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Environment×Combining Ability Interaction for Quality Traits in Tomato (*Solanum lycopersicum* L.)

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Abstract

The multilocational studies were conducted to evaluate 21 hybrids of tomato in Pratapgarh (Uttar Pradesh), Varanasi (Uttar Pradesh) and Burdwan (West Bengal), India during August–February of 2015–16 and 2016–17. Data on four quality traits *viz*., total soluble solids, titrable acidity, carotene content and lycopene content were estimated. Combined analysis of variance (ANOVA) revealed significant effects of locations, genotypes, genotype-location interaction and parents vs hybrids-location interaction for all the traits. The significance of combining ability effects (general combining ability and specific combining ability) and their interaction with location revealed environmental influences on combining ability effects for all the traits. The Present study indicated higher estimates of to , lower estimates of heritability and GCA/SCA ratio for quality traitsandthereby implied preponderance of non-additive gene action in determination of quality traits studied. Desirable parental lines were identified for different traits like EC 620438 and BS 24-2 for TSS, BS 24-2 and Superbug for titrable acidity, Columbia, EC 620438 and Superbug for carotene content, and H 86 and EC 620541 for lycopene content. Similarly, desirable specific combiners for different traits were identified. The hybrid combination EC 620438×BS 24-2 appeared good specific combiner for TSS, carotene and lycopene content. The parental lines/hybrids identified in present study will be useful in identifying hybrids adapted to a range of environments.

Keywords: Combining ability, environments, multi-environment diallel, tomato, quality

1. Introduction

Tomato is one of the most important vegetable crops. It achieved unprecedented popularity within short span, though its domestication is very recent (Bai and Lindhout, 2007). Its sensorial, organoleptic, nutritive and protective values (Dobrin et al., 2019; Kaushik and Dhaliwal, 2018; Vekariya et al., 2019) have made it immensely popular. It has emerged as one of the top choices for processing industry (Aoun et al., 2013; Figueiredo et al., 2016). It has acquired the status of 'model fleshy fruit plant' (Dan et al., 2020; Jaiswal et al., 2020).

Any food commodity is valued based on consumers' preference for both the instant gratification of taste-buds and the long-term nutritive

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value. In this context, biochemical components become much important. Total soluble sugar (TSS) content has relevance in recovery of processed food products (Berry and Uddin, 1991). The proportion of TSS and acidity provides the characteristic sweet-sour taste and flavour (Kader et al., 1977: Rahman et al., 2018; Stevens et al., 1977). The carotene and lycopene found in tomato offer nutritional and protective values. Consumers' preference for lycopene in tomato led to several attempts to develop varieties with improved colour (Gardner, 2006a; Gardner, 2006b). These quality traits determine acceptance of tomatoes and its products (Barrett et al., 2010).

In this context, it becomes mandatory to formulate breeding programmes to develop tomato genotypes with enhanced quality. This can be commercially achieved through hybrid breeding which relies on identification of good combiners. Combining ability analysis identifies potential parents and their hybrids (Singh and Asati, 2011), and predicts heterosis (Yu et al., 2019). Among different mating schemes, diallel mating system developed by Schmidt (1919) is the most balanced experimental design and has been extensively used (Guo et al., 2017; Murtadha et al., 2018; Nath et al., 2018; Teodoro et al., 2019). This scheme provides opportunity for wide recombination of favorable alleles from different parents, and thereby increases the likelihood of the occurrence of superior genotypes (Ferreira et al., 2018)

In general, combining abilities are estimated by evaluating hybrids along with parents in a particular location or year. However, the estimates of combining ability are affected by environmental influences (Ramalho et al., 1988; Nass et al., 2000; Pswarayi and Vivek, 2008; da Rocha et al., 2018) and hold relevance to the particular environment. Consequently, the hybrids so developed, may not perform well acros diverse environments (Senguttuvel et al., 2021). Combining ability studies over environments provide more precise estimates (Melo et al., 1997; Baig and Patil, 2002). Recently, combining ability-environment interaction data have been utilized in genomic prediction (Jarquin et al., 2021).

To be commercial successful, a hybrid must have consistent performances across the environments (Killi and Harem, 2006; Malosetti et al., 2013), particularly in present-day scenario of climatic changes (Muller et al. 2018; Najafi et al., 2018). Combining ability estimates based on multi-environment evaluation may result in identifying climate resilient hybrids. Bhateria et al. (2006) and Dwivedi et al. (1999) recommended combining ability analysis based on various environments. Reports on estimation of combining ability over environments do exist for yield traits in tomato (Chadha et al., 2001) and not for quality traits. Few reports are available in other crops (Nass et al., 2000; Baig and Patil, 2002; Padhar et al., 2013; Golkar et al., 2017; Sharma et al., 2019; Nardino et al., 2020) etc. despite the development of procedure for diallel analysis over environments way back in 1973 by Singh (1973). In above context, present study was aimed at identification of good general combiners and specific combiners over environments in tomato for various quality traits.

2. Materials and Methods

2.1. Experimental material and locations

The seeds of elite accessions representing improved varieties, local germplasm, exotic collections etc. maintained at Department of Genetics and Plant Breeding, Institute of Agricultural Sciences, Banaras Hindu University, were collected. Crosses among seven elite lines of tomato were made in half-diallel fashion. The hybrids so generated were evaluated in three locations representing diverse agro-ecological zones of India viz., Pratapgarh (Uttar Pradesh), Varanasi (Uttar Pradesh) and Burdwan (West Bengal) during two consecutive years (2015–16 and 2016–17). The Pratapgarh and Varanasi located in Uttar Pradesh represented middle Gangetic plains of India and the Burdwan location represented lower Gangetic plains of India. Different geographical, edaphic and average agro-meteorological features during the crop period (August-February) are presented in Table 1.

Table 1: Edaphic and weather conditions of locations under study during 2015–16 and 2016–17

Parameter	Pratapgarh	Varanasi	Burdwan
Geographical features			
Longitude	81.9 °E	82.9 °E	87.6 °E
Latitude	25.9 °N	25.3 °N	23.4 °N
Altitude (Mean sea level)	137 m	81 m	
Edaphic factors			
Soil texture	Sandy loam	Sandy clay loam	Clay
Soil pH	7.5	6.5	6.2
Available Nitrogen (kg ha^{-1})	210	203	230
Available potassium (kg ha^{-1})	180.0	190.0	160.0
Available phosphorous (kg ha^{-1})	10.2	24.2	18.0
Agro-meteorological features			
Average temp (°C)-Minimum	15.6	17.4	18.3
Average temp (°C)-Maximum	28.9	28.0	29.5
Average yearly rainfall (cm)	36.6	43.9	63.5
Relative humidity (%)	71.5	72.3	58.2

2.2. Experimentation

The nursery was raised in 1st week of August. The 25-day-old crop was transplanted in the main field. The experiment was laid out in randomized complete block design with three replications. An inter-row spacing of 60 cm and inter-plant distance of 50 cm was maintained. Each genotype was accommodated in three rows of 5m length to ensure sufficient plants for observation. All the recommended package of practices was followed to get a healthy crop.

2.3. Biochemical analysis

2.3.1. TSS

The total soluble solid (TSS) content of the juice extracted from selected samples was determined with hand refractometer (Model: ERMA Inc. Tokyo, Japan). Few drops of juice were placed on prism of the refractometer and reading was noted. The readings were expressed in ˚B.

2.3.2. Titrable acidity

Total titrable acidity was estimated by treating juice against sodium hydroxide (NaOH) solution. Two ml of juice was taken and titrated against 0.1N sodium hydroxide (NaOH) using phenolphthalein as an indicator. The appearance of pink colour indicated the end point of titration. It was expressed in terms of mg anhydrous citric acid in 100 ml of juice and was calculated as follows:

Total Titrable Acidity=(0.0064×A)/B×100

Where A= Volume (ml) of NaOH used, and

B=Volume (ml) of juice.

2.3.3. Carotene content

Carotene content was estimated by extracting pigment from two gram fruit sample with 10 ml acetone in portions, using 2.0 ml at a time until colourless residue was obtained. The acetone was evaporated to dryness. The volume was made 25 ml with petroleum ether. The optical density was read at 450 nm (since β-carotene has negligible absorbance at this wave length) using spectrophotometer. Petroleum ether was used as blank. Carotene content was expressed in unit of mg 100 g^{-1} and was calculated as below:

Carotene=(Final volume (ml))/(2×Weightofsampletaken)× Opticaldensity

2.3.4. Lycopene content

Lycopene concentration (mg 100 g^{-1}) in the extracting solution prepared as above (for carotene estimation) was determined using spectrophotometric measurement at room temperature in 350–600 nm wavelength range.

2.4. Statistical analyses

Data were recorded from fruits collected from five randomly selected plants. Two-year data of each location was pooled for all the traits studied. Combining ability analysis over three locations was carried out as per (Singh, 1973). The model of the analysis is given below:

$$X_{ijkm}= \mu+G_i+L_j+(GL)_{ij}+(LB)_{jk}+(GLB)_{ijk}+_{ijkm}$$

Where μ is a constant, G_i is the effect of i^{th} variety, L_j is the effect of j^{th} location, $(GL)_{ij}$ is the interaction effect of i^{th} genotype and k^{th} location, $(LB)_{jk}$ is the interaction effect of j^{th} location and k^{th} block, $(GLB)_{ijk}$ is the interaction effect of i^{th} genotype, j^{th} location and k^{th} block, and is the effect of i^{th} genotype, k^{th} block in j^{th} location specific to the m^{th} individual.

3. Results and Discussion

3.1. Combined ANOVA

Combined analysis of variance was performed on the data of four quality traits to estimate the amount of variability existing among parents and their hybrids (F_1s). The analysis of variance indicated highly significant differences among locations for all the traits studied (Table 2) signifying variable effects of locations on all the traits.

Table 2: Combined analysis of variance

Source of variation	df	TSS	Titrable acidity	Carotene content	Lycopene content
Location	2	2.39**	0.02**	8.24**	19.63**
Blocks within Location	6	0.04	0.00	0.04	0.04
Genotypes	27	2.07**	0.04**	1.70**	2.34**
Parents	6	1.07**	0.01**	0.53**	1.81**
Hybrids	20	2.46**	0.04**	1.28**	2.24**
Parents vs Hybrids	1	0.12	0.23**	17.18**	7.56**
Genotypes× Location	54	0.43**	0.01**	0.29**	0.85**
Parents× Location	12	0.85**	0.01**	0.33**	0.81**
Hybrids× Location	40	0.29**	0.01**	0.24**	0.76**
Parents vs Hybrids ×Location	2	0.85**	0.01**	0.88**	3.02**
Error	162	0.06	0.00	0.02	0.02
Total	251	0.37	0.01	0.33	0.61

Significant environmental influences have been reported in earlier studies in other crops involving safflower (Golkar et al., 2017), cowpea (Pandey and Singh, 2010), wheat (Sharma et al., 2019) etc. Genotypic effects were also highly significant indicating differential behaviour of genotypes including parents as well as hybrids. The highly significant 'parents vs hybrids' component indicated substantial heterosis for all the traits with the exception of TSS. The highly significant interaction of genotype and location (which included parent-location interaction and hybrid-location interaction) is suggestive of differential behaviour of the genotypes in different locations. The 'parents vs hybrids×location' component was highly significant and was indicative of location effect on expression of heterosis. Present study indicated significant influence of locations, genotypes (parents and hybrids) and their interaction. The variable effect of location signifies the validity of the experiment and may be ascribed to varied agro-climatic and edaphic factors existing in different locations. Significant genotypic differences were indicative of variable genetic constitution of different genotypes which may be ascribed to their geographic origin or their pedigree. Significant genotypic and environmental influences on expression of quality traits in tomato were reported earlier (Jyothi et al., 2012; Kumar et al., 2019). The variability existing among parents selected and their hybrids may facilitate genetic improvement for these traits using such genetic pools.

Analysis of variance of combining ability indicated highly significant effects of general combining ability (GCA) and specific combining ability (SCA) for all the traits (Table 3) thereby referring to importance of both additive and non-additive gene action in inheritance of the traits studied (Teodoro et al., 2019).The highly significant interaction of location with GCA and SCA depicted the influences of location on combining abilities.

Table 3: ANOVA for combining ability effects

Source of variation	df	TSS	Titrable acidity	Carotene content	Lycopene content
GCA	6	1.58^{**}	0.01^{**}	0.68^{**}	1.23^{**}
SCA	21	0.43^{**}	0.01^{**}	0.54^{**}	0.65^{**}
Location	2	0.79^{**}	0.01^{**}	2.75^{**}	6.54^{**}
GCA× Location	12	0.28^{**}	0.00^{***}	0.09^{**}	0.27^{**}
SCA× Location	42	0.11^{**}	0.00^{**}	0.10^{**}	0.29^{**}
Error	162	0.02	0.00	0.01	0.01
Genetic parameters					
σ^2_{gca}	-	0.06	0.00	0.03	0.05
σ^2_A	-	0.12	0.00	0.05	0.09
σ^2_{sca}	-	0.14	0.01	0.18	0.22
σ^2_D	-	0.14	0.01	0.18	0.22
h^2_{ns} (%)	-	29.8	7.2	15.1	14.5
GCA/SCA ratio	-	0.42	0.06	0.14	0.21

The GCA and SCA effects and their interaction with location was also significant depicting different reactions by different genotypes to the environmental influences. This indicates possible deviations in performances of varieties/hybrids in different environments.Previous studies in different crops (Nass et al., 2000; Golkar et al., 2017; Murtadha et al., 2018; da Rocha et al., 2018; Ferriera et al., 2018; Moura et al., 2018; Yu et al., 2020) also reported significant interaction of environment with GCA and SCA indicating varying estimates of GCA and SCA in different environments. Significant interaction of GCA and SCA with environment suggests selecting different parental lines for hybrids for specific environments.

3.2. *Genetic components quality traits across different environments*

Genetic components for different quality traits viz., TSS, titrable acidity, carotene and lycopene content are presented in Table 3. In the present study, the measures of σ^2_A varied from 0.00 (for titrable acidity) to 0.12 (for TSS) while the measures of varied from 0.01 (for titrable acidity) to 0.22 (for lycopene content). Higher estimates of σ^2_D to σ^2_A manifested importance of dominant gene actions in determination of these traits. This is in agreement with the reports of de Souza et al. (2012) who reported higher estimates of SCA for TSS and titrable acidity.Bhatt et al. (2001) also reported preponderance of non-additive gene action for ascorbic acid and TSS. The maximum narrow sense heritability (29.8%) was noted for TSS followed by carotene content (15.1%) and lycopene content (14.5%). This indicated low degree of additive gene action. The GCA/SCA ratios were also found to be low (ranging from 0.06 for titrable acidity to 0.42 for TSS) for the traits studied. Low estimates of heritability and GCA/SCA ratiofor quality traits in the present study implies preponderance of non-additive gene action in determination of these traitswhich suggests non-effectiveness of selection for improvement of these traits.

3.3. *General combiners for quality traits*

The measure of general combining ability indicates gene flow from parents to offsprings and represents information regarding concentration of additive genes. Higher estimates of GCA indicates high heritability, lesser gene interactions and higher response to selection. A desirable general combiner is defined in terms of better per se performances and desirable GCA effect. The mean per se performances and general combining ability effect of different parents are presented in Table 4.

The entries EC 620438, BS 24-2 and H 86 recorded higher brix reading than the general mean (4.88 °B). Among them, two entries namely EC 620438 and BS 24-2 were good general combiners as they possessed desirable gce effect (0.31 and 0.15, respectively). For the trait titrable acidity, three entries BS 24-2, H 86, NDTVR 73 and Superbug were the good performers. Among them, the entries BS 24-2 and Superbug possessed desirable GCA effect (0.029 and 0.013, respectively). The entry EC 62043 recorded lower mean values (0.39) and negative GCA effect (≈-0.01) for titrable acidity. This entry will have negative contribution to the hybrids in which it participates. Hence, it can be used as prospective parent in breeding where low acidity is the target. Three genotypes

Table 4: Mean performance and general combining ability effects of parents for different traits

Parents	TSS		Titrable acidity		Carotene content		Lycopene content	
	Mean	GCA effect	Mean	GCA effect	Mean	GCA effect	Mean	GCA effect
Columbia	4.03	-0.42**	0.37	0.002	2.96	0.29**	2.26	-0.09**
H 86	4.90	-0.18**	0.44	-0.020**	2.75	-0.13**	3.51	0.36**
EC 620541	4.60	0.14**	0.41	-0.003	2.63	-0.12**	2.99	0.09**
NDTVR 73	4.87	-0.06*	0.43	-0.014**	3.13	0.02	2.43	0.07**
EC 620438	5.60	0.31**	0.39	-0.007**	2.96	0.04*	2.28	-0.34**
BS 24-2	5.53	0.15**	0.48	0.029**	2.48	-0.18**	2.54	-0.10**
Superbug	4.63	0.07**	0.42	0.013**	3.07	0.08**	2.74	0.01
General mean	4.88	-	0.42	-	2.85	-	-	-
Gi-Gj	-	0.08	-	0.007	-	0.05	-	0.04

viz., Superbug, EC 620438 and Columbia manifested superior performances (3.07, 2.96 and 2.96) as well as desirable GCA effects (0.08, 0.04 and 0.29, respectively) for carotene content. Similarly, three entries viz., H 86, EC 620541 and Superbug were better performers. Among them, H 86 and EC 620541 exhibited desirable GCA effects (0.36 and 0.09, respectively). None of the parents was found good general combiner for all traits and hence for improvement in different quality traits different parents have to be involved in breeding programme.

3.4. Specific combiners for quality traits

Specific combining ability identifies the potentiality of inbred lines for generating superior hybrid combinations (Singh and Pawar, 2005; da Rocha et al., 2018). Specific combiningability effects of different crosses and mean performances for different quality traits are presented in Table 5.

Among the test hybrids, EC 620438×BS 24-2 reported maximum SCA effect (0.49) for TSS followed by the crosses EC 620438×Superbug (0.47) and H 86×EC 620541 (0.47) along with higher mean performances. The hybrid combinations Columbia×BS 24-2, Columbia×EC 620438 and Columbia×EC 620541 were good specific combiners for titrable acidity with desirable mean performances and significant SCA effects of 0.12, 0.10 and 0.09, respectively. The best specific combiners for carotene content were EC 620438×BS 24-2, EC 620541 ×EC 620438 and Columbia×EC 620541 with SCA effect of 0.59, 0.57 and 0.44, respectively. Similarly, the cross EC 620541×NDTVR 73 was best specific combiner for lycopene content (0.64) followed by Columbia×H 86 (0.54) and EC-620438×BS 24-2 (0.22). The cross combination EC 620438×BS 24-2 appeared good specific combiner for three traits (TSS, carotene content and lycopene content).The reports on tomato on combining ability analysis over environments are lacking though desirable general and specific combiners for quality traits in tomato were identified in previous studies of single environments (Dagade et al., 2015; de Souza et al., 2012).

Table 5: Specific combining ability effects of crosses for different quality traits

Crosses/Traits	TSS		Titrable acidity		Carotene content		Lycopene content	
	Mean (°B)	SCA effect	Mean (mg 100 ml^{-1})	SCA effect	Mean (mg 100 g^{-1})	SCA effect	Mean (mg 100 g^{-1})	SCA effect
Columbia×H 86	3.89	-0.45**	0.39	-0.07**	3.45	-0.01	3.18	0.54**
Columbia×EC620541	4.98	0.31**	0.56	0.09**	3.91	0.44**	1.70	-0.68**
Columbia×NDTVR73	4.62	0.16*	0.49	0.03**	4.00	0.39**	2.09	-0.27**
Columbia×EC 620438	4.59	-0.24**	0.57	0.10**	3.94	0.31**	2.15	0.19**
Columbia×BS 24-2	4.02	-0.64**	0.62	0.12**	3.74	0.33**	2.26	0.07
Columbia×Superbug	4.46	-0.13	0.43	-0.05**	4.06	0.38**	2.33	0.03
H 86×EC-620541	5.37	0.47**	0.40	-0.05**	3.31	0.25**	2.97	0.15**
H 86×NDTVR 73	4.86	0.16*	0.47	0.03**	3.57	0.37**	2.56	-0.25**
H 86×EC 620438	4.44	-0.62**	0.41	-0.04**	3.09	-0.13**	1.45	-0.95**
H 86×BS 24-2	4.58	-0.32**	0.54	0.06**	2.98	-0.02	2.17	-0.47**
H 86×Superbug	5.10	0.27**	0.51	0.05**	3.41	0.15**	2.89	0.14**

Table 5: Continue...

Crosses/Traits	TSS		Titrable acidity		Carotene content		Lycopene content	
	Mean (°B)	SCA effect	Mean (mg 100 ml^{-1})	SCA effect	Mean (mg 100 g^{-1})	SCA effect	Mean (mg 100 g^{-1})	SCA effect
EC 620541×NDTVR73	4.67	-0.36**	0.48	0.03**	3.09	-0.12**	3.18	0.64**
EC 620541×EC 620438	5.47	0.08	0.52	0.06**	3.79	0.57**	1.86	-0.27**
EC 620541×BS 24-2	5.42	0.19**	0.45	-0.05**	2.66	-0.35**	1.75	-0.62**
EC 620541 ×Superbug	5.18	0.03	0.53	0.05**	3.37	0.10*	2.36	-0.11**
NDTVR73×EC620438	5.38	0.19**	0.40	-0.05**	3.07	-0.30**	2.42	0.31**
NDTVR 73×BS 24-2	5.08	0.06	0.42	-0.07**	3.19	0.04	2.32	-0.04
NDTVR 73×Superbug	4.94	-0.01	0.53	0.06**	3.44	0.04	2.26	-0.20**
EC 620438×BS 24-2	5.88	0.49**	0.52	0.03**	3.76	0.59**	2.16	0.22**
EC 620438×Superbug	5.79	0.47**	0.52	0.04**	3.21	-0.22**	1.38	-0.67**
BS 24-2×Superbug	4.78	-0.38**	0.53	0.02**	3.56	0.35**	2.42	0.13**
Sij-Sik (p=0.05)	-	0.21	-	0.02	-	0.13	-	0.12
Sij-Skm (p=0.05)	-	0.20	-	0.02	-	0.12	-	0.11

4. Conclusion

Control of non-additive gene actions indicated possibility of developing heterotic hybrids for quality traits. The identified combiners (EC 620438 and BS 24-2 for TSS; BS 24-2 and Superbug for titrable acidity; Superbug, Columbia and EC 620438 for carotene, and H 86 and EC 620541 for lycopene) can be used in variety development for diverse environments. The well adapted hybrids were EC 620438×BS 24-2 (for TSS, carotene and lycopene content), and Columbia×EC 620541 (for titrable acidity and carotene content).

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