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Research Article

Combining ability studies under the different environmental conditions for root yield traits and total alkaloid content in Ashwagandha (*Withania somnifera* L.)

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Abstract
The investigation was carried with 65 genotypes of Ashwagandha in three different environments to get information on combining ability for root yield at harvest, yield attributing traits and total alkaloid content. The analysis of variance indicated that experimental material contained considerable variability, furthermore the expression of both GCA as well as SCA was highly influenced by the environment. Based on the study five parental lines *viz*., L_9, L_5, L_{14}, L_{15} and L_8 along with tester T_3 were reported as good general combiners for root yield and total alkaloid content over the environments. Among the crosses 10 hybrids and 22 hybrids were found useful specific combiner for root yield at harvest and total alkaloid content, respectively on pooled basis due to significant desirable SCA effects across the environments. Hence the above-selected genotypes may be useful for further exploitation in breeding programme of ashwagandha.

Keywords: Ashwagandha, Combining ability, Environments, Root yield, Alkaloid.

INTRODUCTION

India is one of the world's twelve mega diversity hubs, with over 7500 species noted for their aroma, flavour, and therapeutic properties. Ayurveda-"life wisdom" is an Indian traditional medicinal discipline that was formed primarily as a result of our forefathers' vast experience and wisdom and has been practiced for over 5000 years (Aneesh *et al.,* 2009). The international market of herbal products is around $6.2 billion, which is poised to grow to $5 trillion by the year 2050 (Ahmed *et al.,* 2022; Kumar *et al.,* 2020[a]). Ashwagandha (*Withania somnifera* L. Dunal) commonly known as "Winter cherry" (Mozaffarian, 2003) is an important medicinal plant that is a member of the Solanaceae family and contains 48 chromosomes (2n= 48) (Ahmed *et al.,* 2022). It has been popularized as herbal plant after domestication and largely uses not only in Ayurveda as a tonic but also in several different herbal products (Shinde *et al.,* 2014). It also obtains the position of versatile herbal medicine that affects various body-systems such as, nervous, immune, energy production-, endocrine as well as the reproductive system. The plant part mainly used in therapeutic purposes is roots; while, the main curative content of plant is alkaloid, especially the 'withanolides' and 'somniferin' along with some other alkaloids which exists in roots as well as to some extent in leaves and seeds (Dhuri, 2016). The phytochemicals from root extracts have antiviral activity and may be effective in controlling the viral infections (Kumar *et al.,* 2020 [b])

The theory of combining ability proposed by Sprague and Tatum (1942) works as an excellent technique which is used to differentiate good as well as poor combiners, besides it also helps in choice of suitable breeding technique. It provides informative idea in relation to the nature of gene action associated with the targeted traits. The idea of both the combining abilities i.e. general (GCA) as well as specific (SCA) may be better approach for selection, but furthermore environment plays an important role to influence of combining ability and the influence of environment on combing ability has been already reported by several workers (Mahdy *et al.*, 2015); (Machado *et al.*, 2009) So analysis of combining ability over the environments would be more informative for selection of good general and specific combiner over the environments. Matting design of line x tester (Kempthorne, 1957) helps to assess initial examination of breeding material for their use in crossing based on the estimation of the GCA and SCA effects of parents and cross combinations, respectively and also useful in estimating various types of gene actions (Ahmed *et al.,* 2016). Therefore, the present experiment was carried out to obtain information on GCA and SCA effects of parents and hybrids, respectively and the influence of different environmental conditions for root yield attributing traits and total alkaloid content in Ashwagandha.

MATERIALS AND METHODS

The experiment includes a total of 65 genotypes, included fifteen lines *viz*., UWS-301 (L_1), UWS-302 (L_2), UWS-303 (L_3), UWS-304 (L_4), UWS-305 (L_5), UWS-306 (L_6), UWS-307 (L_7), UWS-308 (L_8), UWS-309 (L_9), UWS-310 (L_{10}), UWS-311 (L_{11}), UWS-312 (L_{12}), UWS-313 (L_{13}), UWS-314 (L_{14}), UWS-315 (L_{15}), three testers viz., UWS-10 (T_1), WS-90-146 (T_2), RVA-100 (T_3) and resultant 45 F1's crosses (obtained by line x tester matting design *via* use of hand emasculation and pollination method during 2017-18) along with two checks *viz*., JA-20 and JA-134. The lines were obtained from germplasm maintained at Herbal Park, Maharana Pratap University of Agriculture and Technology, Udaipur; two checks JA-20 & JA-134 along with tester T_3 from Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur, whereas two testers T_1 and T_2 from All India Coordinated Research Project on Medicinal and Aromatic Plants & Betel vine, Udaipur, India.

The total experimental materials were grown in randomized block design with three replications at three different locations *viz*., Instructional Farm, Rajasthan College of Agriculture- Udaipur (E1), Krishi Vigyan Kendra- Chittorgarh (E2) and Agriculture Research Sub-Station- Vallabhnagar (E3) during *Kharif* 2018-19 and the observations were recorded on following characters *viz*., days to 75 per cent maturity (DSM), plant height at harvest (PH), number of secondary branches/ plant (NSB), number of berries/ plant (NB), number of secondary and tertiary roots/ plant (NSTR), root diameter in collar region (RD), root yield at harvest (RY), dry matter content of root (DMC), test weight of seed (TW), harvest index (HI) and total alkaloid content (TAC), (Misra, 1996). The pooled data of all three different locations for the above traits were subjected to statistical analysis for combining ability effect estimation as per model proposed by Kempthorne (1957).

RESULTS AND DISCUSSION

Combining ability investigations are required for evaluating parental lines as prospective parents and measuring gene activity involved in transmission of various traits in order to establish an efficient breeding plan (Sprague and Tatum, 1942). Analysis of combing ability on pooled basis (**Table 1**) was observed to be significant among lines, testers, along with lines x testers in term of all characters except harvest index (owing to testers). The interaction of lines with environments was significant for all the characters except number of secondary branches per plant. Furthermore, the interaction of testers with environments was observed to be significant for all characters except days to 75 per cent maturity and root diameter in collar region. The interactions of lines x testers x environments were also found significant for all traits under study. This indicated that the influence of environment was high on the estimates of GCA and SCA effects for all characters. Similar results were also reported by Sahu (2015) and Dhuri (2016) in Ashwagandha and several other workers in different crops such as Mondal and Hossain (2006) in Potato; Timmapur *et al.* (2008) and Sao and Mehta (2010) in BRINJAL.

On the basis of pooled data, the estimate of negative significant GCA effect for 75 per cent maturity indicated that 4 parental lines L_4, L_{13}, L_{12} and L_6 were found good general combiner for earliness. The line L_{13} showed highest negative significant general combining ability effects (-12.12) in E_1, L_4 (-12.12) in E_2 as well as (-6.31) on pooled basis, while L_6 (-8.09) in E_3 environment. Among the testers, T_1 was found significantly superior for earliness on pooled basis as well as in majority of environments (E_1 and E_2). As per specific combining ability effects disclosed that four hybrids *viz*., L_8 x T_3, L_7 x T_2, L_9 x T_1 and L_{10} x T_3 exhibited significantly negative specific combining ability effects and identified excellent specific combiner for early maturity. For plant height, parental lines *viz.,* L_9, L_5, L_{14}, L_{12} and 5 crosses *viz*., L_5 x T_1, L_6 x T_2, L_{14} x T_1, L_{13} x T_2, L_{15} x T_3; were found significantly superior (**Table 2**). For number of secondary branches per plant, five lines L_{14}, L_5, L_9, L_{15}, L_4 and for the trait *i.e*. number of berries per plant four lines L_{14}, L_9, L_5 and L_1 were identified as good general combiner on pooled basis in positive direction (**Table 3**), while a total of 11 hybrids for number of secondary branches per plant and eight crosses for number of berries per plant were found excellent specific combiner. Similar results were also observed by Vilas *et al.* (2015); Sao and Mehta (2010).

The data on estimates of GCA effects for number of secondary and tertiary roots per plant indicated that five lines *viz*., L_{15}, L_5, L_9, L_1, L_8 exhibited significant values of GCA effects in desirable direction on pooled basis and the line L_{15} showed highest and significantly positive GCA effects (0.59) in E_1, (0.36) in E_2 and (0.40) on pooled basis, while it was showed by line L_5 (0.50) in E_3 environment. Among the testers, T_3 exhibited significant

Table 1. Pooled analysis of variance for combining ability (L x T) in Ashwagandha

S.No.	Source	d.f.	Days to 75 % Maturity	Plant height	Number of secondary branches/ plant	Number of berries/ plant	Number of Secondary and tertiary roots/ plant	Root diameter in collar region	Root yield at harvest	Dry matter content of root	Test weight of seed	Harvest Index	Total alkaloid content
1	Environment	2	6559.05**	534.19**	5.18**	8504.04**	1.38**	23.96**	119.48**	63.01**	0.06**	17.89**	0.01**
2	Rep./Env.	6	56.46	10.37	0.25*	125.80	0.09	1.03	1.15	4.35	0.02	2.33	0.00
3	Genotype	64	407.12**	199.44**	29.42**	9988.22**	3.82**	39.86**	80.61**	128.82**	0.21**	19.20**	0.03**
	Line	14	542.95**	333.87**	31.66**	19139.64**	2.01**	75.15**	132.77**	199.89**	0.18**	12.72**	0.06**
	Tester	2	737.05**	1247.54**	31.59**	24472.28**	5.52**	38.40**	143.11**	172.56**	0.29**	2.90	0.12**
	L x T	28	320.67**	30.81**	4.78**	1445.93**	0.83**	13.20**	29.11**	60.26**	0.13**	4.20**	0.01**
4	L x E	28	463.47**	41.96**	0.15	405.46**	0.27**	3.52**	5.85**	34.33**	0.03**	8.46**	0.00**
	T x E	4	92.29	22.00**	0.82**	373.59**	0.36**	1.41	9.55**	57.92**	0.03*	6.28**	0.00**
	L x T x E	56	209.27**	25.55**	0.55**	545.23**	0.22**	2.07**	5.96**	31.59**	0.04**	5.08**	0.00**
5	Pooled Error	384	53.15	7.18	0.11	107.52	0.06	0.72	1.06	3.62	0.01	1.48	0.00

(*, ** Significant at 5% and 1%, respectively)

GCA effects in positive direction on pooled basis in all the three environments. Ten hybrids were found significantly superior. Out of the 15, five lines *viz.,* L_5, L_9, L_{14}, L_8 and L_{15} were observed to be significantly superior for root diameter in collar region. Among the above lines, line L_5 showed maximum positive and significant GCA effects on pooled basis (3.16) in most of the environments *viz.,* (3.48) in E_1 and (3.21) in E_3, while line L_9 (3.25) in E_2 environment, (**Table 4**).

Among the lines, seven lines *viz.,* L_5, L_{15}, L_9, L_{14}, L_1, L_8 and L_{12} were reported superior with significant value of GCA effect for root yield at harvest (**Table 5**). The line L_5 exhibited highest positive and significant GCA effects (3.77) in E_1, (3.94) in E_2 and (3.40) on pooled basis environments, whereas it was showed in E_3 by line L_{15}. The GCA for testers ranged from -1.08 (T_1) to 0.97 (T_3) on pooled basis. Among the testers, T_3 was found significantly superior for root yield at harvest. Among the hybrids, 10 hybrids werefound significantly superior, out of which following five hybrids *viz*., L_8 x T_1 (3.54), L_6 x T_2 (2.84), L_5 x T_1 (2.44), L_4 x T_3 (1.91) and L_7 x T_2 (1.88) were identified as good specific combiner over the environments. Six lines *viz.,* L_9, L_{14}, L_5, L_{10}, L_7 and L_4 were found to be good general combiners for dry matter content of root, out of which the line i.e. L_9 depicted highest positive and significant GCA effects (4.61) in E_1, (6.14) in E_2 and (4.84) on pooled basis environment, while the tester T_3 was significantly superior on pooled basis as well as all the three environments. Among the hybrids, 12 hybrids were found significantly superior, out of which following five hybrids *viz*., L_8 x T_3 (4.56) followed by L_5 x T_2 (3.29), L_{15} x T_2 (3.25), L_6 x T_3 (2.56) and L_{10} x T_1 (2.43) exhibited highest positive and significant SCA effects over the environments and found excellent specific combiner.

The five parental lines L_5, L_{14}, L_9, L_{11}, L_{12} were observed to be good general combiners for test weight, whereas four lines L_9, L_{14}, L_8 and L_5 were good for harvest index over the environments. Furthermore, estimates for SCA effects indicated that among the crosses, 13 hybrids for test weight and the only one cross *i.e*. L_{14} x T_3 with regard to harvest index were identified as significantly superior (**Table 6**). In case of medicinal crop, such as ashwagandha, alkaloid is the ultimate as well as most important economic end product. The pooled data (**Table 7**) on GCA effects for alkaloid content, among lines ranged from -0.06 (L_2) to 0.09 (L_9), whereas out of 15 lines, 8 lines *viz*., L_9, L_5, L_{14}, L_{15}, L_7, L_8, L_{13} and L_{10} were found significantly superior for total alkaloid content. The line L_9 was observed to be best general combiner not only in pooled basis but also in individual environments *i.e*. E_1 and E_2. Estimates of specific combining ability effects among crosses ranged from -0.05 (L_7 x T_2) to 0.05 (L_3 x T_1) on pooled basis. Among the hybrids, 22 hybrids were found significantly superior, out of which the hybrids *viz*., L_3 x T_1 (0.05) followed by L_{10} x T_2 and L_{11} x T_2 (0.04); L_7 x T_1, L_{12} x T_1, L_1 x T_3, L_7 x T_3 and L_{13} x T_3 (0.03) exhibited

Table 2. GCA and SCA effects for days to 75 per cent maturity and plant height

S.No.	Genotype	Days to 75 per cent maturity				Plant height			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
1	T_1	-3.60**	-3.71**	-0.79	-2.70**	-3.43**	-3.49**	-2.64**	-3.19**
2	T_2	1.77	1.84	0.26	1.29	1.09*	0.17	-0.31	0.32
3	T_3	1.83	1.87	0.53	1.41	2.34**	3.32**	2.95**	2.87**
4	L_1	-2.44	10.87**	6.97**	5.13**	-0.90	2.01*	1.60	0.90
5	L_2	0.49	2.91	10.84**	4.75**	-0.43	-0.31	-4.86**	-1.87**
6	L_3	8.34**	-7.75**	3.45	1.35	1.27	-3.94**	1.74	-0.31
7	L_4	-0.33	-12.12**	-6.48*	-6.31**	-1.70	-1.46	-3.08**	-2.08**
8	L_5	15.47**	7.73**	0.54	7.91**	6.47**	2.70**	5.46**	4.87**
9	L_6	-9.24**	1.98	-8.09**	-5.12**	-6.50**	-6.28**	-6.58**	-6.46**
10	L_7	5.00*	-1.40	-7.01**	-1.14	3.18**	-1.41	-0.19	0.53
11	L_8	-0.17	6.89**	-1.81	1.64	-2.33*	2.32**	2.63**	0.87
12	L_9	0.26	-3.00	6.88**	1.38	5.06**	11.45**	4.69**	7.07**
13	L_{10}	-2.97	3.55	-5.12*	-1.51	-7.66**	-4.86**	-4.19**	-5.57**
14	L_{11}	-10.93**	0.38	4.47	-2.03	-1.23	-2.68**	-1.62	-1.84**
15	L_{12}	-8.75**	-3.26	-4.31	-5.44**	2.91**	0.12	2.39*	1.81**
16	L_{13}	-12.12**	-6.14*	0.82	-5.81**	0.14	-2.68**	0.19	-0.78
17	L_{14}	22.02**	-3.85	-2.72	5.15**	1.89	5.63**	1.78	3.10**
18	L_{15}	-4.63	3.19	1.58	0.05	-0.19	-0.61	0.05	-0.25
19	L_1 x T_1	-3.06	1.91	-3.91	-1.69	-1.37	2.15	0.01	0.27
20	L_2 x T_1	-0.31	-3.06	-3.18	-2.18	0.09	0.25	2.35	0.90
21	L_3 x T_1	7.98	2.03	-0.89	3.04	3.13	1.67	-0.94	1.29
22	L_4 x T_1	-2.03	6.15	4.73	2.95	0.00	-1.35	3.26	0.64
23	L_5 x T_1	6.86	-7.72	3.73	0.96	1.52	4.88**	2.59	3.00**
24	L_6 x T_1	-2.70	0.78	-4.60	-2.17	-2.62	-1.33	-3.38	-2.44*
25	L_7 x T_1	4.75	-2.64	7.37	3.16	0.89	1.35	-1.38	0.29
26	L_8 x T_1	4.46	14.16**	9.68	9.43**	1.64	1.65	-1.17	0.70
27	L_9 x T_1	-8.94	1.19	-19.81**	-9.19**	-0.29	1.41	-0.60	0.17
28	L_{10} x T_1	-9.65*	-9.96	7.08	-4.18	-1.24	-5.66**	1.24	-1.88
29	L_{11} x T_1	4.32	-1.49	-0.35	0.83	-2.16	-2.63	2.64	-0.72
30	L_{12} x T_1	8.35	-17.86**	0.18	-3.11	4.20*	3.42	-3.88*	1.25
31	L_{13} x T_1	2.87	9.69	3.69	5.42	-4.85*	-3.18	-1.21	-3.08**
32	L_{14} x T_1	-5.11	6.48	-6.79	-1.81	2.16	4.68**	1.33	2.72*
33	L_{15} x T_1	-7.82	0.33	3.08	-1.47	-1.11	-7.31**	-0.87	-3.10**
34	L_1 x T_2	5.01	6.46	4.85	5.44	1.43	-0.91	-3.28	-0.92
35	L_2 x T_2	7.72	2.72	4.89	5.11	0.56	1.57	-1.63	0.17
36	L_3 x T_2	-1.39	-7.21	-1.07	-3.22	-3.05	-1.30	1.96	-0.80
37	L_4 x T_2	-4.04	-7.29	-0.00	-3.78	0.38	2.32	-5.38**	-0.89
38	L_5 x T_2	0.38	-2.76	6.00	1.21	-0.64	-6.37**	-1.19	-2.73*
39	L_6 x T_2	-1.78	1.87	-6.53	-2.15	3.07	1.45	4.29*	2.94**
40	L_7 x T_2	-2.07	-9.81	-16.32**	-9.40**	-2.28	-1.65	3.33	-0.20
41	L_8 x T_2	-1.52	-3.60	9.84	1.57	-1.17	1.23	-1.94	-0.63
42	L_9 x T_2	8.39	-7.01	6.30	2.56	2.11	1.09	0.45	1.22
43	L_{10} x T_2	11.41*	12.83*	10.84*	11.69**	2.08	1.29	0.61	1.33
44	L_{11} x T_2	-8.55	1.31	1.40	-1.95	-1.01	-0.33	2.70	0.45
45	L_{12} x T_2	-5.81	17.42**	-2.41	3.07	-0.23	-3.57*	1.72	-0.69
46	L_{13} x T_2	-2.28	-5.84	-6.80	-4.97	2.09	3.46	1.37	2.31*
47	L_{14} x T_2	3.89	-6.72	-1.69	-1.51	-2.73	-1.76	-2.73	-2.40*
48	L_{15} x T_2	-9.36	7.63	-9.30	-3.68	-0.63	3.45	-0.29	0.84
49	L_1 x T_3	-1.95	-8.37	-0.94	-3.75	-0.06	-1.25	3.27	0.65
50	L_2 x T_3	-7.41	0.34	-1.71	-2.93	-0.66	-1.82	-0.73	-1.07

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S.No.	Genotype	Days to 75 per cent maturity				Plant height			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
51	L_3 x T_3	-6.60	5.18	1.95	0.18	-0.08	-0.37	-1.03	-0.49
52	L_4 x T_3	6.07	1.14	-4.73	0.83	-0.38	-0.97	2.12	0.26
53	L_5 x T_3	-7.24	10.47*	-9.73	-2.17	-0.88	1.48	-1.40	-0.27
54	L_6 x T_3	4.47	-2.65	11.13*	4.32	-0.45	-0.12	-0.91	-0.50
55	L_7 x T_3	-2.68	12.46*	8.95	6.24*	1.39	0.30	-1.95	-0.09
56	L_8 x T_3	-2.95	-10.56*	-19.52**	-11.01**	-0.46	-2.88	3.11	-0.07
57	L_9 x T_3	0.55	5.81	13.51**	6.63*	-1.83	-2.51	0.15	-1.39
58	L_{10} x T_3	-1.77	-2.87	-17.91**	-7.52*	-0.84	4.37*	-1.85	0.56
59	L_{11} x T_3	4.23	0.18	-1.05	1.12	3.16	2.95	-5.33**	0.26
60	L_{12} x T_3	-2.54	0.44	2.22	0.04	-3.97*	0.14	2.16	-0.56
61	L_{13} x T_3	-0.60	-3.85	3.11	-0.45	2.76	-0.29	-0.16	0.77
62	L_{14} x T_3	1.22	0.24	8.48	3.31	0.56	-2.91	1.39	-0.32
63	L_{15} x T_3	17.18**	-7.96	6.23	5.15	1.74	3.86*	1.16	2.25*
	Standard error								
	Ti	1.20	1.30	1.27	0.72	0.48	0.44	0.46	0.27
	Lj	2.40	2.59	2.53	1.45	0.97	0.88	0.92	0.53
	Sij	4.81	5.18	5.06	2.90	1.93	1.76	1.83	1.07
	Ti-j	1.47	1.59	1.55	0.89	0.59	0.54	0.56	0.33
	Li-j	3.29	3.55	3.47	1.98	1.32	1.21	1.26	0.73
	Ti-Lj	2.55	2.75	2.69	1.54	1.03	0.93	0.97	0.56
	STi-Tj	5.89	6.35	6.20	3.55	2.37	2.16	2.25	1.30
	SiL-Jl	6.58	7.09	6.93	3.97	2.65	2.41	2.51	1.46
	Sij-kl	6.74	7.27	7.11	4.07	2.71	2.47	2.57	1.49

*, ** Significant at 5% and 1%, respectively

Table 3. GCA and SCA effects for number of secondary branches per plant and number of berries per plant

S.No.	Genotype	Number of secondary branches per plant				Number of berries per plant			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
1	T_1	-0.60**	-0.60**	-0.47**	-0.56**	-16.19**	-13.19**	-9.85**	-13.07**
2	T_2	0.19**	0.29**	0.36**	0.28**	1.17	-0.06	-3.36	-0.75
3	T_3	0.41**	0.31**	0.11	0.28**	15.02**	13.25**	13.20**	13.82**
4	L_1	0.28*	0.11	0.00	0.13	4.93	9.04*	1.97	5.31*
5	L_2	-0.54**	-0.81**	-0.64**	-0.66**	-19.08**	-6.26	-8.77*	-11.37**
6	L_3	-0.64**	-0.47**	-0.73**	-0.61**	-25.29**	-8.51*	-15.77**	-16.52**
7	L_4	0.09	0.16	0.18	0.14*	-8.54*	8.45*	-3.78	-1.29
8	L_5	1.53**	1.64**	1.83**	1.67**	41.99**	47.92**	40.75**	43.55**
9	L_6	-0.75**	-0.80**	-0.89**	-0.81**	-21.85**	-14.30**	-14.24**	-16.79**
10	L_7	-0.45**	-0.58**	-0.31**	-0.44**	-15.64**	-19.89**	-16.30**	-17.28**
11	L_8	0.01	-0.05	-0.22	-0.09	-11.55**	-20.25**	-2.49	-11.43**
12	L_9	1.35**	1.64**	1.58**	1.52**	52.38**	42.39**	38.57**	44.45**
13	L_{10}	-1.02**	-1.13**	-0.93**	-1.03**	-25.05**	-35.62**	-29.47**	-30.05**
14	L_{11}	-0.96**	-0.85**	-0.82**	-0.88**	-17.91**	-28.81**	-23.03**	-23.25**
15	L_{12}	-0.42**	-0.55**	-0.53**	-0.50**	-2.64	-0.92	12.03**	2.82
16	L_{13}	-1.13**	-1.11**	-1.04**	-1.10**	-16.89**	-33.00**	-22.91**	-24.27**
17	L_{14}	2.70**	2.46**	2.37**	2.51**	57.04**	56.74**	46.70**	53.49**
18	L_{15}	-0.05	0.35**	0.15	0.15*	8.11*	3.00	-3.26	2.62
19	L_1 x T_1	0.40	0.00	-0.53*	-0.04	-5.44	-23.07**	1.84	-8.89*
20	L_2 x T_1	-0.06	0.27	-0.19	0.01	-9.56	-8.28	18.61**	0.26
21	L_3 x T_1	0.56*	0.64**	0.92**	0.70**	29.48**	6.61	33.01**	23.03**
22	L_4 x T_1	-0.90**	-1.29**	-1.17**	-1.12**	-15.09*	-29.26**	-25.39**	-23.25**
23	L_5 x T_1	0.47*	0.07	0.13	0.23	14.20	-4.54	11.89	7.18
24	L_6 x T_1	-0.56*	-0.55*	-0.30	-0.47**	-1.07	-9.83	-10.32	-7.07

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S.No.	Genotype	Number of secondary branches per plant				Number of berries per plant			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
25	$L_7 \times T_1$	-0.20	0.36	0.40	0.19	-6.45	17.83*	-7.68	1.23
26	$L_8 \times T_1$	-0.03	-0.42	-0.43	-0.29*	-16.92*	27.90**	-8.80	0.73
27	$L_9 \times T_1$	1.61**	1.29**	0.99**	1.30**	5.63	9.78	-3.90	3.84
28	$L_{10} \times T_1$	0.63**	1.08**	0.04	0.58**	17.92*	-5.64	1.35	4.54
29	$L_{11} \times T_1$	0.03	0.31	-0.02	0.11	0.22	-3.45	6.67	1.15
30	$L_{12} \times T_1$	0.15	0.30	0.51*	0.32*	11.08	24.68**	-10.63	8.38*
31	$L_{13} \times T_1$	-0.20	-0.16	0.04	-0.11	-4.83	4.99	19.54**	6.57
32	$L_{14} \times T_1$	-0.03	-0.59**	-0.19	-0.27*	-7.69	-4.27	-19.10**	-10.36*
33	$L_{15} \times T_1$	-1.88**	-1.30**	-0.21	-1.13**	-11.47	-3.46	-7.08	-7.34
34	$L_1 \times T_2$	-1.00**	-0.30	-0.38	-0.56**	-9.38	11.99	-6.74	-1.37
35	$L_2 \times T_2$	-0.18	-0.44	0.26	-0.12	15.67*	-5.34	-5.48	1.62
36	$L_3 \times T_2$	-0.39	0.08	-0.28	-0.20	-7.47	1.89	-15.15*	-6.91
37	$L_4 \times T_2$	-0.53*	-0.10	-0.21	-0.28*	-5.55	-9.90	-1.93	-5.79
38	$L_5 \times T_2$	0.70**	0.73**	0.35	0.59**	-23.57**	-9.68	-17.89*	-17.05**
39	$L_6 \times T_2$	0.14	-0.31	0.02	-0.05	-12.27	8.37	3.81	-0.03
40	$L_7 \times T_2$	-0.26	-0.56*	-0.35	-0.39**	-4.04	-8.82	-8.95	-7.27
41	$L_8 \times T_2$	0.58*	0.97**	-0.28	0.42**	20.44**	-0.27	15.65*	11.94**
42	$L_9 \times T_2$	-0.93**	-0.82**	-0.45	-0.73**	-5.31	-5.11	-8.07	-6.16
43	$L_{10} \times T_2$	-0.21	-0.46*	0.10	-0.19	3.04	-1.72	19.33**	6.89
44	$L_{11} \times T_2$	-0.45	-0.08	-0.09	-0.21	-5.20	-8.59	4.28	-3.17
45	$L_{12} \times T_2$	-0.38	-0.41	-0.44	-0.41**	5.59	-13.76	3.52	-1.55
46	$L_{13} \times T_2$	0.29	-0.52*	0.17	-0.02	9.05	12.71	-5.71	5.35
47	$L_{14} \times T_2$	0.32	0.58*	0.59*	0.50**	7.21	3.64	15.63*	8.82*
48	$L_{15} \times T_2$	2.30**	1.63**	0.98**	1.63**	11.78	24.59**	7.68	14.69**
49	$L_1 \times T_3$	0.61**	0.30	0.91**	0.60**	14.82*	11.08	4.90	10.26*
50	$L_2 \times T_3$	0.24	0.17	-0.07	0.11	-6.11	13.62	-13.14	-1.88
51	$L_3 \times T_3$	-0.16	-0.71**	-0.64**	-0.51**	-22.01**	-8.50	-17.86*	-16.12**
52	$L_4 \times T_3$	1.43**	1.38**	1.38**	1.40**	20.64**	39.16**	27.32**	29.04**
53	$L_5 \times T_3$	-1.17**	-0.80**	-0.49*	-0.82**	9.37	14.22*	6.00	9.86*
54	$L_6 \times T_3$	0.42	0.87**	0.28	0.52**	13.35	1.45	6.51	7.10
55	$L_7 \times T_3$	0.46	0.20	-0.05	0.20	10.49	-9.01	16.64*	6.04
56	$L_8 \times T_3$	-0.55*	-0.55*	0.70**	-0.13	-3.52	-27.62**	-6.86	-12.67**
57	$L_9 \times T_3$	-0.68**	-0.47*	-0.55*	-0.57**	-0.33	-4.67	11.97	2.32
58	$L_{10} \times T_3$	-0.42	-0.62**	-0.14	-0.40**	-20.96**	7.36	-20.68**	-11.43**
59	$L_{11} \times T_3$	0.41	-0.22	0.11	0.10	4.98	12.03	-10.95	2.02
60	$L_{12} \times T_3$	0.23	0.10	-0.06	0.09	-16.66*	-10.92	7.11	-6.82
61	$L_{13} \times T_3$	-0.10	0.68**	-0.21	0.12	-4.22	-17.70*	-13.83	-11.92**
62	$L_{14} \times T_3$	-0.28	0.01	-0.40	-0.23	0.49	0.64	3.47	1.53
63	$L_{15} \times T_3$	-0.42	-0.32	-0.77**	-0.50**	-0.32	-21.13**	-0.60	-7.35
	Standard error								
	Ti	0.06	0.06	0.06	0.03	1.80	1.79	1.76	1.03
	Lj	0.12	0.11	0.11	0.07	3.60	3.58	3.53	2.06
	Sij	0.23	0.23	0.23	0.13	7.21	7.16	7.05	4.12
	Ti-j	0.07	0.07	0.07	0.04	2.21	2.19	2.16	1.26
	Li-j	0.16	0.15	0.16	0.09	4.93	4.90	4.83	2.82
	Ti-Lj	0.12	0.12	0.12	0.07	3.82	3.80	3.74	2.19
	STi-Tj	0.28	0.28	0.28	0.16	8.83	8.77	8.64	5.05
	SiL-jL	0.32	0.31	0.31	0.18	9.87	9.80	9.66	5.64
	Sij-kl	0.32	0.32	0.32	0.19	10.11	10.05	9.89	5.78

*, ** Significant at 5% and 1%, respectively

Table 4. GCA and SCA effects for number of secondary and tertiary roots per plant and root diameter in collar region

S.No.	Genotype	No. of secondary and tertiary roots per plant				Root diameter in collar region			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
1	T_1	-0.05	-0.17**	-0.12**	-0.11**	-0.30	-0.65**	-0.51**	-0.49**
2	T_2	-0.23**	-0.07	-0.06	-0.12**	-0.08	-0.08	-0.09	-0.08
3	T_3	0.29**	0.24**	0.18**	0.23**	0.38*	0.73**	0.60**	0.57**
4	L_1	0.15	0.25**	0.43**	0.28**	0.90**	-0.51	-0.88**	-0.16
5	L_2	-0.23**	-0.27**	0.16	-0.11*	-0.02	-0.99**	-1.11**	-0.71**
6	L_3	-0.16	-0.30**	-0.19*	-0.22**	-1.54**	-2.40**	-2.10**	-2.01**
7	L_4	-0.37**	-0.45**	-0.13	-0.32**	-1.45**	-1.50**	-0.75**	-1.23**
8	L_5	0.45**	0.24**	0.50**	0.40**	3.48**	2.78**	3.21**	3.16**
9	L_6	-0.10	0.30**	-0.22*	-0.01	0.02	-1.46**	-0.72**	-0.72**
10	L_7	0.22*	0.08	-0.18*	0.04	-1.62**	-1.63**	-1.70**	-1.65**
11	L_8	0.26**	0.15	0.06	0.16**	1.00**	1.84**	1.34**	1.40**
12	L_9	0.38**	0.17*	0.33**	0.30**	1.83**	3.25**	2.65**	2.57**
13	L_{10}	-0.76**	-0.18*	-0.42**	-0.45**	-1.70**	-1.98**	-0.52*	-1.40**
14	L_{11}	-0.43**	-0.23**	-0.34**	-0.33**	-0.95**	-1.21**	-1.32**	-1.16**
15	L_{12}	0.10	0.10	-0.08	0.04	-0.98**	0.29	-0.51*	-0.40*
16	L_{13}	0.03	0.07	0.15	0.08	-1.58**	0.13	-1.30**	-0.92**
17	L_{14}	-0.15	-0.27**	-0.31**	-0.24**	2.61**	2.06**	2.82**	2.49**
18	L_{15}	0.59**	0.36**	0.24**	0.40**	0.00	1.34**	0.90**	0.75**
19	$L_1 \times T_1$	0.06	0.22	-0.28	0.00	-1.16	-1.61**	-1.14*	-1.30**
20	$L_2 \times T_1$	0.39*	0.45**	0.82**	0.55**	-1.90**	-0.93	-0.83	-1.22**
21	$L_3 \times T_1$	0.19	-0.15	-0.23	-0.06	-0.78	0.39	0.40	0.00
22	$L_4 \times T_1$	0.29	-0.08	-0.33	-0.04	-0.48	-0.87	-0.69	-0.68*
23	$L_5 \times T_1$	-0.34*	-0.12	0.11	-0.12	1.78**	1.77**	0.74	1.43**
24	$L_6 \times T_1$	-0.27	-0.69**	-0.37*	-0.44**	-1.46*	-1.20*	-0.87	-1.18**
25	$L_7 \times T_1$	-0.67**	-0.46**	-0.21	-0.44**	0.43	0.19	0.84	0.49
26	$L_8 \times T_1$	0.48**	0.49**	0.48**	0.48**	2.35**	1.76**	2.29**	2.13**
27	$L_9 \times T_1$	-0.26	0.10	0.29	0.04	1.50*	0.38	-0.24	0.55
28	$L_{10} \times T_1$	0.27	-0.42**	-0.43*	-0.19*	0.54	0.60	-0.29	0.29
29	$L_{11} \times T_1$	-0.08	0.54**	0.23	0.23*	0.23	0.23	1.30*	0.59
30	$L_{12} \times T_1$	0.12	0.11	0.08	0.10	1.19	0.19	-0.26	0.37
31	$L_{13} \times T_1$	-0.51**	-0.38*	-0.43*	-0.44**	-1.12	-0.59	-0.14	-0.62
32	$L_{14} \times T_1$	0.01	0.26	0.19	0.15	-1.29	-0.71	-1.31*	-1.11**
33	$L_{15} \times T_1$	0.31	0.14	0.08	0.18	0.17	0.38	0.21	0.25
34	$L_1 \times T_2$	-0.17	-0.16	0.15	-0.06	-1.15	-0.23	-0.53	-0.64
35	$L_2 \times T_2$	-0.42*	-0.07	-0.25	-0.25*	0.40	0.79	0.42	0.54
36	$L_3 \times T_2$	0.12	-0.07	-0.13	-0.03	0.52	-0.22	-0.40	-0.04
37	$L_4 \times T_2$	0.05	0.14	-0.09	0.03	-0.79	-1.05	-0.14	-0.66
38	$L_5 \times T_2$	0.30	-0.01	-0.07	0.07	-0.92	-1.37*	-0.81	-1.04**
39	$L_6 \times T_2$	0.34	0.26	0.14	0.25*	1.13	0.69	1.11*	0.98**
40	$L_7 \times T_2$	0.09	0.17	0.42*	0.22*	0.86	0.12	0.16	0.38
41	$L_8 \times T_2$	-0.22	0.01	-0.19	-0.13	-0.62	-0.08	1.31*	0.20
42	$L_9 \times T_2$	0.32	-0.00	-0.08	0.08	0.17	-0.17	1.41**	0.47
43	$L_{10} \times T_2$	-0.17	0.30	0.36*	0.16	-0.70	-0.71	-2.38**	-1.27**
44	$L_{11} \times T_2$	0.35*	-0.36*	0.05	0.02	-1.53*	-0.06	-1.41**	-1.00**
45	$L_{12} \times T_2$	-0.49**	-0.57**	-0.61**	-0.56**	-0.06	0.72	0.98	0.55
46	$L_{13} \times T_2$	0.07	0.33*	0.25	0.22*	0.68	0.36	-0.83	0.07
47	$L_{14} \times T_2$	-0.04	-0.04	0.14	0.02	1.92**	0.92	2.84**	1.89**
48	$L_{15} \times T_2$	-0.13	0.07	-0.08	-0.05	0.10	0.30	-1.71**	-0.44
49	$L_1 \times T_3$	0.11	-0.07	0.14	0.06	2.31**	1.84**	1.68**	1.94**
50	$L_2 \times T_3$	0.03	-0.38*	-0.57**	-0.31**	1.50*	0.14	0.42	0.68*

S.No.	Genotype	No. of secondary and tertiary roots per plant				Root diameter in collar region			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
51	L_3 x T_3	-0.31	0.22	0.36*	0.09	0.26	-0.16	0.01	0.03
52	L_4 x T_3	-0.34	-0.07	0.43*	0.01	1.27	1.92**	0.83	1.34**
53	L_5 x T_3	0.05	0.13	-0.04	0.05	-0.86	-0.40	0.07	-0.40
54	L_6 x T_3	-0.07	0.42**	0.23	0.19*	0.33	0.51	-0.24	0.20
55	L_7 x T_3	0.58**	0.29	-0.21	0.22*	-1.30	-0.31	-1.01	-0.87*
56	L_8 x T_3	-0.26	-0.49**	-0.29	-0.35**	-1.73*	-1.68**	-3.60**	-2.34**
57	L_9 x T_3	-0.07	-0.09	-0.21	-0.12	-1.67*	-0.21	-1.17*	-1.01**
58	L_{10} x T_3	-0.10	0.12	0.07	0.03	0.16	0.11	2.66**	0.98**
59	L_{11} x T_3	-0.27	-0.18	-0.28	-0.24*	1.30	-0.18	0.11	0.41
60	L_{12} x T_3	0.36*	0.47**	0.53**	0.45**	-1.13	-0.91	-0.72	-0.92**
61	L_{13} x T_3	0.44*	0.05	0.18	0.22*	0.44	0.23	0.97	0.55
62	L_{14} x T_3	0.03	-0.21	-0.33	-0.17	-0.63	-0.21	-1.53**	-0.79*
63	L_{15} x T_3	-0.18	-0.21	-0.00	-0.13	-0.27	-0.68	1.51**	0.19
	Standard error								
	Ti	0.04	0.04	0.04	0.02	0.17	0.14	0.13	0.08
	Lj	0.09	0.08	0.09	0.05	0.33	0.28	0.26	0.17
	Sij	0.17	0.16	0.18	0.10	0.66	0.57	0.51	0.34
	Ti-j	0.05	0.05	0.05	0.03	0.20	0.17	0.16	0.10
	Li-j	0.12	0.11	0.12	0.07	0.45	0.39	0.35	0.23
	Ti-Lj	0.09	0.08	0.09	0.05	0.35	0.30	0.27	0.18
	STi-Tj	0.21	0.20	0.21	0.12	0.81	0.69	0.63	0.41
	SiL-jL	0.24	0.22	0.24	0.13	0.91	0.77	0.70	0.46
	Sij-kl	0.24	0.22	0.25	0.14	0.93	0.79	0.72	0.47

*, ** Significant at 5% and 1%, respectively

Table 5. GCA and SCA effects for root yield at harvest and dry matter content of root

S.No.	Genotype	Root yield at harvest				Dry matter content of root			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
1	T_1	-1.53**	-0.72**	-1.00**	-1.08**	0.27	-1.20**	-1.93**	-0.96**
2	T_2	0.33	-0.35	0.37*	0.12	-1.02**	0.47	-0.32	-0.29
3	T_3	1.20**	1.06**	0.63**	0.97**	0.75*	0.74*	2.26**	1.25**
4	L_1	2.88**	0.95**	0.44	1.42**	-3.89**	0.54	1.56*	-0.60
5	L_2	0.08	-1.11**	0.12	-0.31	-3.34**	-1.22	-3.48**	-2.68**
6	L_3	-2.35**	-2.80**	-2.76**	-2.64**	0.19	1.38*	-0.28	0.43
7	L_4	-3.14**	-1.80**	-1.82**	-2.25**	4.15**	-0.97	1.09	1.42**
8	L_5	3.77**	3.94**	2.50**	3.40**	3.90**	1.85**	3.45**	3.06**
9	L_6	-1.05**	-1.50**	-1.18**	-1.24**	-1.95**	0.04	-2.01**	-1.31**
10	L_7	-2.10**	-3.77**	-2.93**	-2.93**	1.43*	1.31	2.62**	1.78**
11	L_8	0.81*	1.11**	1.32**	1.08**	-0.58	-1.42*	-1.88**	-1.29**
12	L_9	3.14**	1.80**	2.69**	2.54**	4.61**	6.14**	3.76**	4.84**
13	L_{10}	-3.53**	-3.56**	-2.72**	-3.27**	1.61*	5.67**	-0.78	2.17**
14	L_{11}	-1.07**	-2.21**	-0.14	-1.14**	-2.71**	-3.85**	-6.68**	-4.41**
15	L_{12}	0.15	2.03**	0.48	0.89**	-0.62	-2.78**	-1.74**	-1.71**
16	L_{13}	-0.74*	0.41	-1.09**	-0.47*	-4.79**	-5.09**	0.99	-2.96**
17	L_{14}	1.15**	3.03**	2.36**	2.18**	3.79**	2.36**	4.71**	3.62**
18	L_{15}	2.01**	3.50**	2.74**	2.75**	-1.81**	-3.96**	-1.32*	-2.36**
19	L_1 x T_1	-1.44*	-2.64**	-1.72*	-1.93**	-3.17*	2.71	1.73	0.42
20	L_2 x T_1	-2.64**	-0.51	-1.14	-1.43**	3.08*	0.88	1.12	1.69*
21	L_3 x T_1	0.98	-0.66	-0.41	-0.03	-1.11	1.98	4.21**	1.69*
22	L_4 x T_1	1.09	0.03	-1.56*	-0.15	-1.73	0.69	1.40	0.12
23	L_5 x T_1	2.20**	2.00**	3.12**	2.44**	-3.54**	-2.73	-3.21*	-3.16**

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S.No.	Genotype	Root yield at harvest				Dry matter content of root			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
24	L_6 x T_1	-3.10**	-1.27	-1.50*	-1.96**	5.90**	-1.51	0.16	1.52*
25	L_7 x T_1	-0.28	-0.54	-0.75	-0.52	2.43	3.17*	0.43	2.01**
26	L_8 x T_1	1.84*	5.07**	3.71**	3.54**	-0.49	-7.28**	-3.36*	-3.71**
27	L_9 x T_1	0.76	-1.68*	0.71	-0.07	-1.90	3.18*	-1.80	-0.17
28	L_{10} x T_1	-0.26	1.24	-1.25	-0.09	3.38**	-0.86	4.77**	2.43**
29	L_{11} x T_1	2.32**	1.77*	0.03	1.37**	-5.34**	-3.40*	-0.72	-3.15**
30	L_{12} x T_1	-1.02	-0.78	2.01**	0.07	5.39**	1.35	-2.42	1.44
31	L_{13} x T_1	-1.35	-2.59**	-1.33	-1.76**	-0.50	7.07**	-0.95	1.87*
32	L_{14} x T_1	-0.36	-0.11	0.45	-0.01	1.23	-2.37	0.98	-0.06
33	L_{15} x T_1	1.26	0.67	-0.37	0.52	-3.64**	-2.87*	-2.34	-2.95**
34	L_1 x T_2	0.85	0.67	-0.38	0.38	-1.03	-0.07	-1.78	-0.96
35	L_2 x T_2	0.49	1.00	-1.60*	-0.04	-1.79	-2.39	5.12**	0.31
36	L_3 x T_2	-2.45**	-0.28	-1.11	-1.28**	2.28	-1.17	-1.03	0.03
37	L_4 x T_2	-0.84	-1.64*	-2.83**	-1.77**	0.05	-0.36	4.94**	1.54*
38	L_5 x T_2	-2.84**	-1.96**	-1.67*	-2.16**	4.57**	3.06*	2.22	3.29**
39	L_6 x T_2	3.68**	2.72**	2.13**	2.84**	-5.08**	-3.62*	-3.53**	-4.07**
40	L_7 x T_2	2.28**	1.55*	1.80**	1.88**	-4.54**	-2.41	-1.85	-2.94**
41	L_8 x T_2	1.67*	-0.78	1.11	0.67	-2.25	3.01*	-3.32*	-0.85
42	L_9 x T_2	-0.83	0.43	0.64	0.08	1.73	0.21	-0.64	0.43
43	L_{10} x T_2	-1.23	-0.10	0.02	-0.44	3.57**	1.38	-0.96	1.33
44	L_{11} x T_2	-2.66**	-0.27	-0.17	-1.04*	4.01**	-1.49	0.67	1.06
45	L_{12} x T_2	0.49	-0.32	-1.21	-0.35	-1.86	1.22	1.44	0.27
46	L_{13} x T_2	2.28**	0.99	1.46*	1.58**	-2.07	-4.10**	-1.72	-2.63**
47	L_{14} x T_2	0.43	0.47	-0.07	0.27	-0.61	1.03	-0.61	-0.06
48	L_{15} x T_2	-1.34	-2.47**	1.89**	-0.64	3.03*	5.68**	1.05	3.25**
49	L_1 x T_3	0.59	1.97**	2.09**	1.55**	4.21**	-2.64	0.04	0.54
50	L_2 x T_3	2.15**	-0.49	2.74**	1.47**	-1.30	1.51	-6.25**	-2.01**
51	L_3 x T_3	1.47*	0.94	1.52*	1.31**	-1.17	-0.81	-3.17*	-1.72*
52	L_4 x T_3	-0.25	1.61*	4.39**	1.91**	1.68	-0.33	-6.33**	-1.66*
53	L_5 x T_3	0.64	-0.04	-1.45*	-0.28	-1.03	-0.33	0.99	-0.12
54	L_6 x T_3	-0.58	-1.45*	-0.63	-0.89*	-0.82	5.13**	3.36*	2.56**
55	L_7 x T_3	-2.00**	-1.01	-1.05	-1.35**	2.11	-0.76	1.42	0.93
56	L_8 x T_3	-3.51**	-4.30**	-4.82**	-4.21**	2.74*	4.27**	6.68**	4.56**
57	L_9 x T_3	0.07	1.25	-1.35	-0.01	0.17	-3.39*	2.44	-0.26
58	L_{10} x T_3	1.49*	-1.14	1.22	0.53	-6.96**	-0.52	-3.81**	-3.76**
59	L_{11} x T_3	0.34	-1.49*	0.15	-0.34	1.33	4.89**	0.04	2.09**
60	L_{12} x T_3	0.53	1.11	-0.80	0.28	-3.53**	-2.57	0.98	-1.70*
61	L_{13} x T_3	-0.93	1.60*	-0.13	0.18	2.58*	-2.97*	2.67*	0.76
62	L_{14} x T_3	-0.07	-0.36	-0.38	-0.27	-0.62	1.34	-0.36	0.12
63	L_{15} x T_3	0.08	1.80*	-1.52*	0.12	0.61	-2.82*	1.29	-0.30
	Standard error								
	Ti	0.18	0.18	0.17	0.10	0.31	0.35	0.33	0.19
	Lj	0.36	0.36	0.34	0.20	0.62	0.69	0.65	0.38
	Sij	0.72	0.72	0.68	0.41	1.23	1.39	1.31	0.76
	Ti-j	0.22	0.22	0.21	0.13	0.38	0.42	0.40	0.23
	Li-j	0.49	0.49	0.47	0.28	0.84	0.95	0.89	0.52
	Ti-Lj	0.38	0.38	0.36	0.22	0.65	0.73	0.69	0.40
	STi-Tj	0.88	0.89	0.84	0.50	1.51	1.70	1.60	0.93
	SiL-jL	0.99	0.99	0.94	0.56	1.69	1.90	1.79	1.04
	Sij-kl	1.01	1.01	0.96	0.58	1.73	1.94	1.83	1.06

*, ** Significant at 5% and 1%, respectively

Table 6. GCA and SCA effects for test weight of seed and harvest index

S.No.	Genotype	Test weight of seed				Harvest index			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
1	T_1	-0.06**	-0.03	-0.07**	-0.05**	-0.29	0.38	-0.36	-0.09
2	T_2	0.01	0.03	0.02	0.02*	-0.10	-0.20	0.06	-0.08
3	T_3	0.05**	0.00	0.05**	0.03**	0.39	-0.18	0.30	0.17
4	L_1	0.05	0.03	0.00	0.03	-0.88*	0.02	-0.25	-0.37
5	L_2	-0.16**	-0.14**	-0.10**	-0.14**	-1.10**	0.28	-0.63	-0.48*
6	L_3	-0.14**	-0.09**	-0.07*	-0.10**	1.09**	-0.79	-1.18**	-0.29
7	L_4	-0.11**	0.10**	0.04	0.01	0.78	-0.51	-0.63	-0.12
8	L_5	0.16**	0.10**	0.18**	0.14**	1.22**	0.26	0.29	0.59*
9	L_6	-0.11**	-0.16**	-0.11**	-0.13**	-0.21	0.02	-0.35	-0.18
10	L_7	0.09**	-0.07*	0.04	0.02	1.35**	-0.55	-0.76	0.01
11	L_8	-0.03	0.12**	-0.10**	-0.00	1.44**	-0.24	1.27**	0.82**
12	L_9	-0.00	0.12**	0.13**	0.08**	2.70**	0.49	0.76	1.32**
13	L_{10}	-0.01	-0.08**	-0.06	-0.05**	-0.42	0.70	1.08*	0.45
14	L_{11}	0.08*	0.09**	0.02	0.06**	-1.48**	0.23	-1.49**	-0.91**
15	L_{12}	0.12**	-0.02	0.03	0.04*	-2.06**	-0.48	0.32	-0.74**
16	L_{13}	-0.06	-0.00	-0.09**	-0.05**	-1.41**	0.08	-0.89*	-0.74**
17	L_{14}	0.14**	0.06	0.12**	0.11**	-0.13	0.38	2.83**	1.03**
18	L_{15}	0.00	-0.06	-0.02	-0.02	-0.87*	0.10	-0.36	-0.37
19	$L_1 \times T_1$	-0.06	0.19**	-0.02	0.04	-1.81*	0.37	2.06*	0.20
20	$L_2 \times T_1$	-0.10	0.14*	-0.05	-0.00	0.18	1.07	-1.11	0.05
21	$L_3 \times T_1$	-0.07	-0.10	-0.09	-0.09*	0.15	-1.19	0.49	-0.18
22	$L_4 \times T_1$	-0.01	-0.13*	-0.04	-0.06	0.59	1.40	0.12	0.71
23	$L_5 \times T_1$	-0.17*	-0.28**	-0.17**	-0.21**	-0.85	-0.74	-0.07	-0.55
24	$L_6 \times T_1$	0.19**	0.07	0.19**	0.15**	-0.37	-0.47	0.22	-0.20
25	$L_7 \times T_1$	-0.00	0.24**	0.06	0.10**	0.15	-1.01	0.94	0.03
26	$L_8 \times T_1$	0.22**	0.20**	0.17**	0.20**	0.73	1.23	0.73	0.90
27	$L_9 \times T_1$	-0.12	-0.05	-0.12	-0.10**	0.45	-0.20	-0.53	-0.09
28	$L_{10} \times T_1$	0.09	-0.09	-0.06	-0.02	1.63*	0.92	-1.22	0.44
29	$L_{11} \times T_1$	0.01	-0.26**	-0.01	-0.09*	-2.10*	-1.05	0.15	-1.00*
30	$L_{12} \times T_1$	0.05	0.20**	0.14*	0.13**	0.43	1.22	-0.74	0.31
31	$L_{13} \times T_1$	-0.03	0.08	-0.00	0.02	0.54	2.32**	-0.29	0.86
32	$L_{14} \times T_1$	-0.06	-0.18**	0.02	-0.07	-0.52	-2.71**	-0.08	-1.10*
33	$L_{15} \times T_1$	0.08	-0.03	-0.01	0.01	0.79	-1.18	-0.68	-0.35
34	$L_1 \times T_2$	-0.03	-0.32**	-0.09	-0.15**	0.37	0.31	-0.77	-0.03
35	$L_2 \times T_2$	-0.03	-0.18**	-0.02	-0.08*	-0.47	0.25	1.63	0.47
36	$L_3 \times T_2$	0.06	0.17**	0.04	0.09*	-0.07	1.12	-0.36	0.23
37	$L_4 \times T_2$	-0.08	-0.06	-0.12	-0.09*	0.17	-0.37	1.01	0.27
38	$L_5 \times T_2$	0.12	0.11	0.12	0.12**	1.41	-0.23	-0.09	0.36
39	$L_6 \times T_2$	-0.18**	0.07	-0.20**	-0.10**	1.54	-0.85	-1.41	-0.24
40	$L_7 \times T_2$	0.02	-0.15*	0.02	-0.04	0.25	0.30	-1.20	-0.22
41	$L_8 \times T_2$	-0.03	0.02	-0.04	-0.01	-0.64	-0.07	-2.77**	-1.16*
42	$L_9 \times T_2$	-0.06	0.04	-0.04	-0.02	0.26	0.18	0.50	0.31
43	$L_{10} \times T_2$	0.08	-0.09	0.21**	0.07	-1.82*	1.03	1.48	0.23
44	$L_{11} \times T_2$	0.03	0.11	0.04	0.06	1.15	-0.07	-0.05	0.34
45	$L_{12} \times T_2$	-0.11	-0.17**	-0.11	-0.13**	0.45	-1.06	-0.10	-0.24
46	$L_{13} \times T_2$	0.04	0.11	0.10	0.08*	-1.45	-1.23	0.10	-0.86
47	$L_{14} \times T_2$	0.16*	0.20**	0.10	0.15**	-0.42	-0.07	-0.12	-0.20
48	$L_{15} \times T_2$	0.01	0.13*	-0.02	0.04	-0.72	0.77	2.14*	0.73
49	$L_1 \times T_3$	0.09	0.12	0.11	0.11**	1.44	-0.68	-1.28	-0.17
50	$L_2 \times T_3$	0.13*	0.04	0.07	0.08*	0.29	-1.33	-0.53	-0.52

S.No.	Genotype	Test weight of seed				Harvest index			
		E_1	E_2	E_3	Pool	E_1	E_2	E_3	Pool
51	L_3 x T_3	0.02	-0.07	0.05	-0.00	-0.07	0.06	-0.13	-0.04
52	L_4 x T_3	0.08	0.19**	0.16*	0.15**	-0.77	-1.03	-1.13	-0.98*
53	L_5 x T_3	0.05	0.17**	0.05	0.09*	-0.57	0.97	0.16	0.19
54	L_6 x T_3	-0.01	-0.15*	0.00	-0.05	-1.16	1.31	1.18	0.44
55	L_7 x T_3	-0.01	-0.09	-0.07	-0.06	-0.40	0.71	0.26	0.19
56	L_8 x T_3	-0.19**	-0.22**	-0.14*	-0.18**	-0.09	-1.16	2.04*	0.26
57	L_9 x T_3	0.18**	0.01	0.15*	0.11**	-0.71	0.02	0.02	-0.22
58	L_{10} x T_3	-0.18**	0.18**	-0.15*	-0.05	0.19	-1.94*	-0.26	-0.67
59	L_{11} x T_3	-0.03	0.15*	-0.02	0.03	0.95	1.13	-0.10	0.66
60	L_{12} x T_3	0.06	-0.03	-0.03	-0.00	-0.88	-0.16	0.83	-0.07
61	L_{13} x T_3	-0.01	-0.19**	-0.10	-0.10**	0.91	-1.09	0.19	0.01
62	L_{14} x T_3	-0.11	-0.02	-0.12	-0.08*	0.94	2.78**	0.20	1.31**
63	L_{15} x T_3	-0.09	-0.10	0.03	-0.05	-0.07	0.41	-1.47	-0.37
	Standard error								
	Ti	0.02	0.02	0.02	0.01	0.20	0.21	0.22	0.12
	Lj	0.03	0.03	0.03	0.02	0.40	0.42	0.43	0.24
	Sij	0.07	0.06	0.06	0.04	0.80	0.85	0.86	0.48
	Ti-j	0.02	0.02	0.02	0.01	0.25	0.26	0.26	0.15
	Li-j	0.05	0.04	0.04	0.03	0.55	0.58	0.59	0.33
	Ti-Lj	0.04	0.03	0.03	0.02	0.43	0.45	0.46	0.26
	STi-Tj	0.08	0.08	0.08	0.05	0.99	1.04	1.06	0.59
	SiL-jL	0.09	0.09	0.09	0.05	1.10	1.16	1.18	0.66
	Sij-kl	0.09	0.09	0.09	0.05	1.13	1.19	1.21	0.68

*, ** Significant at 5% and 1%, respectively

Table 7. GCA and SCA effects for total alkaloid content

S.No.	Genotype	Total alkaloid content			
		E_1	E_2	E_3	Pool
1	T_1	-0.02**	-0.03**	-0.03**	-0.03**
2	T_2	-0.01**	0.00	-0.01**	-0.01**
3	T_3	0.03**	0.03**	0.03**	0.03**
4	L_1	-0.05**	-0.03**	-0.05**	-0.04**
5	L_2	-0.06**	-0.06**	-0.06**	-0.06**
6	L_3	-0.05**	-0.03**	-0.05**	-0.04**
7	L_4	-0.03**	-0.02**	-0.01**	-0.02**
8	L_5	0.07**	0.08**	0.08**	0.07**
9	L_6	-0.03**	-0.04**	-0.02**	-0.03**
10	L_7	0.00	0.02**	0.04**	0.02**
11	L_8	0.01**	0.01**	0.02**	0.01**
12	L_9	0.10**	0.09**	0.08**	0.09**
13	L_{10}	0.03**	-0.02**	-0.01**	0.00*
14	L_{11}	-0.07**	-0.05**	-0.04**	-0.05**
15	L_{12}	-0.04**	-0.04**	-0.07**	-0.05**
16	L_{13}	0.02**	-0.00	0.00	0.01**
17	L_{14}	0.06**	0.06**	0.06**	0.06**
18	L_{15}	0.03**	0.03**	0.02**	0.03**
19	L_1 x T_1	-0.02**	-0.03**	0.03**	-0.01**
20	L_2 x T_1	0.01**	0.02**	0.01	0.01**
21	L_3 x T_1	0.08**	0.04**	0.03**	0.05**
22	L_4 x T_1	0.01	0.04**	-0.03**	0.00*
23	L_5 x T_1	-0.05**	-0.03**	-0.00	-0.03**

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S.No.	Genotype	Total alkaloid content			
		E_1	E_2	E_3	Pool
24	L_6 x T_1	0.03**	0.03**	0.00	0.02**
25	L_7 x T_1	0.02**	0.02**	0.04**	0.03**
26	L_8 x T_1	0.02**	-0.02**	-0.01*	-0.00
27	L_9 x T_1	-0.00	-0.03**	-0.01*	-0.02**
28	L_{10} x T_1	-0.01**	-0.02**	0.02**	-0.00
29	L_{11} x T_1	-0.00	-0.03**	0.01**	-0.01**
30	L_{12} x T_1	0.01**	0.06**	0.01**	0.03**
31	L_{13} x T_1	-0.02**	-0.03**	-0.04**	-0.03**
32	L_{14} x T_1	-0.03**	0.01	-0.02**	-0.02**
33	L_{15} x T_1	-0.04**	-0.02**	-0.03**	-0.03**
34	L_1 x T_2	-0.01**	-0.01*	-0.04**	-0.02**
35	L_2 x T_2	0.03**	0.04**	0.01	0.02**
36	L_3 x T_2	-0.02**	-0.02**	-0.01	-0.02**
37	L_4 x T_2	0.05**	-0.02**	0.02**	0.02**
38	L_5 x T_2	0.01**	0.01	0.00	0.01**
39	L_6 x T_2	-0.05**	-0.02**	-0.02**	-0.03**
40	L_7 x T_2	-0.08**	-0.05**	-0.02**	-0.05**
41	L_8 x T_2	0.01**	-0.02**	-0.04**	-0.02**
42	L_9 x T_2	-0.01**	0.02**	0.01	0.01**
43	L_{10} x T_2	0.04**	0.05**	0.02**	0.04**
44	L_{11} x T_2	0.06**	0.05**	0.02**	0.04**
45	L_{12} x T_2	-0.01**	-0.03**	-0.01**	-0.02**
46	L_{13} x T_2	-0.00	0.01	-0.00	0.00
47	L_{14} x T_2	-0.02**	0.00	-0.01	-0.01**
48	L_{15} x T_2	0.01*	-0.00	0.06**	0.02**
49	L_1 x T_3	0.03**	0.04**	0.01*	0.03**
50	L_2 x T_3	-0.04**	-0.06**	-0.01**	-0.04**
51	L_3 x T_3	-0.05**	-0.02**	-0.03**	-0.03**
52	L_4 x T_3	-0.06**	-0.02**	0.01*	-0.02**
53	L_5 x T_3	0.03**	0.02**	-0.00	0.02**
54	L_6 x T_3	0.02**	-0.01	0.01**	0.01**
55	L_7 x T_3	0.06**	0.03**	-0.01**	0.03**
56	L_8 x T_3	-0.03**	0.04**	0.04**	0.02**
57	L_9 x T_3	0.01**	0.01**	0.00	0.01**
58	L_{10} x T_3	-0.03**	-0.04**	-0.04**	-0.04**
59	L_{11} x T_3	-0.06**	-0.02**	-0.04**	-0.04**
60	L_{12} x T_3	-0.00	-0.03**	0.00	-0.01**
61	L_{13} x T_3	0.02**	0.02**	0.05**	0.03**
62	L_{14} x T_3	0.05**	-0.01*	0.03**	0.02**
63	L_{15} x T_3	0.03**	0.02**	-0.03**	0.01**
	Standard error				
	Ti	0.00	0.00	0.00	0.00
	Lj	0.00	0.00	0.00	0.00
	Sij	0.00	0.00	0.00	0.00
	Ti-j	0.00	0.00	0.00	0.00
	Li-j	0.00	0.00	0.00	0.00
	Ti-Lj	0.00	0.00	0.00	0.00
	STi-Tj	0.00	0.00	0.01	0.00
	SiL-jL	0.00	0.01	0.01	0.00
	Sij-kl	**0.00**	**0.01**	**0.01**	**0.00**

*, ** Significant at 5% and 1%, respectively

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highest positive and significant SCA effects across the environments. The highest positive and significant SCA effects was recorded in hybrids *viz*., L_3 x T_1 (0.08) in E_1 and (0.05) on pooled basis, while hybrid L_{12} x T_1 (0.06) in E_2 and L_{15} x T_2 (0.06) in E_3 environment,

On the basis of above study, five promising lines *viz.,* L_9, L_5, L_{14}, L_{15}, L_8 along with one tester i.e. T_3 have been identified as excellent general combiners across the environments for both the economic important traits *i.e.* root yield at harvest as well as total alkaloid content simultaneously. Apart from the above traits, three lines L_9, L_5, L_{14} also showed as good general combiner for dry matter content and harvest index. Hence these parents may be used as a potential source for improvement of total alkaloid content along with root yield. Among the crosses, for root yield at harvest five hybrids *viz*., L_8 x T_1, L_6 x T_2, L_5 x T_1, L_4 x T_3 and L_7 x T_2 and the hybrids L_3 x T_1, L_{10} x T_2, L_{11} x T_2, L_7 x T_1, L_{12} x T_1, L_1 x T_3, L_7 x T_3 and L_{13} x T_3 were identified as best specific combiners for total alkaloid content due to significant desirable SCA effects across the environments. Therefore, it is recommended that for improvement of root yield and total alkaloid content, above identified experimental materials may be beneficial in further exploitation in breeding programme of Ashwagandha.

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