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Genotype by environment interaction effects on yield and curcumin in turmeric (*Curcuma longa* L.)

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ABSTRACT

Eleven cultivars were evaluated for fresh yield (10 environments), curing per cent, cucumin and dry yield (five environments) across India, four each in North and South India and two in North East India, ranging from 43 to 893 m above mean sea level. Combined analyses showed significant differences among cultivars, environments, and cultivar by environment interactions for yield, curing per cent and curcumin contents. A large proportion (70.8%) of variation on fresh yield was attributed to environments; however, for curing per cent, curcumin content and dry yield, genotype effect accounted for 31.2%, 17.7% and 15.7% of variation, respectively. Mega Turmeric was the most stable for fresh yield with above average yield per plant across all environments. Rajendra Sonia was performing well at specific locations as the fresh yield was high and was highly responsive to favorable environments. Results on curcumin and curing per cent showed that, IISR Kedaram performed consistently across five environments with regression values almost equal to one and non-significant deviation from regression was adjudged to be the most stable cultivar for curcumin production. High curcumin cultivar Narendra Tumeric-1 was least responsive at environments with regression values less than one and significant deviation from regression. Mega Turmeric, IISR Prathiba and IISR Kedaram showed high stability for dry yield across environments. Three varieties, Mega Turmeric, IISR Kedaram and IISR Prathiba could serve as a good genetic source for stability in breeding programs for high dry yield and curcumin content.

1. Introduction

Turmeric (*Curcuma longa* L.) is a rhizomatous small perennial plant from the ginger family (Zingiberaceae). It has been used as a medicine, condiment and as a dye in India and many East Asian countries for centuries (Anandaraj and Sudharshan, 2011). Turmeric is a native to South Asia, particularly India, but is cultivated in many warm regions of the world. India is the largest producer, consumer and exporter (approximately 90%) of turmeric in the world. The primary active constituent of turmeric is an important secondary metabolite namely, curcumin. It's role as an antimalarial (Nandakumar et al., 2006), anti-inflammatory (Gupta et al., 2012, 2013) and antitumor (Gupta et al., 2012) compound has been well appreciated worldwide and it has also been known to modulate lipid metabolism, which has been implicated in obesity (Alappat and Awad, 2010). In addition, curcumin is also used in clinical trials to treat Azheimer's (Hamaguchi et al., 2010). A genotype or cultivar that shows consistent performance across different environments over years for a given trait is considered stable. Interpretation of performance of a number of genotypes in a broad range of environments is always affected by genotype × environment interactions (GEI) (Gauch and Zobel, 1996). A genotype that has stable trait expression across environments contributes little to GEI and its performance should be more predictable from the main

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effects of genotypes and environments than the performance of an unstable cultivar (Sneller et al., 1997). Several statistical methods have been proposed for stability analysis, with the aim of explaining the information contained in the GEI. Regression technique was proposed by Finlay and Wilkinson (1963) and was improved by Eberhart and Russell (1966). Generally, genotype stability was estimated by the slope of and deviation from the regression line for each of the genotypes. This is a popular method in stability analysis and has been applied in many crops. Stability of curcumin and yield in turmeric is one of the concerns in spices industries, as genotypes perform differently across environments. Given the limitation of information on the stability for yield and curcumin contents in turmeric, this study was conducted across 10 environments to understand the responses and to identify varietal stability on curcumin and yield.

2. Materials and methods

2.1. Plant materials and field experiments

Eleven cultivars (Table 1) from different sources and with different yield and curcumin levels were used for stability test. These cultivars were sampled among the released varieties and most promising cultivars. Field experiments were conducted across 30 testing environments for fresh yield (combination of 10 locations and three consecutive cropping seasons, 2008–2011) and five testing environments for curcumin and curing per cent (2010–2011) under Co-ordinating centres of All India Co-ordinated Research Project on Spices (AICRPS). The additional information on the environments is given in Table 2. At each environment, experimental layout was a randomized complete block design with three replications (40 plants/replication/genotype). For curcumin, curing per cent and dry yield, the samples were collected from Barapani, Coimbatore, Kumarganj, Kolasib and Kozhikode environments during 2010–2011 cropping season.

2.2. Curing per cent

Fresh turmeric is processed to obtain the dried rhizome by boiling with water followed by sun drying. Boiling is to reduce the drying time and this process of boiling and drying is referred as curing. One kilogram of fresh rhizomes per replication per genotype (containing 20% mother rhizomes, 60% primary rhizomes and 20% secondary rhizomes) were boiled in water for 1 h uniformly and sun dried for 72 h (approximately 9 days, 6–8 h/day) to reach a moisture level of 10% approximately. Curing per cent was calculated by noting the differences between fresh and dry weight. The dry yield (t/ha) was projected based on the per-plant-fresh yield and its curing per cent for each cultivar.

2.3. Curcumin analysis

The dried rhizomes was powdered to uniform mesh and used for extracting curcumin. It was estimated from the powdered and sieved sample by ASTA procedure (American Spice Trade Association (ASTA), 1968a,b). The absorption maxima of curcumin were measured in a Shimadzu UV-160 I spectrophotometer at 425 nm and percentage was computed based on the concentration of pure crystalline curcumin (98%) (American Spice Trade Association (ASTA), 1968c). The analysis of curcumin was replicated thrice and the mean was taken for data analysis.

2.4. Data analysis

Yield (fresh and dry) and curcumin traits were statistically analyzed for each environment. Error variances were tested for homogeneity with Bartlett's test as described by Gomez and Gomez (1984). Duncan multiple range test (DMRT) was used to compare mean differences for significant cultivar and environment effect. Combined analysis of variance for curcumin, curing per cent and dry yield was done for six environments according to a statistical model explained by Freeman and Dowker (1973). Since there was significant interactions between $G \times E$, stability parameters were calculated as suggested by Eberhart and Russell (1966). Means across environments, linear regression coefficient (b), deviation from regression (Sd^2) of genotype means over environment index were calculated. Significance of regression coefficient (b) and deviation from regression (Sd^2) were tested using t-test and F-test, respectively.

3. Results

3.1. Cultivar by environment interaction

The results of combined analysis of variance for yield and curcumin traits are presented in Table 3. There were significant differences among cultivars, environments, and for cultivar by environment interactions for all the four traits. A large proportion (70.8%) of variation on fresh yield per plant was attributed to environments. Source of variation on fresh yield by cultivar (G) × environment (E) and cultivar accounted, respectively, for 25.0% and 4.2% of the total variation. Also, high variations due to environment were observed for curcumin, curing per cent and dry yield. The variations due to cultivar were 31.2%, 17.7% and 15.7% for curing per cent, curcumin and dry yield, respectively.

Mean squares due to environment (linear) was found highly significant for all the four characters, indicating differences between environments and their influence on genotypes for expression of these characters (Table 3). Further, the higher magnitude of mean squares due to environments (linear) as compared to genotype × environment (linear) exhibited that linear response of environments accounted for the major part of total variation for all the traits studied. The environment + (genotype × environment) was significant for all the traits indicating distinct nature of environments and genotype × environment interactions in phenotypic expression. The genotype × environment (linear) interaction component showed significance for all the four characters. This indicated significant differences among the genotypes as an outcome of the linear function of environmental components enabling to predict the stable behavior of genotypes over environments more precisely.

3.2. Environment evaluation

Due to highly significant differences among cultivar by environment interactions, the mean of 10 cultivars for yield, curing per cent and curcumin traits from each environment was used to rank the environmental effects on each trait as suggested by Finlay and Wilkinson (1963). Among genotypes, Rajendra Sonia produced high mean fresh yield of 413.12 g/plant across 10 environments, however, it was not significantly different from Narendra Turmeric-1 (Table 4). Dholi was the most favorable environment with mean fresh yield of 555.05 g/plant. The variation on fresh yield per plant ranged from 105.26 g/plant for IISR Kedaram at Raigarh to 1040.00 g/plant for Rajendra Sonia at Dholi (Table 4).

Curing per cent, and curcumin showed similar responses among cultivars across five environments. IISR Kedaram recorded the highest curing per cent (22.16) among cultivars, across all environments (Table 5). Environmental mean for curing per

Table 1
Description of turmeric cultivars used in experiment.

Cultivar	Pedigree name	Source	Characteristics
Mega turmeric	Selection form Lakadong type	ICAR Research Complex for NEH Region, Shillong, Meghalaya	Bold rhizomes, curcumin 6.8%, dry recovery 16.37%, duration 300–315 days
IISR Alleppy Supreme	A clonal selection from Alleppy turmeric	Indian Institute of Spices Research, Kozhikode, Kerala	Tolerant to leaf blotch, curcumin 5.55%, oleoresin 16.0%, dry recovery 19.0%, duration 210 days
IISR Kedaram	Clonal selection from Thodupuzha collection	Indian Institute of Spices Research, Kozhikode, Kerala	Tolerant to leaf blotch, curcumin 5.5%, oleoresin 13.6%, dry recovery 18.9%, duration 210 days
IISR Prathiba	Open pollinated progeny selection	Indian Institute of Spices Research, Kozhikode, Kerala	High yield, curcumin 6.2%, oleoresin 16.2%, essential oil 6.2%, dry recovery 18.5%, duration 225 days
BSR 2	Induced mutant from Erode local	Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu	High yielding, bigger rhizomes, resistant to scale insects, duration 245 days
Suranjana	Clonal selection from local types of West Bengal (TCP-2)	Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar	Curcumin 5.7%, oleoresin 10.9%, essential oil 4.1%, dry recovery 21.2%, tolerant to leaf blotch and rhizome rot, resistant to rhizome scales and moderately resistant to shoot borer, duration 235 days
Rajendra Sonia	Selection from local germplasm	Rajendra Agricultural University, Dholi	Curcumin 8.4%, essential oil 5.0% and dry recovery 18.0%, duration 225 days
Roma	Clonal selection from T. Sunder	Orissa University of Agriculture and Technology, Pottangi	Curcumin 6.1%, oleoresin 13.2%, essential oil 4.2%, dry recovery 31.0%, duration 250 days
Rasmi	Clonal selection from Rajpuri local	Orissa University of Agriculture and Technology, Pottangi	Curcumin 6.4%, oleoresin 13.4%, essential oil 4.4% and dry recovery 23.0%, duration 240 days
Narendra Turmeric-1	Clonal selection	Narendra Deva University of Agriculture and Technology, Kumarganj, Faizabad	Curcumin 8.0%, dry recovery 22.0%, suitable to Uttar Pradesh and Uttarakhand, duration 205–210 days
Duggriala Red (Cl. 317)	Clonal selection from Duggriala red	Dr. YSR Horticultural University, AICRPS, Jagtial, Andhra Pradesh	High yielding, bold rhizomes, curcumin 4.1%, moderately resistant to leaf spot and leaf blotch, duration 240–270 days

Singh et al. (2009).

Table 2
Description of environments where trials were conducted during 2008–2011.

Environments	Geographical coordinates	Altitude (m asl)	Temperature (°C)		Rainfall (mm)	Soil type	Cultivation system
			Max	Min			
Barapani, Meghalaya	25.71′N; 91.98′E	893	31.0	3.0	2578.8	Lateritic	Raised beds, rain fed
Coimbatore, Tamil Nadu	11.01′N; 76.94′E	433	34.9	18.4	722.8	Clay loam	Ridges and furrows, irrigated
Kumarganj, Uttar Pradesh	26.55′N; 81.84′E	113	38.5	7.9	1294.4	Silty loam	Ridges and furrows, irrigated
Kolasib, Mizoram	24.23′N; 92.68′E	673	29.9	14.7	2252.0	Sandy loam	Raised beds, rain fed
Kozhikode, Kerala	11.30′N; 75.84′E	154	35.9	18.6	4121.0	Laterite	Raised beds, rain fed
Chintapalli, Andhra Pradesh	16.53′N; 78.60′E	408	32.6	10.5	911.6	Lateritic	Ridges and furrows, irrigated
Dholi, Bihar	25.99′N; 85.59′E	55	35.2	9.2	1458.4	Sandy loam	Ridges and furrows, irrigated
Pundibari, West Bengal	26.41′N; 89.38′E	43	33.9	9.6	2095.3	Sandy loam	Ridges and furrows, irrigated
Raigarh, Chattisgarh	21.89′N; 83.39′E	237	42.9	10.4	1373.0	Clay	Ridges and furrows, irrigated
Jagtial, Andhra Pradesh	18.79′N; 78.91′E	243	42.9	11.2	733.8	Sandy loam	Ridges and furrows, irrigated

cent (23.12) was highest at Kumarganj and lowest at Kozhikode (16.35). In summary, curing per cent among cultivars followed the ranking: IISR Kedaram > IISR Prathibha > Roma > Rasmi > Mega Turmeric > IISR Alleppy Supreme > Suranjana > BSR-2 > Duggriala Red > Narendra Turmeric-1. For curcumin, it was highest (5.98) at Barapani followed by 5.55 at Kolasib. In addition, among individual cultivars, Mega Turmeric showed the maximum curcumin per cent (7.2) at Barapani, while IISR Prathiba recorded lowest (2.9) at Coimbatore (Table 6).

Dry yield is the most important agronomic trait in the development of turmeric cultivars. Identification of a cultivar with high dry yield and stability is of immense value. A perusal of mean for dry yield per ha (Table 7) indicated that out of 11 cultivars, Mega Turmeric and BSR-2 registered higher dry yield. The variation on

Table 3
Combined analysis of variance for yield, dry recovery and curcumin of 11 turmeric cultivars evaluated at different environments.

Source of variation	df	Mean square								
		Fresh yield (g/plant)	% of total SS	df	Curing (%)[a]	% of total SS	Curcumin (%)[a]	% of total SS	Dry yield (t/ha)[a]	% of total SS
Cultivars (G)	10	$42,650.77^{**}$	4.2	10	27.89^{**}	31.2	0.94^{**}	17.7	5.29^{**}	15.7
Environment (E)	29	$255,286.99^{**}$	70.8	4	64.87^{**}	33.6	5.72^{**}	42.9	46.29^{**}	54.8
G × E interaction	290	9015.93^{**}	25.0	40	7.30^{**}	35.2	0.52^{**}	39.3	2.50^{**}	29.5
Environment +(G × E)	319	$31,404.21^{**}$		44	12.54^{*}		1.00^{*}		6.48^{**}	
Environment (linear)	1	$7,403,316.25^{**}$		1	259.49^{**}		22.87^{**}		185.14^{**}	
(G × E) linear	10	$30,265.08^{**}$		10	5.14^{*}		0.56^{*}		1.03^{*}	
Pooled deviation	308	7506.42^{**}		33	7.30^{**}		0.47^{**}		2.71^{**}	
Pooled error	660	1143.60		110	0.71		0.06		0.32	

* Significant at $P \leq 0.05$ probability level.
** Significant at $P \leq 0.01$ probability level.
a Tested at five environments.

Table 4
Fresh yield per plant (g) of 11 turmeric cultivars at 10 environments during 2008–2011.

Cultivars	Environments										
	Barapani	Coimbatore	Kumarganj	Kolasib	Kozhikode	Chintapalli	Dholi	Pundibari	Raigarh	Jagtial	Mean
Mega turmeric	464.11c	382.17bc	231.12bc	437.00a	455.83cd	401.18b	555.56c	285.15cd	148.08de	319.78bc	367.99BC
IISR Alleppy Supreme	391.11de	412.00a	227.67c	345.89bc	394.86de	291.44c	386.67d	246.73ef	113.81f	280.33d	309.05D
IISR Kedaram	383.67de	350.56ef	228.23c	327.89bc	367.33ef	317.07bc	393.33d	348.92ab	105.26f	341.78ab	316.40D
IISR Prathiba	357.78de	360.44dc	206.67e	379.33b	493.06bc	275.91c	405.56d	252.80de	121.64ef	282.33d	313.55D
BSR-2	672.89a	402.11ab	251.34a	281.22ef	490.74bc	404.22b	530.00c	254.81de	195.46bc	312.00bc	379.48B
Suranjana	502.22c	292.22g	200.00e	351.00bc	560.61b	365.33bc	516.67c	382.90a	262.89a	332.33ab	376.62B
Rajendra Sonia	407.22d	355.11e	216.52d	297.11de	657.86a	394.11b	1040.00a	265.87cd	166.81cd	330.56ab	413.12A
Roma	558.89b	393.44ab	236.63b	326.78cd	347.25ef	500.96a	518.89c	307.87bc	126.18ef	310.56cd	362.75BC
Rasmi	315.56f	391.22ab	203.23e	246.89f	302.67f	370.11bc	510.00c	299.92ef	114.51f	372.78a	312.69D
Narendra Turmeric-1	515.89bc	328.44f	246.41a	377.11bc	658.89a	338.96bc	698.89b	296.70cd	216.99b	363.39ab	404.17A
Duggriala Red	352.17ef	368.22cd	236.38b	362.67bc	510.69bc	339.89bc	550.00c	232.85f	189.22bc	366.00ab	350.81C
Mean	447.41C	366.90D	225.84G	339.35E	476.35B	363.56D	555.05A	288.59F	160.08H	328.35E	355.14
CV %	12.59	7.68	2.62	18.16	17.07	28.27	15.61	18.52	23.28	18.49	

Mean in the same column and row followed by a common letter are not significantly different at $P \leq 0.01$ by DMRT. Different capital letter(s) indicate significant difference between environments and between cultivars.

Table 5
Curing (%)of 11 turmeric cultivars at five environments during 2010–2011.

Cultivars	Environments					
	Barapani	Coimbatore	Kumarganj	Kolasib	Kozhikode	Mean
Mega turmeric	22.00	20.49cd	18.80e	23.00bc	18.71a	20.60B
IISR Alleppy Supreme	17.47	21.83a	23.20cd	21.63c	18.30a	20.49B
IISR Kedaram	21.83	21.12bc	24.60bc	25.67a	17.60a	22.16A
IISR Prathiba	18.33	21.62ab	25.00ab	24.63ab	19.27a	21.77A
BSR-2	17.37	21.46ab	18.60e	21.17c	12.70b	18.26C
Suranjana	15.10	20.28de	24.30bc	17.30d	16.75a	18.75C
Rajendra Sonia	13.43	14.70g	21.90d	13.47e	11.21b	14.94E
Roma	19.87	16.47f	26.40a	24.77ab	18.74a	21.25AB
Rasmi	20.07	16.20f	24.30bc	24.17ab	18.45a	20.63B
Narendra Turmeric-1	12.70	19.77e	24.10bc	12.23e	11.81b	16.12D
Duggriala Red	17.77	15.23g	16.90f	21.70c	17.25a	17.77C
Mean	17.82D	19.39C	23.12A	20.80B	16.35E	19.34
CV %	28.01	2.15	4.28	6.00	13.40	

Mean in the same column and row followed by a common letter are not significantly different at $P \leq 0.01$ by DMRT. Different capital letter(s) indicate significant difference between environments and between cultivars.

dry yield ranged from 1.06 t/ha for Rasmi at Kolasib to 12.39 t/ha for BSR-2 at Barapani.

3.3. Stability for yield and curcumin

Stability parameters for yield (fresh and dry), curing per cent and curcumin content traits are shown in Tables 8 and 9. Five genotypes for fresh yield per plant *viz.*, Rajendra Sonia, Duggriala Red, IISR Prathiba, BSR-2 and Mega Turmeric; two genotypes *viz.*, IISR Kedaram and Rajendra Sonia for curcumin; six genotypes for curing per cent *viz.*, BSR-2, Rasmi, IISR Alleppey Supreme, Suranjana, IISR Kedaram and IISR Prathiba and four genotypes for dry yield *viz.*, Duggriala Red, IISR Alleppey Supreme, Rasmi and IISR Kedaram had values near to unit regression. Hence, these genotypes are suitable for over all environmental conditions and are considered as stable genotypes. Rajendra Sonia produced high fresh yield and showed stability ($b = 0.98$), but high and significant deviation from regression (21,956), implying that this cultivar is

Table 6
Curcumin (%) of 11 turmeric cultivars at five environments during 2010–2011.

Cultivars	Environments					
	Barapani	Coimbatore	Kumarganj	Kolasib	Kozhikode	Mean
Mega turmeric	7.2a	5.3b	4.2cd	5.5	3.7cd	5.18BC
IISR Alleppy Supreme	6.3c	3.0g	4.7bc	5.4	3.6d	4.60DE
IISR Kedaram	6.4bc	5.0d	4.5cd	5.4	4.2bc	5.09BC
IISR Prathiba	6.9ab	2.9g	4.2cd	5.2	4.6ab	4.75DE
BSR-2	3.7f	3.7f	3.8d	5.8	4.1cd	4.22F
Suranjana	5.1d	5.2bc	4.8bc	5.5	3.8 cd	4.87CD
Rajendra Sonia	6.2c	5.1cd	4.8bc	6.1	4.1bc	5.26B
Roma	6.8ab	5.1cd	5.3ab	5.3	3.7cd	5.27B
Rasmi	5.0de	5.0d	3.8d	5.3	5.3a	4.87CD
Narendra Turmeric-1	6.2c	6.2a	5.6a	6.0	5.0ab	5.78A
Duggriala Red	4.5e	4.1e	4.5cd	5.6	3.8cd	4.49EF
Mean	5.98A	4.65C	4.57C	5.55B	4.21D	4.94
CV %	5.58	1.19	9.65	8.75	13.08	

Mean in the same column and row followed by a common letter are not significantly different at $P \leq 0.01$ by DMRT. Different capital letter(s) indicate significant difference between environments and between cultivars.

Table 7
Dry yield (t/ha) of 11 turmeric cultivars at five environments during 2010–2011.

Cultivars	Environments					
	Barapani	Coimbatore	Kumarganj	Kolasib	Kozhikode	Mean
Mega turmeric	12.12a	9.60d	4.34ef	6.01a	7.04b	7.82A
IISR Alleppy Supreme	6.65de	10.69b	5.12cd	4.87bc	7.13b	6.89B
IISR Kedaram	9.52b	9.77cd	5.56bc	5.61ab	5.74bc	7.24AB
IISR Prathiba	7.67bc	11.42a	5.05cd	5.06ab	7.25b	7.29AB
BSR-2	12.39a	10.21c	4.69de	4.70bc	6.45bc	7.69A
Suranjana	7.00cd	7.83ef	4.92d	4.53cd	5.66bc	5.99C
Rajendra Sonia	5.29de	6.72h	4.83de	2.14f	6.00bc	4.99D
Roma	9.22bc	7.61fg	6.26a	1.84fg	8.03b	6.59BC
Rasmi	6.01de	7.41fg	4.95d	1.06g	6.38bc	5.16D
Narendra Turmeric-1	4.85e	7.93e	5.90ab	3.74de	11.32a	6.75BC
Duggriala Red	6.62de	8.16e	3.92f	2.80ef	4.41c	5.19D
Mean	7.94B	8.85A	5.05D	3.85E	6.85C	6.51
CV %	17.72	3.08	6.49	16.13	21.99	

Mean in the same column and row followed by a common letter are not significantly different at $P \leq 0.01$ by DMRT. Different capital letter(s) indicate significant difference between environments and between cultivars.

Table 8
Stability analyses for yield of 11 turmeric cultivars grown at 10 environments during 2008–2011.

Cultivars	Fresh yield (g/plant)		
	Mean	b	Sd^2
Mega turmeric	367.99	0.927	1964
IISR Alleppy Supreme	309.05	0.796	2518
IISR Kedaram	316.40	0.698	1988
IISR Prathiba	313.55	1.033	4290*
BSR-2	379.48	1.072	6396*
Suranjana	376.62	0.882	6024*
Rajendra Sonia	413.12	0.980	21956**
Roma	362.75	1.041	8307**
Rasmi	312.69	0.884	5285*
Narendra Turmeric-1	404.17	1.213	6688**
Duggriala Red	350.81	0.974	4550*
Mean	355.14		

* Significant from 1.0 (for b) at $P \leq 0.01$ or $P \leq 0.05$ probability level indicates unstable cultivars.
** Significant from regression value (for Sd^2) at $P \leq 0.01$ or $P \leq 0.05$ probability level indicates unstable cultivars.

very sensitive to changes in environment. Although, IISR Prathiba, Duggriala Red and BSR-2 had regression coefficient for fresh yield $b = 1.033$, 0.974 and 1.072, respectively, their deviation from regression values were significant, making them not stable in diverse environments. Mega Turmeric with above average yield (mean yield = 367.99 g/plant), regression coefficient of $b = 0.927$ and non-significant deviation from regression indicated its general adaptability for fresh yield across environments.

Among the 11 genotypes, Mega Turmeric, IISR Prathiba and IISR Kedaram registered high dry yield, non significant b value (near unity) and non significant deviation from regression near zero. Therefore, these genotypes were stable for dry yield in all the environments. Even though BSR-2 produced high dry yield with stability, its high and significant deviation from regression (3.75) implied that this cultivar is very sensitive to changes in environment.

IISR Kedaram showed good stability with $b = 1.13$ and 1.16 for curcumin, and curing per cent, respectively, besides non significant Sd^2 (Table 9) indicating its higher adaptability for these traits. IISR Kedaram and Rajendra Sonia were the cultivars that showed stability for curcumin. All other cultivars showed significant and high deviation from regression, indicating high fluctuation in curcumin contents across environments. Narendra Turmeric-1 had the highest curcumin, but with low regression value, highlighting its poor responsiveness to changes in environment. Roma had second highest cucumin content, $b > 1$ and high deviation from regression thereby implying its suitability as a good performar only for specific locations. Even though six cultivars had above average curing per cent (location mean yield = 19.34%) only IISR Prathiba, and IISR Kedaram showed good stability with $b = 1.16$ and less and non-significant deviation from regression making them more stable genotypes for curing per cent across the environments (Table 9).

4. Discussion

Significant $G \times E$ effects indicated that cultivar responded differently to changes in environments. High proportion of variation

Table 9
Stability analyses for curing (%), curcumin and dry yield of 11 turmeric cultivars grown at 5 environments during 2010–2011.

Cultivars	Curcumin (%)			Curing (%)			Dry yield (t/ha)		
	Mean	b	Sd^2	Mean	b	Sd^2	Mean	b	Sd^2
Mega turmeric	5.18	1.71	0.40**	20.60	0.06	4.11**	7.82	1.08	1.37
IISR Alleppy Supreme	4.60	1.61	0.53**	20.49	0.89	1.18	6.89	0.99	1.49
IISR Kedaram	5.09	1.13	0.05	22.16	1.16	2.14	7.24	0.92	1.40
IISR Prathiba	4.75	1.51	1.20**	21.77	1.16	0.95	7.29	1.15	1.29
BSR-2	4.22	0.48	0.90**	18.26	0.94	9.25**	7.69	1.46	3.75**
Suranjana	4.87	0.69	0.23**	18.75	1.12	6.89**	5.99	0.66	−0.16
Rajendra Sonia	5.26	1.22	−0.006	14.94	1.41	5.90**	4.99	0.75	0.60
Roma	5.27	1.30	0.41**	21.25	1.40	7.27**	6.59	1.17	2.86**
Rasmi	4.87	0.20	0.46**	20.63	1.10	6.71**	5.16	1.08	1.23
Narendra Turmeric-1	5.78	0.49	0.11	16.12	1.54	21.55**	6.75	0.64	9.22**
Duggriala Red	4.49	0.66	0.24**	17.77	0.24	6.48**	5.19	1.00	0.27
Mean	4.94			19.34			6.51		

** Significant from 1.0 (for b) at $P \leq 0.01$ or $P \leq 0.05$ probability level indicates unstable cultivars.
** Significant from regression value (for Sd^2) at $P \leq 0.01$ or $P \leq 0.05$ probability level indicates unstable cultivars.

on yield was found for the environment effect, therefore more testing sites are needed or the environments in locations need to be controlled (Gill et al., 1984). Existence of wide variability among the cultivars with respect of yield attributes, and quality characters was reported by various workers (Ratnambal, 1986; Jalgaonkar and Jamdagni, 1989; Yadav and Singh, 1989; Indiresh et al., 1992; Chandra et al., 1997; Kumar and Jain, 1996; Lynrah and Chakraborty, 2000; Mohanty, 1979; Nirmal Babu et al., 1993; Nirmal and Yamgar, 1998; Pathania et al., 1988; Poduval et al., 2001; Rakhunde et al., 1998; Sasikumar, 2005; Sharma, 2005; Velayudhan et al., 1999). Rama Rao and Rao (1994); Singh et al. (2013) reported that curcumin content of turmeric varies from place to place due to genetic and influence of environment and agro-climatic conditions. We found that environment played a major role in fresh yield, dry yield and curcumin contents as 70.8%, 54.8% and 42.9% of the variation was due to environment effect, respectively although $G \times E$ were significant. For curing per cent, cultivars showed almost equal effect of variation (31.2%) as that of environments (33.6%) when tested across five environments.

Since there was significant cultivar × environment interaction, it will lessen the usefulness of cultivar mean as single parameter to measure stability (Rasamivelona et al., 1995; Pritts and Luby, 1990). According to Eberhart and Russell (1966) model, a genotype is considered stable in performance if it has high mean performance, unit regression coefficient, and least deviation from regression. Accordingly, the mean and deviation from regression of each genotype were considered for stability and linear regression was used for testing the varietal response.

I. Genotypes with high mean, bi = 1 with non significant Sd^2 are suitable for general adaptation, *i.e.*, suitable over all environmental conditions and they are considered as stable genotypes.
II. Genotypes with high mean, bi > 1 with non significant Sd^2 are considered as below average in stability. Such genotypes tend to respond favourably to better environments but give poor yield in unfavourable environments. Hence, they are suitable for favourable environments only.
III. Genotypes with low mean, bi < 1 with non significant Sd^2 do not respond favourably to improved environmental conditions and hence, it could be regarded as specifically adapted to poor environments.
IV. Genotypes with any bi value with significant Sd^2 are unstable

Mega Turmeric was the most stable for fresh yield with above average yield per plant. This cultivar performed uniformly across environments. IISR Prathiba and Duggriala Red though showed unit regression coefficient were not stable cultivars with below average yield per plant. Rajendra Sonia is good for specific locations as the fresh yield was high and was highly responsive to favorable environments. Similar results were reported by Sharma (2005) and Shahi et al. (1994a). Considering our results, IISR Kedaram with high mean, regression values almost equal to one and low, non significant deviation from regression performed consistently for curing per cent and curcumin across five environments. Therefore, this was the most stable cultivar for curcumin and could be selected for stability of curcumin production. High curcumin cultivar, Narendra Haldi was least responsive with regression values less than one. However, other high curcumin cultivars, Rajendra Sonia, Mega Turmeric and Roma showed regression values more than one indicated its adaptation to specific locations. The results are similar with the finding of Gurung et al. (2012) in chilli for capsaicin. The two high yielding (fresh) varieties, Rajendra Sonia and Narendra Turmeric-1 recorded lowest curing per cent. Chandra et al. (1997) also reported high yield in genotypes with low curing percentage which corresponds to our results. Hence, stable cultivars for yield should be selected based on dry yield. Mega Turmeric, IISR Prathiba and IISR Kedaram showed good responses and were stable for dry yield across environments. Shahi et al. (1994a,b) reported high stability in genotypes with high yield and curcumin. However, because of the significant difference from unity and large deviation from regression we could not conclude stability of other cultivars except IISR Kedaram (for dry yield, curcumin and curing percent), Mega Turmeric (fresh and dry yield) and IISR Prathiba (curing per cent and dry yield) that were stable across all locations. These three cultivars could be a good genetic source for stability in breeding programs for dry yield and curcumin.

5. Conclusions

Turmeric is an ancient spice has been used as a medicine, condiment and as a dye. It is accepted that curcumin has wide range of beneficial properties, including anti-inflammatory, antioxidant, chemo-preventive and chemotherapeutic activity. Stability of curcumin and yield in turmeric is one of the concerns in spices industries, as genotypes perform differently across environments. A genotype that has stable trait expression across environments contributes little to genotype by environment interaction and its performance should be more predictable from the main effects of genotypes and environments than the performance of an unstable cultivar. Eleven genotypes were evaluated for fresh yield, curing per cent, cucumin and dry yield across 10 locations in India. Mega Turmeric was the most stable for fresh yield with above average yield per plant across all environments. Results on curcumin and curing per cent showed that, IISR Kedaram performed consistently across five environments with regression values almost equal to one and non-significant deviation from regression was adjudged to be the most stable cultivar for curcumin production. Mega Turmeric, IISR Prathiba and IISR Kedaram showed high stability for dry yield across environments. Overall, three varieties, Mega Turmeric, IISR Kedaram and IISR Prathiba could serve as a potential genotypes for high dry yield and curcumin content.

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