 20 while the four seed rate treatments were 30, 40, 50 and 60 kg ha^{-1}. Coriander sowed in the third decade of July at Arsi Robe and from the first to the third decades of July at Kulumsa and Sagure gave the highest fruit and biomass yields. Earlier sowing in the second decade of June, and delayed sowing in the second decade of August brought fruit yield reductions of 37-66 and 37% at Arsi Robe, 27-45 and 58-66% at Kulumsa, and 24-40 and 26% at Sagure, respectively. However, coriander did not respond to seed rates. Owing to the enhanced yields of coriander, intermediate cultivation at a seed rate of 30 kg ha^{-1} was found optimum.

1. Introduction

Coriander (*Coriandrum sativum L.*), which belongs to the family of Umbelliferae (Apiaceae) is one of the most important annual spice and medicinal herb. It is grown in Ethiopia and throughout the world for its seeds as well as leaves and has immense uses (Diederichsen, 1996; Hedburg and Hedburg, 2003; Parthasarathy *et al.*, 2008; Nowak and Szemplinski, 2014). Coriander originated from the Mediterranean and Western Asian regions (Burdock and Carabin, 2009). Along with central Asia and near east countries, Vavilov (1992) mentioned Ethiopia in the lists of centers of origin for coriander. Ivanova and Stoletova (1990) also reported that India, Northern Africa, Central Asia and Ethiopia are centers of formation and cradles for different types of coriander. There is a long-standing tradition of cultivation of coriander in Ethiopia (Diederichsen, 1996; Geremew *et al.*, 2014).

The immense uses of coriander depend on the choice of fruits or green herbs, which are linked to their chemical compositions. The most important constituents are the essential and fatty oils (Diederichsen, 1996). Coriander has got significant importance as a spice in culinary, food, beverage, medicine, perfumery, pharmaceuticals and sanitary industries (Jansen, 1981; Diederichsen, 1996; Delaquis *et al.*, 2002; Kubo *et al.*, 2004). On the other hand, its green foliage is used in vegetables owing to its richness in vitamins and other minerals (Singh *et al.*, 2005). In Ethiopia, coriander is widely used for domestic culinary. The seeds are used for flavoring the powder of hot red pepper locally called "*berbere*" and used for numerous meat and vegetarian dishes, leavened flat Ethiopian bread locally called "*injera*", cakes and bread. The leaves are added as an aromatic herb to tea and stew locally called "*wot*" (Jansen, 1981; Geremew *et al.*, 2014).

Coriander is also a good melliferous plant since it produces a considerable quantity of nectar and thereby attracts many different insects for pollination. Studies indicated that one hectare of coriander allows honeybees to collect about 500 kg of honey (Diederichesen, 1996). The residues left after extraction of the essential oils are used as best ruminant feed since they still contain as nearly the same digestible fat and protein content as the whole fruits (Diederichesen, 1996).

The success of coriander production is influenced by genetic, weather and agronomic factors (Nowak and Szemplinski, 2014). The maximum fruit and essential oil yields are attained only when an appropriate combination of these factors are provided for the plant (Rangappa *et al*., 1997; Gil *et al*., 2002). Coriander is among the tropical crops and generally sown in winter season if the objective is seed for production (Sharangi and Roychowdhury, 2014). As a temperature-sensitive crop, it generally requires a relatively cool, comparatively dry and frost-free weather during its early stage for good vegetative growth and relatively warm temperature during flowering and reproductive stage for high yields and good quality (Peter, 2004; Kalra, 2008; Sharangi and Roychowdhury, 2014). The ideal temperature for germination and growth of coriander is 20-25°C (Singhania *et al.*, 2006).

Coriander exploits the environment most favorably when it is sown at optimum time (Kuri *et al.*, 2015) since sowing date significantly affects the photoperiodic response of plants and determines yields and qualities (Rasam *et al.*, 2007). Time of sowing controls the crop phenological development along with efficient conversion of biomass into economic yield (Khichar and Niwas, 2006). Earliness in sowing leads to untimely flowering; however, it may also pose susceptibility to the damage of extreme cold and frost. On the other hand, delay in sowing hampers growth, yield and quality of the crop due to deficiency of soil moisture at latter stages (Sharangi and Roychowdhury, 2014; Rashed and Darwesh, 2015).

Determination of optimum seed rate is also a basic element for successful coriander production (Rasam *et al.*, 2007). Many agronomic studies conducted in the world revealed that seed rate had a highly significant effect on the productivity and quality of coriander (Diederichsen, 1996; Kumar *et al*., 2007; Ghobadi and Ghobadi, 2010). Both low and high seed rates resulted in reduced yield and oil concentrations.

Rapid life cycle of coriander allows it to fit into different growing seasons, making it possible to grow the crop under a wide range of conditions (Lopez *et al.*, 2007). Cultivation of coriander in Ethiopia; however, is limited to the mid to highlands (1500-2500 m a.s.l.), where sufficient soil moisture can be provided from rainfall. It can also be cultivated in the lowlands if the rainfall is sufficiently supplemented by irrigation (Jansen, 1981; Geremew *et al.*, 2014).

Although coriander has got diverse uses, economic importance and one of the several plant species for which Ethiopia is known as a center of origin and diversity (Jansen, 1981; Diederichsen, 1996), it is one of the most neglected or under-utilized aromatic and spice crop (Beemnet and Getinet, 2010). The wealth of coriander is not yet exploited in Ethiopia. Compared to other crops, there is no or very limited information available on the agronomic packages. This study was, therefore, carried out to determine optimum sowing date and seed rate for increased yield of coriander in the southeastern mid-highlands of Ethiopia.

2. Materials and Methods

Description of the study sites

The experiment was conducted at three locations, namely Arsi Robe, Kulumsa and Sagure in the southeastern mid-highlands of Ethiopia. The sites are representatives of the region, where coriander cultivation can potentially be carried out, and optimum sowing dates and seed rate studied. It was conducted for two seasons in 2011 and 2012 at Arsi Robe, and 2011 and 2014 at Kulumsa and Sagure. Due to infestation by unknown disease, the crop could not perform well in 2012 and 2013 at Kulumsa and Sagure, and harvesting could not be done. Arsi Robe, Sagure and Kulumsa are located from 8.4 to 8.6 N and 40.1 to 40.4 E, 8.01 to 8.15 N and 39.2 to 39.3 E and from 7.77 to 8.03 N and 38.94 to 39.31 E, respectively. The altitudes of the locations vary from 2200 m a.s.l. at Kulumsa to about 2500 m a.s.l. at Arsi Robe and Sagure. The dominant soil type of the three locations is characterized as vertisol (IUSS Working Group WRB, 2014).

Climate

Long-term mean annual rainfall at Arsi Robe, Kulumsa and Sagure were 937, 812 and 653 mm, respectively. Hence, Arsi Robe and Sagure had the highest and lowest, respectively rainfall with intermediate values at Kulumsa (Fig. 1). 56, 55 and 67% of the annual rainfall concentrated in the months of July and August at Arsi Robe; June, July and August at Sagure and July, August and September at Kulumsa. The major crop production activities are conducted between June to November; therefore, the rainfall amount and distribution during these months have significant influence on the yield and yield attributes. The highest rainfall was recorded in August at all study sites (Fig. 1). From August, the rainfall amount and distribution reduce sharply and reach the lowest in the month of December at all locations. November, December, January and February are dry months with the lowest records of rainfall amounts.

Long-term mean maximum temperature records of Arsi Robe, Kulumsa and Sagure were 22.3, 23.2 and 22.5°C, respectively. The corresponding values for mean minimum temperatures were 8.3, 10.5 and 8.8°C, respectively (Fig. 2). February was the hottest month at Arsi Robe and Sagure while the corresponding month at Kulumsa was March. December was the coldest month at all locations with the lowest records of 4.9, 8.0 and 5.1°C at Arsi Robe, Kulumsa and Sagure, respectively.

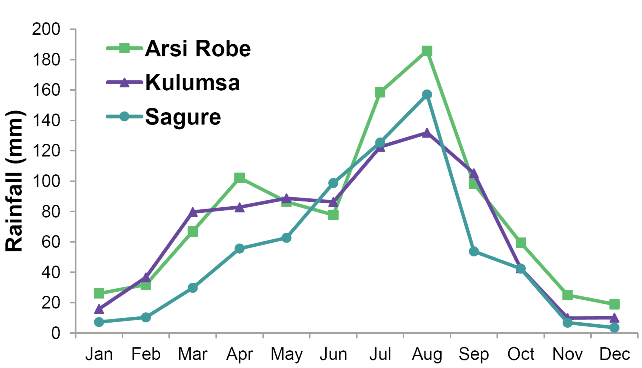

Fig. 1 - Total mean monthly rainfall at Arsi Robe, Kulumsa and Sagure.

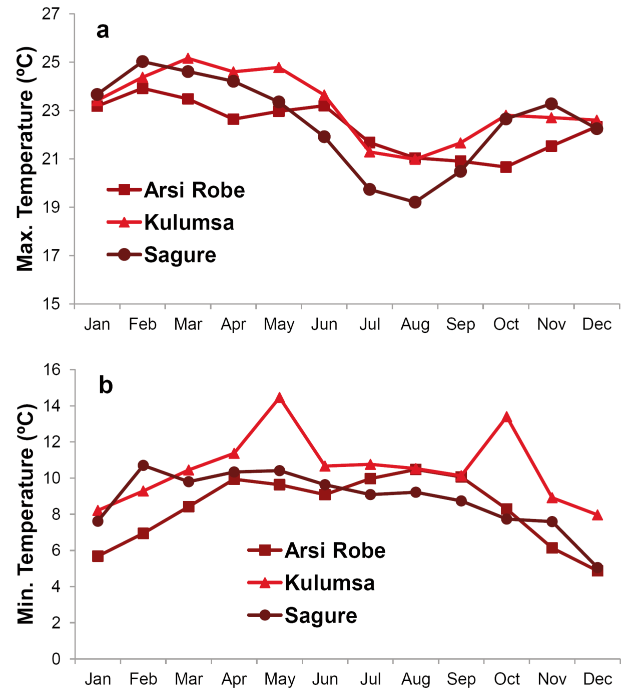

Fig. 2 - Mean annual maximum (a) and minimum (b) temperatures at Arsi Robe, Kulumsa and Sagure.

Experimental set-up and procedure

The experiment had split plot design in randomized complete block with three replications, in which the sowing dates and seed rates were the main and sub-plot treatments, respectively. The four sowing date treatments were June 20, July 10, July 30 and August 20 whereas the four seed rate treatments were 30, 40, 50 and 60 kg ha^{-1}. The sowing dates were set to choose the optimum time by allowing coriander to make maximum benefit from the suitable environmental parameters, especially rainfall and temperature for its successful establishment, survival and performance. On the hand, the seed rates were set by making reference to the existing recommendation of 40 kg ha^{-1}.

The seedbed preparation started in early April and totally plowed four times prior to planting. All experimental plots at each location and season were planted with coriander (cv. *Keteba*). The seedbeds were prepared in ridge and furrow, and seeds were drilled on raised beds by hand at 0.30m spacing between rows on the aforementioned sowing dates for all sites in plot sizes of 1.8 m by 6 m. The spacing between plots and replications were 0.5 m and 1 m, respectively. The recommended phosphorus (20 kg P ha^{-1}) and nitrogen (18 kg N ha^{-1}) nutrients were uniformly applied to all plots close to the seed rows as basal dose at the time of sowing from di-ammonium phosphate (20-18 P-N). Weeds were controlled by manual cleaning.

Data collection

Twenty-five randomly selected plant samples were manually cut at the ground level from the inner four rows by excluding the outer two to avoid any border effect, air-dried, the moisture content adjusted to constant level and used for measuring above ground total biomass. The harvest index was calculated by dividing the dry mass of seeds collected from the 25 plant samples and threshed manually by the dry mass of biomass, and multiplying the ratio by 100. For the measurement of fruit yield, the whole crop was harvested from a net plot area of 6 m^2 (1.2 m by 5 m), subjected to air-drying and threshed manually. The fruits were detached from the biomass, cleaned and weighed. The seed moisture content was determined by placing samples from each plot in an oven at 105°C for 24 hours. The above ground total biomass and seed mass from each plot were then adjusted to 0 g kg^{-1} moisture content (dry weight) and expressed in kg ha^{-1} for statistical analysis purpose. Plant height data were taken from each plot at physiological maturity from ten plant samples.

Data analysis

All yield and yield components data were combined across sites and seasons and subjected to analysis of variance using the general linear model procedure (Proc GLM) of SAS statistical package version 9.2 (SAS Institute, 2002). Least significance difference (LSD) tests were employed to evaluate the means of the main and interaction effects of the treatments for each parameters measured (determined). Mean separation for the interaction effects were conducted using Minitab®18 statistical package (Minitab Inc.). When P<0.05, means values of treatments were declared as significantly different.

3. Results

The analysis of variance over two seasons indicated that sowing date and season as well as their interaction had very significant (p<0.001) effect on most of the traits measured at all locations (Tables 1-3).

Table 1 - Effects of sowing dates and rates by year, and their interaction on yield and yield components of coriander at Arsi Robe in 2011 and 2012

Sources of variation	Yield and yield components of coriander			
	Plant height (cm)	Harvest index (%)	Fruit yield (kg ha^{-1})	Biomass yield (kg ha^{-1})
Rep	NS	NS	NS	NS
Sowing Date (SD)	***	***	***	***
Error (a)	45.64	11.12	19566.89	317296
Year (Y)	***	NS	***	***
Seed rate (SR)	***	NS	NS	NS
SD x SR	NS	NS	*	NS
Y x SD	***	***	***	***
Y x SR	NS	NS	NS	NS
Y x SD x SR	NS	NS	NS	NS
Error (b)	32.67	13.5	16423.2	202979
CV	6.63	10.02	13.21	16.75

*** and NS means significant at P<0.001 and not significant at P<0.05, respectively.

Table 2 - Effects of sowing dates and rates by year, and their interaction on yield and yield components of coriander at Kulumsa in 2011 and 2014

Sources of variation	Yield and yield components of coriander			
	Plant height (cm)	Harvest index (%)	Fruit yield (kg ha^{-1})	Biomass yield (kg ha^{-1})
Rep	NS	NS	*	NS
Sowing Date (SD)	***	***	***	***
Error (a)	5.86	1.83	14609.46	870629
Year (Y)	***	***	***	NS
Seed rate (SR)	*	NS	NS	NS
SD x SR	NS	***	***	NS
Y x SD	***	***	***	NS
Y x SR	***	***	NS	NS
Y x SD x SR	*	***	NS	NS
Error (b)	7.09	8.84	46135.74	2447414
CV	3.02	10.06	13.2	25.05

*** and NS means significant at P<0.001 and not significant at P<0.05, respectively.

Table 3 - Effects of sowing dates and rates by year, and their interaction on yield and yield components of coriander at Sagure in 2011 and 2014

Sources of variation	Yield and yield components of coriander			
	Plant height (cm)	Harvest index (%)	Fruit yield (kg ha^{-1})	Biomass yield (kg ha^{-1})
Rep	NS	NS	NS	NS
Sowing Date (SD)	***	***	***	***
Error (a)	11.04	4.24	295392.79	2299583
Year (Y)	***	***	***	NS
Seed rate (SR)	***	NS	NS	NS
SD x SR	***	***	***	***
Y x SD	***	***	***	***
Y x SR	NS	***	NS	***
Y x SD x SR	*	***	NS	*
Error (b)	19.36	11.21	69124.93	928593
CV	4.93	10.71	18.52	20.75

*** and NS means significant at P<0.001 and not significant at P<0.05, respectively.

The effects of seed rate on fruit and biomass yields were not significant; however, its interaction with sowing date and season brought significant improvement on some of the variables measured. Results further showed that the interaction effects among sowing date, seed rate and season were not significant on most of the yield and yield components. The amount of variance associated with the sowing date x season interaction was the most important for this study.

Effect of sowing date

Sowing dates and their interaction with season significantly ($P<0.001$) affected the fruit and biomass yields of coriander at all locations except for the biomass yield at Kulumsa. The highest fruit yields of coriander were attained from coriander sowed on July 30 in 2012 and 2014 at Arsi Robe and Kulumsa, respectively; and July 30 and July 10 in 2014 and 2011 at Sagure, respectively (Tables 4-6). The coriander sown on July 30 and June 20 in 2012 and 2011, respectively at Ari Robe and July 10 in 2014 at Sagure gave the highest biomass yields. Fruit yields of 2713, 2028 and 2006 kg ha^{-1} were obtained at Kulumsa in 2014, Sagure in 2014 and Arsi Robe in 2012, respectively from coriander sowed on July 30. July 10 sown coriander at Sagure gave a fruit yield of 1928 kg ha^{-1}, which was statistically equivalent to the July 30 sown coriander. Similarly, biomass yields of 4732 and 4573 kg ha^{-1} were harvested at Arsi Robe in 2012 and 2011 from July 30 and June 20 sown coriander, respectively. The highest biomass yield at Sagure, 7217 kg ha^{-1}, was found from the coriander sowed on July 10 in 2011. The result further revealed that early (June 20) and late (August 20) sown coriander produced inferior fruit and biomass yields compared to the intermediate sowing dates.

The effects of sowing date and its interaction with season on the harvest index were also very significant ($P < 0.001$) at all locations (Table 1-3). The highest harvest indexes were obtained from the August 20 sown coriander at Arsi Robe and Kulumsa in both years (Tables 4-6). The values of harvest index from the August 20 sown coriander at Arsi Robe were 42.7 and 40.9% in 2012 and 2011, respectively. The corresponding values from the same sowing date at Kulumsa were 42.1 and 41% in 2014 and 2011,

Table 4 - Influences of sowing date and season on yield and yield components of coriander at Arsi Robe in 2011 and 2012

Sowing date	Year							
	Plant height (cm)		Harvest index (%)		Fruit yield (kg ha^{-1})		Biomass yield (kg ha^{-1})	
	2011	2012	2011	2012	2011	2012	2011	2012
June 20	72 de	112 a	34 cd	28 e	239 f	1272 b	721 e	4573 a
July 10	79 c	108 a	34.8 c	31.1 d	502 e	1147 c	1446 d	3702 b
July 30	68 e	96 b	38.6 b	42.9 a	683 d	2028 a	1809 d	4732 a
August 20	76 cd	80 c	40.9 ab	42.7 a	696 d	1193 bc	1736 d	2828 c

Table 5 - Influences of sowing date and season on yield and yield components of coriander at Kulumsa in 2011 and 2014

Sowing date	Year							
	Plant height (cm)		Harvest index (%)		Fruit yield (kg ha^{-1})		Biomass yield (kg ha^{-1})	
	2011	2014	2011	2014	2011	2014	2011	2014
June 20	106 a	105 a	18.9 e	20.5 de	1366 c	1493 c	7841 ab	8013 ab
July 10	100 b	101 b	29.2 c	27.5 c	1835 b	1991 b	6326 c	7206 bc
July 30	88 c	105 a	22 d	35 b	1876 b	2713 a	8559 a	7859 ab
August 20	48 d	50 d	41 a	42.1 a	793 d	934 d	1942 d	2220 d

Table 6 - Influences of sowing date and season on yield and yield components of coriander at Sagure in 2011 and 2014

Sowing date	Year							
	Plant height (cm)		Harvest index (%)		Fruit yield (kg ha^{-1})		Biomass yield (kg ha^{-1})	
	2011	2014	2011	2014	2011	2014	2011	2014
June 20	96 c	108 a	33.4 b	26.5 e	1523 b	1162 c	4638 cd	4507 cd
July 10	96 c	103 b	28.2 cde	29.1 cd	2006 a	1435 b	7217 a	4947 bc
July 30	78 d	102 b	40.4 a	35 b	1557 b	1928 a	3846 de	5495 b
August 20	64 e	66 e	30.2 c	27.4 de	888 d	845 d	3204 e	3320 e

respectively. Statistically equivalent harvest index (42.9%) was also provided at Arsi Robe from the coriander sowed on July 30 in 2012. The highest harvest index at Sagure (40.4%) was obtained from the July 30 sown coriander in 2011.

The influences of sowing date and its interaction on plant height was also very significant (P <0.001). Generally, early and late sown coriander resulted in the tallest and shortest plant heights, respectively, which were consistent over years and locations. Early sown coriander resulted in the tallest plant at Arsi Robe in 2012 (112 cm), Kulumsa in 2011 (106 cm) and 2014 (105 cm), and Sagure in 2014 (108 cm). The tallest plant heights at Kulumsa in 2014 (105 cm) and Arsi Robe in 2012 (108 cm) were also attained from coriander sowed on July 30 and July 10, respectively. Delay in sowing of coriander (August 20) brought the shortest plant height at Kulumsa (48 and 50 cm in 2011 and 2014, respectively) and Sagure (64 and 66 cm in 2011 and 2014, respectively).

Temporal variabilities significantly affected both yield and yield components of coriander at all locations (Tables 1-3). Most of the variables measured at Arsi Robe, Kulumsa and Sagure gained better advantage owing to sowing of coriander in 2012 than 2011, 2014 than 2011 and 2011 than 2014, respectively implied the influences of seasonal variabilities on yield and yield attributes. The effects of temporal variations on yield and yield attributes were more pronounced at Arsi Robe than Kulumsa and Sagure areas, which could be justified by the magnitudes of differences in the fruit yields recorded during the study period. The variances in the highest fruit yields between 2012 (2028 kg ha^{-1}) and 2011 (696 kg ha^{-1}) at Arsi Robe, 2014 (2713 kg ha^{-1}) and 2011 (1876 kg ha^{-1}) at Kulumsa, and 2011 (2006 kg ha^{-1}) and 2014 (1928 kg ha^{-1}) at Sagure were 1331, 837 and 78 kg ha^{-1}, respectively (Tables 4-6). This implied that the magnitude of the variabilities associated with the fruit yields between the two years were so large at Arsi Robe compared to Kulumsa and Sagure.

Spatial variabilities were also accountable for large disparities in yield and yield components of coriander among the testing locations. Fruit and biomass yields of coriander were superior at Kulumsa compared to Sagure and Arsi Robe. Mean fruit yields of coriander combined over season at Arsi Robe, Kulumsa and Sagure were 970, 1625 and 1418 kg ha^{-1}, respectively. The corresponding values for biomass yields were 2693, 6246 and 4647 kg ha^{-1}, respectively (Tables 4-6). Compared to Arsi Robe, Kulumsa and Sagure produced 68 and 46% more fruit yields and 132 and 73% more biomass yields of coriander, respectively.

Effect of seed rate

Seed rate did not bring significant effect on most of the yield and yield components of coriander measured at all locations (Tables 1-3), which were consistent over years and locations. However, its interaction with sowing date and year had significant effect on some of the yield and yield attributes of coriander at all locations (Tables 1-3). The fruit yields obtained from the July 30 sown coriander at a seed rate of 30 kg ha^{-1} at Arsi Robe and any one of the four seed rates at Kulumsa were found to be statistically superior over all other possible sowing date x seed rate interactions. This implied that the lowest seed rate, 30 kg ha^{-1}, could be sufficient for optimum yield of coriander in the study areas. Sowing of coriander on July 30 at a seed rate of 30 kg ha^{-1} gave fruit yield of 1526 kg ha^{-1}. Similarly, coriander sowed on July 30 at seed rates of 30, 40, 50 and 60 kg ha^{-1} at Kulumsa gave fruit yields of 2239, 2306, 2427 and 2204 kg ha^{-1}, respectively, which were statistically equivalent to each other but significantly different from the other treatments (Table 7). The seed rate x sowing date interactions at Sagure were not significant for the fruit yields of coriander.

Seed rate interaction with year brought significant effect on the fruit and biomass yields of coriander at Sagure only (Tables 1-3). Except for the biomass yield at Sagure, the sowing date x seed rate x year interac-

Table 7 - Influence of sowing date x seed rate interactions on the fruit yield of coriander at Arsi Robe, Kulumsa and Sagure from 2011 to 2014

Sowing date	Seed rate (kg ha^{-1})											
	Arsi Robe				Kulumsa				Sagure			
	30	40	50	60	30	40	50	60	30	40	50	60
June 20	907 de	746 f	695 f	674 f	1378 de	1293 e	1506 cde	1541 cd	1508 bcd	1272 def	1456 cde	1133 efg
July 10	781 ef	909 de	822 def	786 ef	2176 b	2086 b	1702 c	1688 c	1846 ab	1708 abc	1677 abc	1650 abc
July 30	1526 a	1356 b	1355 b	1184 c	2239 ab	2306 ab	2427 a	2204 ab	1544 bcd	1955 a	1683 abc	1787 abc
August 20	936 d	958 d	958 d	926 de	969 f	834 f	850 f	802 f	783 h	942 fgh	917 gh	826 gh

tions were also not significant at all locations for most of the attributes measured (Tables 1-3).

4. Discussion and Conclusions

The highest fruit and biomass yields from the July 30 sown coriander at Arsi Robe and Kulumsa, and July 10 to 30 sown coriander at Sagure attributed to the fulfillment of optimum soil moisture and thermal conditions from vegetative to reproductive stages (Figs. 3-5). Rainfall and its expected consequent soil moisture had significant impact on the performance of coriander at all locations. Coriander seeded to the sowing dates within or after the highest precedent rainfall events provided the highest fruit and biomass yields. The third decade of July in 2011 and 2012 at Arsi Robe, and the first decade of July in 2011 and 2014 at Sagure fell within the highest precedent rainfall amounts and linked with the highest fruit and biomass yields (Figs. 3-5). The highest amount of precedent rainfall could lead to the retention of optimum amount of water in the soil, which soak the seeds, soften its cover and assist embryonic stem to be emerged very easily. Compared to the other three sowing dates, the third sowing date (July 30) at Arsi Robe and the second sowing date (July 10) at Sagure in both years were linked with the highest rainfall events of the previous 10 days, and the highest fruit and biomass yields. The highest rainfall events of the previous 10 days at Kulumsa occurred in the second decade of August. Though the performance of crop at its initial stages was greater, it faced acute moisture stress at its latter development stage and resulted in inferior fruit and biomass yields. Compared to the remaining two sowing dates, the highest rainfall event at Kulumsa was recorded in the third decade of July, which was associated with superior fruit and biomass yields of coriander. Katar et al. (2016) reported increase in the fruit yield of coriander with increase in precedent rainfall.

The variations in the responses of coriander to sowing time were also accounted for temperature. The superior yield and yield attributes of coriander were found to be linked to the sowing dates, when their maximum temperatures were the lowest. The maximum temperature records of the periods were the lowest in the third decade of July at Arsi Robe, Kulumsa and Sagure (Figs. 3-5), which were associated with the highest fruit and biomass yields. The minimum temperatures at each location were not too low enough to affect the germination of seeds; rather it was modest for coriander. For successful germination, coriander requires low temperature since it favors germination by promoting the breakdown of reserve proteins in seeds to particular amino acids, which are necessary for growth of embryo (Robinson, 1954; Guha *et al.*, 2014). Temperature above optimum value hampers germination of seeds owing to the encouraged activities of several microorganisms such as bacteria and fungi. Activation of microorganisms, in turn, adversely affects the embryo and endosperm of coriander seeds (Naeem et al*.,* 2002; Ali et al., 2015). Generally, winter crops like coriander are vulnerable to high temperature particularly during reproductive stages (Kalra, 2008).

Earlier sowing (June 20) resulted in the fruit yield reductions of 37 and 66% in 2012 and 2011, respectively at Arsi Robe, 45 and 27% in 2014 and 2011, respectively at Kulumsa, and 24 and 40% in 2011 and 2014, respectively at Sagure. The corresponding declines in biomass yield were 60% in 2011 at Arsi Robe, and 36 and 18% in 2011 and 2014, respectively at Sagure (Tables 4-6). Those reductions in yields could be because of the storage of excess soil moisture in the root zone during seeding and the adverse effect of intensive rainfall particularly in August on the leaves and flower of coriander. The relatively older leaves and flowers of coriander sown earlier (June 20 and July 10) at Arsi Robe and Kulumsa, and (June 20) at Sagure fell due to heavy rainfall in August (Figs. 3-5). The premature shed of leaves and flowers reduced the performance of photosynthesis, fruit formation and ultimately the yield of coriander. The July 30 and August 20 sown coriander were not adversely affected due to the intensive rain fell in August as their leaves were still so young enough to recover soon, and the flowers were not yet blossomed.

Delayed sowing (August 20) of coriander also produced inferior fruit and biomass yields. With delay in sowing to August 20, fruit yield reductions of 37% in 2012 at Arsi Robe, 66 and 58% in 2014 and 2011, respectively at Kulumsa, and 26% in 2011 at Sagure were recorded. Similarly, delayed sowing resulted in biomass yield reductions of 40% in 2012 at Arsi Robe, 77 and 72% in 2011 and 2014 at Kulumsa, and 26% in 2011 at Sagure (Tables 4-6). The inferior yields of coriander attributed to the acute scarcities of rainfall in November at all locations (Figs. 3-5). Owing to delayed sowing and its consequential soil moisture stress, coriander had inadequate time to complete its vegetative growth since it entered to the reproductive phase at quicker rates and generally the whole crop-growing period was shortened (Carrubba *et al.*, 2006; Sharangi and Roychowdhury, 2014). Consequently, inferior development of shoots and reduced yield attributes occurred (Tables 4-6), which were the coriander's response to the acute shortage of rainfall and high temperatures that encountered at latter stages in the growing season (Carrubba *et al.*, 2006; Nowak and Szemplinski, 2014). Shortage of rainfall and its resulting soil moisture stress during the growing season brought physiological disorders such as a reduction in transpiration and photosynthesis (Sarker *et al.*, 2005; Carrubba *et al.*, 2006). Besides, reduced vegetative as well as reproductive growth of coriander and their consequent decrease in seed yield could be accounted for the above optimum temperatures. The optimum temperature might have been surpassed for the late sown coriander, and adversely influenced its physiological processes including photosynthesis and respiration (Sharma *et al.*, 2003).

The influences of precipitation and air temperatures on yield and yield components of coriander were reported in the works of Nowak and Szemplinski (2014). Bhadkariya *et al.* (2007) found 30.6 and 76.4% declines in the fruit yield of coriander owing to delay in sowing from March 30 to April 14 and April 29, respectively. Moosavi *et al.* (2012) reported that with delay in sowing, coriander fruit and biomass yields reduced by 76.4 and 74.7%, respectively. Moniruzzaman *et al.* (2015), Carrubba *et al.* (2006) and Zheljazkov *et al.* (2008) also reported that productivity declined as sowing postponed to latest dates.

Though earlier sowing resulted in the tallest plant heights, it could not increase the yields of coriander. The inferior yields attributed to logging of the crop, shed of leaves and flowers during the cropping season in response to heavy rain fell particularly in August. This result is in agreement with Pan *et al.* (2003), Carrubba *et. al.* (2006), Bhadkariya *et al.* (2007), Ghobadi and Gobadi (2010), and Moosavi *et al.* (2012) who reported that earlier sowing of coriander led to the highest plant height. Delay in sowing resulted in stunted growth and finally led to reduced yields of coriander. The significant decrease in plant height because of delay in sowing could be correlated with higher temperatures that the plants experienced at their latter stages. This incidence shortened their growing period and assimilate-building process owing to earlier maturity. Thus, plants could not maintain adequate opportunity for conducting photosynthesis; hence, their height and branch-bearing capacity could be decreased (Moosavi *et al.*, 2012). Sharangi and Roychowdhury (2014) found that with delay in sowing from October to December, plant height of coriander decreased significantly. Moosavi

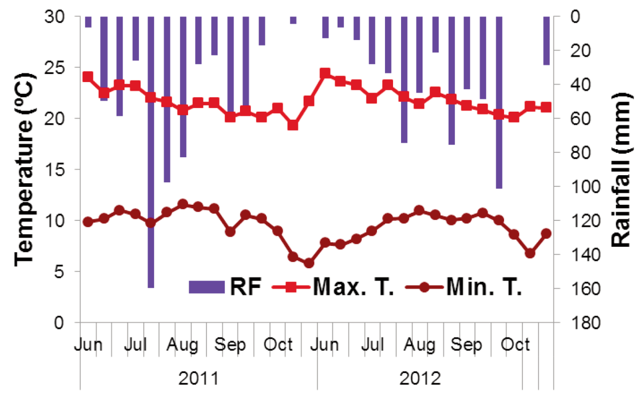

Fig. 3 - Ten-day values of rainfall, maximum and minimum daily air temperature records in Arsi Robe from June to October in 2011 and 2012 cropping seasons.

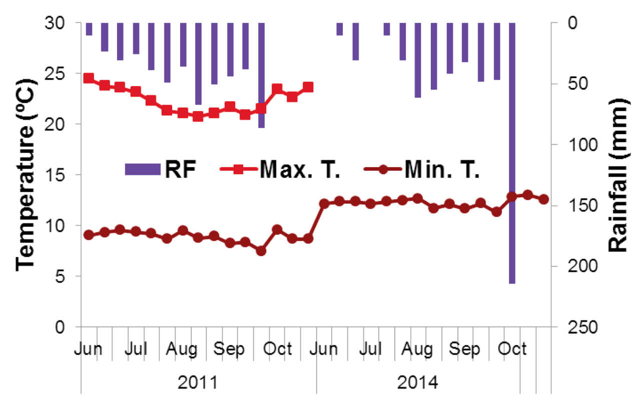

Fig. 4 - Ten-day values of rainfall, maximum and minimum daily air temperature records in Kulumsa from June to October in 2011 and 2014 cropping seasons.

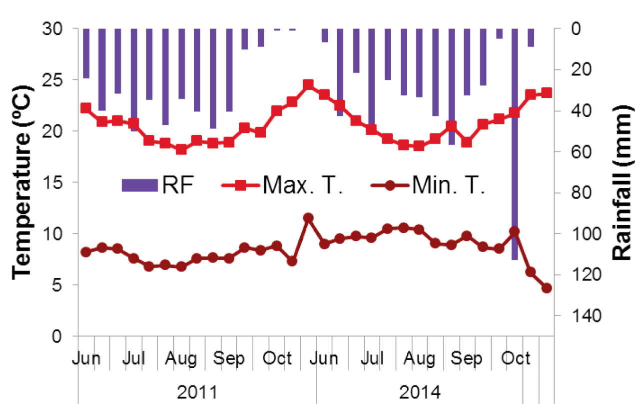

Fig. 5 - Ten-day values of rainfall, maximum and minimum daily air temperature records in Sagure from June to October in 2011 and 2014 cropping seasons.

(2012) also reported significant decrease in plant height with delay in sowing from March 30 to April 29.

The major factors that attributed to the variations in yields of coriander among locations and seasons were related to climate particularly rainfall and soil. In their studies, Rashed and Darwesh (2015) found that microclimate significantly affected sowing dates implied the need for determination optimum site-specific sowing date. Rainfall had contrasting effect at Arsi Robe and Kulumsa in 2011; it was excess at Arsi Robe, but optimum at Kulumsa. Compared to 2011, the rainfall amount and distribution in 2012 at Arsi Robe and 2014 at Kulumsa were optimum; hence, fruit and biomass yields obtained could be superior. These results corroborate the findings of Carrubba *et al.* (2006), who reported a highly significant dependence of coriander yields on precipitation during its growing period with linear correlation coefficient of 0.93. Nowak and Szemplinski (2014) also reported the significant influence of temporal variations on coriander yield and yield attributes.

The rainfall amount and its influence need to be interpreted in relation to the soil types of the study areas. Compared to Arsi Robe and Sagure, where the soils are heavy vertisols, the soil type of Kulumsa is relatively light vertisol. Hence, the occurrence of water logging at Kulumsa particularly during the months with heavy rainfalls was lower as compared to Arsi Robe and Sagure. Coriander gave the highest fruit and biomass yields in areas, where rainfall was modest and the soil was light vertisol. During the cropping season, rainfall was lower at Kulumsa than Sagure and Arsi Robe, and Sagure was lower than Arsi Robe. For example, cumulative rainfall from the first decade of June to the end of the third decade of August at Arsi Robe, Kulumsa and Sagure were 508, 282 and 302 mm, respectively indicating rainfall at Kulumsa was robust for the development of coriander. This further implied that rainfall amount had strong effect on fruit and biomass yields of coriander at the studied sites. As rainfall amount increased, fruit and biomass yields of coriander decreased; hence, fruit and biomass yield obtained from Kulumsa was superior followed by Sagure.

Among the tested seed rates, the lowest, 30 kg ha^{-1}, has been found optimum because under lower seed rate, plants tended to compensate the reduced sowing density by producing new branches and result in optimum fruit and biomass yields (Diederichsen, 1996). Okut and Yidirum (2005) reported that seed rate had no effect on harvest index of coriander while Ghobadi and Ghobadi (2010) observed no significant effect on 1000 fruit weights of coriander. The superior yield and yield attributes in response to the seed rate of 30 kg ha^{-1} signified the need for investigation under further reduced rates. Diederichsen (1996) reported that based on the weight of 1000 fruits, 3 to 20 kg ha^{-1} fruits of coriander could be sufficient for optimum yield.

The results of the current study indicated that sowing date significantly influenced the yield and yield attributes of coriander. However, the effects of seed rate and its interaction with sowing date were not significant on most of the variables measured. The optimum sowing dates that gave the highest fruit and biomass yields of coriander fall on third decade of July at Arsi Robe, and from first-third decades of July at Kulumsa and Sagure. Earliness and delay in sowing resulted in inferior yields. Though coriander did not respond to seed rate in this study, the lowest rate, 30 kg ha^{-1}, was found sufficient to give optimum yield. However, further low seed rate studies need to be conducted. Considering the demand of low input, fruit and biomass yields obtained throughout experimental periods, cultivation of coriander was satisfactory provided the crop was sown at appropriate sowing time. Owing to its economic benefits, soil improvement, nutritional qualities and reproductive roles, wider cultivation of coriander in the southeastern mid-highlands of Ethiopia and other areas with similar agro ecologies is encouraged.

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