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Genotype by Environment Interaction and Yield Stability of Potato Cultivars under Tropical Conditions

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ABSTRACT

Potato (*Solanum tuberosum ssp. tuberosum*) cultivars grown under tropical conditions exhibit comparatively poor yields compared to the temperate conditions, hence, there is need for stable cultivars with greater yields. The interactions of four cultivars with ten environments for 2 years under All India Coordinated Research Project (Potato) across the country for 2 harvesting stage (75 and 90 DAP) revealed that the cultivars were significantly different among themselves for Total Yield (TY) and Marketable Yield (MY) harvested at 75 and 90 DAP at seven and eight environments, respectively. The pooled analysis showed a significant difference for cultivar and environmental main effects for all traits, indicating the existence of cultivars genetic variability justified from the heterogeneity of environments. The significant effect of G×E interaction for TY and MY at 90 DAP, and a non significance for the same traits at 75 DAP clearly indicated that the prevailing environments during early crop stage were uniform as compared to its later harvesting stage. Partitioning of G×E interaction into linear and non linear components were highly significant for all traits, strongly suggesting the real differences in cultivars for regression over environmental means and the response of cultivars to environment was controlled genetically. The cultivar K. Pukhraj was proven as early bulking and stable cultivar for TY and MY at 75 DAP and predictable in nature, as against K. Khyati which was stable cultivar for TY and MY at 90 DAP across growing environments. Hence, K. Khyati, which recorded the highest TY (27.45 t ha^{-1}) and MY (25.24 t ha^{-1}) for harvesting at 75 DAP, and TY (31.28 t ha^{-1}) and MY (28.19 t ha^{-1}) at 90 DAP, can be recommended for tropical conditions.

Keywords: G×E interaction, Indian potato cultivars, Marketable yield, Stable cultivar, Tuber yield.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is considered to be the fourth most important food crop in the world, and is grown in more than 125 countries. Almost 52% of the area under the crop lies in the temperate region in Europe, 34% in Asia, and 14% in Africa. The total world potato production is estimated at 364.8 million tonnes in 2012 (FAO, 2014). The yield potential of this crop is reported to be greater under temperate as compared to the tropical conditions, while the potential yield of potato ranges from 40 to 140 t ha^{-1} under optimal growing

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environments (Beukema and Van der Zaag, 1990). India is one of the lowland tropics, and the second largest producer of potato in the world (Scott and Suarez, 2012) by producing 41.5 million tons from 1.97 million ha at an average yield of 21.1 tons ha^{-1} during 2013-14 (Saxena, 2014). Potato is grown from hills, plateaus to plains, where the Indo-Gangetic Plains (IGPs) of the country are the major potato growing regions contributing 85% of total production. However, the climatic normal's of the representative growing regions of AICRP locations revealed the existence of wider variations for the mean maximum (21.1 to 32.6°C) and the minimum temperature (8.0 to 20.9°C) of the growing period of 90 days. Considering the optimum temperature of potato for photosynthesis (20°C), an increment of 5.0°C above the optimum is expected to decrease photosynthetic rate by 25% (Burton, 1981) and greatly reflect on the yield potential of any genotype, causing huge yield gap between growing environments. Furthermore, tuber yield is a polygenic trait, displaying greater variations (Bradshaw, 2006) and instability in several cultivars by environments (Bombik *et al*., 2007; Rymuza and Bombik, 2010; Flis *et al*., 2014). The problems with pest and disease pressure at elevated temperatures, drought and short day conditions (tropical conditions), and yield breakdown in potato cultivars is proven (Bradshaw, 2009). Considering the huge diversity in potato growing environments in India, identifying suitable varieties for each of the different environments as well as proper delineation of target domains of the cultivar is an onerous task.

A Successful cultivar must have good and reliable yield over a wide range of environmental conditions. The basic cause of differences in stability between cultivars is a wide occurrence of genotype by environment interactions (G×E). Cultivars are determined neither by their genes nor by their environment; they are the consequence of the interaction of genes and environment (Suzuki *et al*. 1981). Hence, very often a situation is encountered where the relative rankings of cultivars change from location to location and/or from year to year. According to Allard and Bradshaw (1964) "a cultivar which can adjust its genotypic or phenotypic state in response to transient fluctuations in environment to give a high and stable economic return for place and year, is termed as well buffered", thus, implying its variance among environments is zero (Becker and Leon, 1988). Potato is being harvested at differential stage for specific purposes; this necessitates evaluating stability of performance and range of adaptation of potato cultivars under tropical conditions (Miheretu, 2014). Therefore, this study aimed to study G×E interactions of four commercial cultivars, namely, Kufri Jyoti, Kufri Pushkar, Kufri Khyati and Kufri Pukhraj for stability in respect to Total Yield (TY) and Marketable Yield (MY), under ten different environments.

MATERIALS AND METHODS

Cultivars

The study material consisted of four commercial cultivars Kufri Jyoti, Kufri Pushkar, Kufri Khyati and Kufri Pukhraj, which were assessed for G×E interactions and stability in respect to Total Yield (TY) and Marketable Yield (MY) for harvesting at 75 and 90 Days After Planting (DAP), at 10 locations for two growing seasons i.e. 2013-2014 and 2014-2015 (Table 1). All the cultivars of medium maturity type which mature between 90-110 days. These cultivars were bred at Central Potato Research Institute, Shimla (India) and recommended for commercial cultivation in different parts of the country. To realize the greater yield potential per unit area, these cultivars were incorporated in the All India Coordinated Research Project on Potato, Shimla for its evaluation at across growing environments of the country.

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Table 1. Cultivars and its parentage and maturity group of potato used in the study.

Sl. No	Cultivars	Parentage	Maturity	Tuber morphology
1.	K. Jyoti	3069d(4)×2814a(1)	Medium	Moderately round, white cream, ovoid with shallow eyes and cream flesh
2	K. Pushkar	QB/A-9-120×Spartz	Medium	Moderately oval, yellow, ovoid with medium-deep eyes and cream flesh
3	K. Khyati	MS/82-638×K. Phukraj	Medium	Moderately oblong, white cream, ovoid with medium- deep eye and cream flesh
4	K. Pukhraj	Craige Defiianee×JBX/B-687	Medium	Moderately oblong, yellow, ovoid with medium-deep eyes and yellow flesh

Site Description and Experimental Design

The field trials were conducted at 10 locations spread across the country in two subsequent growing seasons between 2013-2014 and 2014-2015. These locations were highly unique in their climatic conditions (Table 2). All experiments were performed in a completely randomized block design with four replications. Potato cultivars were planted at 60×20 cm spacing at optimum crop season of the respective location to realize the maximum total yield. The recommended dose of N, P, and K was applied in respective locations and other plant protection measures were followed effectively. Data collected from each plot were: (a) Total tuber yield (kg plot^{-1}), (b) Marketable yield (kg plot^{-1}), and the Total Yield (TY) and Marketable Yield (MY) per ha was estimated for harvesting at 75 and 90 days after planting.

Statistical Analysis

The data were analyzed in two steps. The first step was a classical one-way ANOVA for each trait to determine differences among cultivars in all the 10 field experiments, and the means were compared using Duncan's Multiple Range Tests. Secondly, Pooled ANOVA for all the sites was also conducted. Stability analysis (Genotype×Environment interaction) for TY and MY was performed according to Eberhart and Russell (1966). Stability parameters calculated were regression coefficient (bi) and deviation from regression coefficient (S^2di). Cultivars were considered as fixed effects and the locations were considered as random effects. Mean square deviations from linear regression response were used to compare magnitude of *SE* (b) as a method in which average yield of each cultivar at each location was used as an environmental index for subsequent regression analysis. The data was subjected to statistical analysis using OPSTAT developed by Haryana Agricultural University, Hisar (Haryana), India (Sheoran *et al*., 1998).

RESULTS

Cultivars Differentiation in Each Environment of Indo-Gangetic Plains

The analysis of variance estimated for TY and MY for harvesting at 75 (Table 3) and 90 DAP (Table 4) at 10 growing environments showed that cultivars were significant for TY and MY harvesting at 75 DAP. Considering the environments, locations with a highly significant (Jalandar, Pasighat and Pune) to non significant (Kalyani and Kanpur) difference for cultivars TY and MY were observed.

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Table 2. Description of the test environments of the field experiment in the study.

Sl .No	Locations	State	Latitude	Longitude	Altitude (M)	Seasonal mean temperature	Cumulative *p* days	Cumulative GDD
1	Bhubaneswar	Orissa	20°.15'	85°.51'	26	23.43	669.44	1712.44
2	Dholi	Bihar	26°.07'	85°.45'	60	18.98	722.83	1312.52
3	Jalandhar	Punjab	31°.33'	75°.57'	228	18.13	648.07	1235.95
4	Jorhat	Assam	26°.45'	94°.13'	116	21.43	682.19	1532.35
5	Kalyani	West Bengal	19°.15'	73°.07'	14	21.60	691.62	1548.35
6	Kanpur	Uttar Pradesh	26°.28'	80°.21'	581	17.51	662.63	1179.55
7	Pasighat	Arunachal Pradesh	28°.06'	95 °.23'	157	17.08	693.05	1141.35
8	Patna	Bihar	25°.36'	85°.06'	60	18.97	721.83	1311.03
9	Pant Nagar	UttaraKhand	28°.97'	79°.41'	344	17.98	750.15	1222.35
10	Pune	Maharastra	18°.32'	73°.51'	559	22.33	713.28	1613.35

Table 3. Mean values of total and marketable yield (t ha^{-1}) at 75 days after planting in ten environments of potato growing regions in India.

Cultivars	Growing Environments[a]										Genotypic Mean
	BHU	DHL	JAL	JRH	KAL	KAN	PAS	PAT	PNT	PUN	
					Total yield (t ha^{-1}) at 75 days						
K. Jyoti	18.16	14.94	32.64	23.96	23.91	26.23	39.75	22.92	28.89	16.20	24.80
K. Pushkar	19.77*	20.32*	39.61**	23.94	27.80	25.13	42.37	25.90	29.30	17.64*	27.18
K. Khyati	19.81*	17.54	39.77**	27.46*	25.64	26.77	44.80**	23.09	32.01	17.66*	27.45
K. Pukhraj	18.45	18.07	37.13**	25.89	27.28	25.29	42.91*	26.33*	32.87	18.44**	27.26
Site Mean	19.05	17.72	37.29	25.31	26.16	25.86	42.46	24.56	30.77	17.49	26.67
SE	0.40	1.21	0.26	0.97	1.25	1.40	0.79	0.98	1.40	0.39	0.905
CV (%)	2.56	8.35	0.84	4.69	5.45	6.61	2.27	4.89	5.57	2.72	4.51
F value	*	*	**	*	ns	ns	**	*	ns	**	
LSD (0.05%)	1.38	4.18	0.89	3.35	4.03	4.83	2.73	3.39	4.85	1.35	3.39
					Marketable yield (t ha^{-1}) at 75 days						
K. Jyoti	17.60	12.60	31.55	19.26	22.62	22.83	37.79	19.65	25.32	15.33	22.46
K. Pushkar	18.91**	16.44*	37.38**	18.91	29.44	22.38	41.35**	21.60	25.02	16.72*	24.81
K. Khyati	18.88**	15.18	38.78**	22.33*	24.78	23.01	43.59**	19.63	29.42	16.76*	25.24
K. Pukhraj	17.70	15.38	35.46**	21.11	26.06	21.49	41.52**	22.56	30.05	17.49**	24.88
Site Mean	18.27	14.90	35.79	20.40	25.73	22.43	41.06	20.86	27.45	16.58	24.35
SE	0.17	0.92	0.26	0.75	2.18	1.65	0.50	1.99	1.51	0.38	1.031
CV (%)	1.17	7.52	0.89	4.47	10.39	9.03	1.48	11.69	6.74	2.82	6.29
F value	**	*	**	*	ns	ns	**	ns	*	**	
LSD (0.05%)	0.61	3.17	0.90	2.58	7.55	5.72	1.72	6.89	5.22	1.32	4.32

[a] BHN= Bhubaneswar, DHL= Dholi, JAL-Jalandhar, JRH= Jorhat, KAL= Kalyani, KAN= Kanpur, PAS= Pasighat, PAT= Patna, PNT=Pantnagar , PUN= Pune.
* Significant at the level P= 0.05, and ** Significant at the level P= 0.01

Table 4. Mean values of total and marketable yield (t ha^{-1}) at 90 days after planting in ten environments of potato growing regions in India.

Cultivars	Growing Environments[a]										Genotypic Mean
	BHU	DHL	JAL	JRH	KAL	KAN	PAS	PAT	PNT	PUN	
					Total yield (t ha^{-1}) at 90 days						
K. Jyoti	18.92	15.10	40.65	24.59	28.55	32.67	40.25	28.76	32.34	16.53	27.83
K. Pushkar	21.67**	23.29**	49.66**	25.98**	35.07**	30.48	42.98	30.32	32.38	18.23**	31.00
K. Khyati	20.49**	18.86**	49.28**	23.75	34.28**	35.01*	44.87	31.47	36.20*	18.09*	31.23*
K. Pukhraj	17.64	14.38	46.71**	24.51	37.13**	38.16**	43.15	33.02	35.67	18.67**	30.90
Site Mean	19.68	17.91	46.58	24.71	33.76	34.08	42.81	30.89	34.15	17.88	30.24
SE	0.46	0.50	0.71	0.34	0.54	1.22	1.52	1.71	1.00	0.31	0.831
CV (%)	2.87	3.41	1.87	1.70	1.98	4.40	4.36	6.79	3.59	2.13	3.89
F value	**	**	**	**	**	**	ns	ns	*	**	
LSD (0.05%)	1.60	1.72	2.47	1.19	1.88	4.24	5.27	5.93	3.46	1.08	3.33
					Marketable yield (t ha^{-1}) at 90 days						
K. Jyoti	18.24	12.88	38.61	19.20*	27.89	28.43	39.67	25.06	29.28	15.92	25.51
K. Pushkar	20.82**	19.46**	47.64**	18.12	33.58**	25.59	42.31	25.58	29.16	17.58**	27.98
K. Khyati	19.57**	14.79*	47.85**	17.85	32.97*	30.46*	44.07	23.69	33.26*	17.45*	28.19
K. Pukhraj	16.88	12.07	45.40**	18.88	34.83**	28.85	44.01	29.34*	32.71*	17.98**	28.09
Site Mean	18.88	14.80	44.88	18.51	32.32	28.33	42.52	25.92	31.10	17.23	27.44
SE	0.39	0.78	0.60	0.38	1.05	1.15	2.07	1.18	0.98	0.30	0.888
CV (%)	2.52	6.43	1.63	2.51	3.98	4.97	5.97	5.59	3.88	2.10	4.56
F value	**	**	**	*	**	*	ns	*	**	**	
LSD (0.05%)	1.35	2.69	2.07	1.31	3.63	3.98	7.18	4.09	3.41	1.02	3.54

[a] BHN= Bhubaneswar, DHL= Dholi, JAL-Jalandhar, JRH= Jorhat, KAL= Kalyani, KAN= Kanpur, PAS= Pasighat, PAT= Patna, PNT= Pantnagar, PUN= Pune.
* Significant at the level P= 0.05, and ** Significant at the level P= 0.01.

Although a significant yield difference was observed among the cultivars in their preferred growing environments, the cultivar K. Khyati registered the highest mean TY (27.45 t ha^{-1}) and MY (25.24 t ha^{-1}) for harvesting at 75 DAP at across locations, followed by K. Phukraj (27.26 and 24.88 t ha^{-1}, respectively) with at par level. The cultivar K. Khyati recorded a significantly higher TY at five locations for harvesting 75 DAP as compared to K. Phukraj (4) and K. Pushkar (4). The location Pasighat (42.46 t ha^{-1}), Jalandar (37.26 t ha^{-1}) and Pant Nagar (30.77 t ha^{-1}) were recorded as high yielding growing environments for TY as against the poor yielding environments like Pune (17.79 t ha^{-1}), Dholi (17.72 t ha^{-1}) and Bhubaneswar (19.05 t ha^{-1}). The results on harvesting at 90 DAP revealed a significant yield difference among cultivars at eight locations for TY and nine locations for MY (Table 4). The cultivar K. Khyati had a significantly higher yield at seven locations for TY (31.23 t ha^{-1}) and MY (28.19 t ha^{-1}). Among 10 locations, Pasighat recorded a non-significant difference for cultivars despite its highest TY and MY (42.81 and 42.52 t ha^{-1}, respectively). The location Jalandar (46.58 t ha^{-1}), Pasighat (42.81 t ha^{-1}) and Pant Nagar (34.15 t ha^{-1}) registered as high yielding environments for TY, and Jalandhar, Pasighat, Kalyani for MY harvesting at 90 DAP. The poor yielding environments were Pune (17.88 t ha^{-1}), Dholi (17.91 t ha^{-1}) and Bhubaneswar (19.68 t ha^{-1}) for TY and MY.

Pooled Analysis of Cultivars Differentiation in Indo-Gangetic Plains

The pooled analysis of variance showed that cultivar and environment mean square when tested against G×E interactions, were highly significant for all the traits (Table 5). The mean squares due to G×E interaction were highly significant when tested against pooled error for TY and MY for harvesting at 90 DAP; however, it was non significant for TY and MY at 75 DAP. Portioning of G×E interaction into linear (E+G×E) and non linear (Pooled deviations) components to determine the differential response of cultivars to varying agro climates revealed the environments (linear) were highly significant for all the traits in harvesting at 75 and 90 DAP. Except for TY at 75 DAP, all the other traits showed significant G×E (linear) in the present study. The sum of squares of G×E (linear) was a large portion of the G×E interaction as compared to environment (linear) sum of squares and the residual. Pooled deviations were highly significant when tested against pooled error for all the traits in the present study.

Tuber Yield Stability

The stability analysis using mean (x), regression coefficient (bi), and Stability index (S^2di) was estimated for TY and MY for harvesting at 75 and 90 DAP and simultaneous selection for yield and stability of cultivars (Table 6). Except K. Jyoti, the other three cultivars recorded above average mean yield compared to its specific location yield for all the traits under study. However, K. Khyati recorded the highest above average mean yield for both TY (27.45 t ha^{-1}) and MY (25.24 t ha^{-1}) for harvesting at 75 and 90 DAP (31.23 t ha^{-1} and 28.19 t ha^{-1}, respectively). The regression coefficient (bi) value observed for TY (0.913 to 1.104) and MY (0.890 to 1.108) for harvesting at 75 DAP was very wider in range, as that of its deviation from regression value (S^2di), which was ranging from 0.480 to 1.860 (TY) and from 0.407 to 2.428 (MY). TY and MY harvested at 90 DAP also showed a wider range of bi (from 0.890 to 1.107 and from 0.856 to 1.091, respectively) and S^2di values (from 0.197 to 6.066 and from 1.117 to 4.780, respectively). In the case of TY and MY at 75 DAP, K. Pukhraj recorded greater above mean yield, bi value equal to unity (bi= 1.004; bi= 0.996) and a non significant S^2di nearing zero (S^2di= 0.480; S^2di= 0.463). K. Khyati, on the other hand, recorded greater above mean yield, *bi* value slightly greater than unity (bi= 1.104; bi= 1.108) and

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Table 5. Mean Squares (MS) variation for total tuber yield and marketable yield (at 75 and 90 days) at ten growing environments in India.[a]

Source of variation	df	Mean sum of square values			
		Total yield at 75 days (t ha^{-1})	Marketable yield at 75 days (t ha^{-1})	Total yield at 90 days (t ha^{-1})	Marketable yield at 90 days (t ha^{-1})
Cultivar	3	15.67**	16.23**	25.97**	16.67*
Environment	9	269.68**	284.37**	406.53**	439.18**
Cultivar×Environment	27	2.20	2.63	5.38**	5.044**
Environ+ (Cultivar×Environment)	36	69.07	73.07	105.6	113.57
Environ (L)	1	2427.1**	2559.3**	3658.7**	3952.64**
Environ×Cultivar (L)	3	3.83	5.09*	10.23*	12.3*
Pooled deviation	32	1.49**	1.74**	3.58**	3.09**
Pooled error	60	1.47	2.34	1.38	1.56

[a] Significant at 5% level for G, E was tested against G×E interaction; Significant at 5% level for G (L) and G×E (L) was tested against pooled deviation; Significant at 5% level for G×E, E+ (G×E) was tested against pooled error. * Significant at the level P= 0.05, ** Significant at the level P= 0.01.

Table 6. Mean, regression coefficient and stability index for total tuber yield and marketable yield (at 75 and 90 days) at 10 growing environments in India.[a]

Cultivars	Indo-Gangetic Plains											
	Total yield at 75 days (t ha^{-1})			Marketable yield at 75 days (t ha^{-1})			Total yield at 90 days (t ha^{-1})			Marketable yield at 90 days (t ha^{-1})		
	x	b_i	S^2d_i	x	b_i	S^2d_i	x	b_i	S^2d_i	x	b_i	S^2d_i
K. Jyoti	24.80	0.913	1.038	22.46	0.890	0.407	27.83	0.890	2.004	25.51	0.856	1.931
K. Pushkar	27.18	0.978	1.860	24.81	1.007	2.428	31.00	0.931	6.066*	27.98	0.996	4.780*
K. Khyati	27.45	1.104	0.646	25.24	1.108	0.567	31.23	1.072	0.197	28.19	1.091	1.117
K. Pukhraj	27.26	1.004	0.480	24.88	0.996	0.463	30.90	1.107	4.225*	28.09	1.087	2.461
Mean	26.67	1.00		24.35	1.00		30.24	1.00		27.44	1.00	
SE	0.41	0.050		0.44	0.052		0.63	0.063		0.59	0.056	

[a] x= Mean, b_i= Regression coefficient, S^2di= Stability index.* Significant at the level P= 0.05, ** Significant at the level P= 0.01.

a non significant S^2di nearing zero (S^2di= 0.646; S^2di= 0.567). However, the cultivar K. Jyoti exhibited below average mean yield, bi value nearer unity (bi= 1.00), and a non significant S^2di value. Despite the greater above average yield of the cultivar K. Pushkar, its *bi* value was near unity and its S^2di value was found greater. Similarly, for TY and MY at 90 DAP, the cultivars K. Pukhraj and K. Pushkar recorded greater above average yield, bi value slightly greater and lesser than unity in the respective cultivars, and greater S^2di value. However, K. Khyati resulted in the above average mean yield, bi value slightly greater than unity (bi= 1.072), and minimum S^2di nearing zero (S^2di= 0.197).

DISCUSSION

Food production is the high priority for feeding more than 9.0 billion people in the world by 2050, where potato is believed to be a significant component in accomplishing this monumental task (Staff, 2015). The contribution of tropical ecosystem is challenged with high temperature, the climate change effects on potato production have been predicted to decrease yield by 10-19% in 2010-2039, and by 18-32% in the 2050s (Hancock *et al*. 2013). India is one of the low land tropics, and a model country comprising wider climatic diversity of zone with a long frost free growing season (6.0-7.0 months) and the zone having a short growing period (4 months). Hence, assessing the resultant promising cultivars developed by using local and exotic parents for yield potential at specific and multi environment is very much imperative, as yielding ability of a cultivar is an outcome of the reactions of that cultivar in different agro-ecological conditions. The genotype×environment interactions could be attributed to predictable and non-predictable effects (Allard and Bradshaw, 1964), which are determined by macro and micro-environmental conditions, respectively.

The cultivars, parentage and their special features differed for tuber shape, colour, eye depth, etc (Table 1). The six climatic normals observed at 10 environments for 90 days of growing season exhibited wider diversity (Table 2). The expression of phenotype of any trait is strongly influenced by cultivars and growing environment, as supported by ANOVA estimated for TY and MY for harvesting at 75 (Table 3) and 90 DAP (Table 4) at each location level. Among the 10 environments tested, the significant effect of G×E was observed at seven environments for TY and MY at 75 DAP (Table 3), at eight environments for TY at 90 DAP, and nine environments for MY at 90 DAP (Table 4). This clearly showed that the performance of cultivars varied highly significantly from one environment to another for all traits (Haydar *et al*., 2009; Flis *et al*., 2014). However, the non significant difference of G x E interactions observed for TY (Kalyani, Kanpur and Pant Nagar) and MY (Kalyani, Kanpur and Patna) at 75 DAP and for TY and MY (Pasighat) at 90 DAP at few environments clearly showed that the cultivars were not influenced strongly by the environments at these locations, as the limits and optimal temperature for the growth of the above-ground parts and for the tubers were different (Van Dam *et al*., 1996).

From pooled analysis, the higher magnitudes of variances due to environments over the cultivars for all the traits varied and its magnitude among the traits such as TY varied 17.2 fold and for MY 17.52 fold, for harvesting at 75 DAP; and at 90 DAP, from 15.65 fold for TY to 26.34 fold for MY. This proved its suitability for further stability analysis (Abo-Hegazy *et al*. 2013). In totality, 30 and 50 % of the study areas exhibited a highly significant difference for both TY and MY at 75 (Jalandar, Pasighat, and Pune) and 90 DAP (Bhubaneswar, Dholi, Jalandhar, Kalyani, and Pune), respectively, which strongly support that at earlier harvest stage the interaction of G×E was minimal as compared to later harvesting. This finding is

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justified from the fact that the tuber yield increase with the progress of growth and maturing of tuber, attributed to a progressive increase in day-length and sunlight intensity during the crop cycle (Ierna, 2009) and differential influence of harvesting time on cultivars yield (Sogut and Ozturk, 2011; Dessalegn *et al*., 2008; Flis *et al*., 2014). However, similar to early bulking cultivars, the medium and late bulking is also preferred by the farmers for want of greater yield or other quality traits. In such conditions, early bulking potatoes are harvested at their physiological maturity, and the rest are harvested prematurely either to sustain greater market price or vacating field for raising other subsequent crop immediately, in the major potato growing areas. Hence, the pair wise mean yield comparison performed for different harvesting time (75 and 90 DAP) indicated that the cultivar K. Khyati invariably registered the highest mean TY and MY at 75 (27.26 and 25.24 t ha^{-1}, respectively) and 90 DAP (31.23 and 28.19 t ha^{-1}, respectively) across growing environments. This reflects its suitability for early harvesting, too. Further, the yield potential observed among the cultivars at their specific preferred environments was found greater as compared to across environments. The greatest TY at 75 and 90 DAP (Pasighat, Jalandar, and Pant Nagar) at about > 30.0 t ha^{-1} of the identified high yielding growing environments is justified with their ideal seasonal mean temperatures (17-18^{o}C) and cumulative GDD (< 1,250) most suiting to these cultivars for their growth and development during crop season (Rymuza *et al*., 2015). The lowest TY at about < 20 t ha^{-1} of the identified poor yielding environments (Pune and Bhubaneswar) might be due to their greater seasonal mean temperature (22-24^{o}C) and cumulative GDD (> 1600). These yield differentials of potato at the contrasting environments justified that haulm growth is fastest at 20-25°C against the optimal range for tuberization and tuber growth (15-20°C), which significantly inhibited tuberization and greatly reduced potato assimilate partitioning to tubers (Haynes *et al*., 1989; Thornton *et al*., 1996).

The pooled analysis showed that the main effects (cultivar and environment) were significant for all the traits, indicating the existence of genetic variability among the cultivars justified from the heterogeneity of environments based on its significant difference for environment. The significant effect of G×E interaction of TY and MY at 90 DAP, but not for the same traits at 75 DAP, clearly indicated that the cultivars were strongly influenced at later harvest only and the prevailing environments at early growth stage was assumed similar. Further, a significant G×E interaction may be of a cross-over type in which case the ranking of genotypes non constant across environments and the interaction is non-significant, because of change in magnitude of response of cultivars (Baker, 1988; Flis *et al*., 2014).

Portioning of G×E interaction into linear (E+G×E) and non linear (Pooled deviations) components are important in determining the differential response of cultivars to varying growing environments. Hence, *E+G×E* interactions were partitioned into Environment (linear), Genotypes×Environment (linear) interaction (bi) and unexplainable deviation from regression (S^2di). Accordingly, a highly significant effect of Environment (linear) for all the traits strongly suggested that the real differences in cultivars for regression over environmental means and the response of cultivars to environment were controlled genetically. Further, there were genetic divergences among cultivars taking into account their responses variation of environmental conditions (Eberhart and Russell, 1966). A higher magnitudes of variance due to Environments (linear) observed for all the traits might be responsible for high adaptability and stability of TY and MY for harvesting at 75 and 90 DAP (Flis *et al*., 2014) in potato.

The non significance of G×E (linear) observed for TY at 75 DAP clearly showed that the G×E interactions was of non-linear type and lacking genetic differences among cultivars for their response to varying environments. However, the rest of traits exhibited significant G×E (linear), suggesting that the major portion of interaction was linear in nature and prediction over environments may be possible for MY at 75 DAP, and TY and MY at 90 DAP. The sum of squares value for the G×E (linear) was a large portion of the G x E interaction, when compared with the environment E (linear) and the residual. The highly significant trend observed for genotype and environment for TY and MY for harvesting at 75 and 90 DAP showed that the cultivars were greatly and significantly different from one environment to another, which is due to their different genetic makeup or the variation due to the environments or both (Rymuza *et al*., 2015). It is interesting to note that the existence of a non significant difference for genotype and environment (main effect) observed for TY and MY for harvesting at 75 DAP reflects the homogeneity of genotype performance under the prevailing environments. A significance effect due to a non-linear component (pooled deviation) observed for TY as well as MY for harvesting at 75 and 90 DAP indicated that the major components for differences in stability were due to deviation from linear function. Therefore, it may be concluded that the relatively unpredictable components of the interaction may be more important than the predictable components. In this respect, it is proved that the environmental variation can be classified into predictable and unpredictable variation (Becker and Leon, 1988) caused by more permanent features and by year to year fluctuations in the weather, respectively (Abd El-Moula, 2011).

Eberhart and Russel (1966) emphasized that both linear (bi) and non-linear (S^2di) components of G×E interaction should be considered in judging the phenotypic stability of a particular genotype. The greater variations for estimates of stability parameters bi and S^2di values for TY and MY for harvesting at 75 DAP, indicated differentials in cultivar performance and adaptability to different environmental conditions (Rymuza *et al*., 2015). While considering x, bi and S^2di values together, except K. Jyoti, all the other three cultivars (K. Khyati, K. Puhkraj, and K. Pushkar) recorded with above average mean yield over the specific location mean yield (Table 6). The cultivar K. Khyati recorded the highest above average mean yield for both TY and MY at 75 DAP and 90 DAP, indicating its superiority performance for yield and wider adaptability due to bi value of unity (bi=1.00) and non significant S^2di value. For TY and MY at 75 DAP, K. Pukhraj recorded greater above mean yield, high stability, and wider adaptability across the environments (Rymuza and Bombik, 2010; Flis *et al*., 2014). The cultivars K. Khyati on the other hand, recorded greater above mean yield, high stability and wider adaptability across the favourable environments (Rymuza *et al*., 2015) and the cultivar K. Jyoti showed greater stability and wider adaptability to poor environments (Flis *et al*., 2014).

Similarly, for TY and MY at 90 DAP, the wider range of *bi* and S^2di values for TY and MY strongly indicated different response of genotype performance and adaptability to different environmental conditions. The cultivars K. Pukhraj and K. Pushkar recorded greater above average yield, and adaptable for favourable and unfavourable environments with unpredictable response to environment (Flis *et al*., 2014). Some researchers are also of the opinion that the cultivar must have the genetic potential for superior performance under ideal growing conditions, and yet must also produce acceptable yields under less favourable environments (Koemel *et al*., 2004). This is proven by the cultivars K. Khyati, which resulted in the above average mean total yield, bi value slightly greater than unity (bi= 1.072), and S^2di nearing zero (S^2di= 0.197), showing its high stability and wider adaptability across environments and proving the stability principles of Eberhart and Russel (1966). Similar findings have

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been reported earlier in potato (Haydar *et al*., 2009; Flis *et al*., 2014; Rymuza *et al*., 2015).

CONCLUSIONS

The locations tested were highly distinct from each other and could be grouped into high yielding (Pasighat, Jalandhar, and Pantnagar) and low yielding environments (Pune and Bhubaneswar).

The cultivar K. Pukhraj is stable cultivar for TY (27.26t ha^{-1}) and MY (24.88t ha^{-1}) for harvesting at 75 DAP and its predictable nature due to its x, bi, and S^2di values.

The cultivars K. Khyati is a stable cultivar for TY (31.23 t ha^{-1}) and MY (28.19 t ha^{-1}) for harvesting at 90 DAP across the growing environments of Indo-Gangetic plains.

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برهمکنش (اثر متقابل) ژنوتیپ و محیط و پایداری عملکرد در کولتیوارهای سیب زمینی در شرایط گرمسیری

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چکیده

کولتیوارهای سیب زمینی (*Solanum tuberosum ssp. tuberosum*) در شرایط رشد گرمسیری عملکرد نسبتا ضعیفی در مقایسه با مناطق معتدل نشان می دهند و از این رو، سیب زمینی هایی با عملکرد زیاد و پایدارمورد نیاز است. در این پژوهش ، برهمکنش چهار کولتیوار با ده محیط (اقلیم) در برنامه پروژه سراسری تحقیقات هندوستان (برنامه سیب زمینی) طی دو سال و در دو هنگام برداشت (

75 و 90 روز بعد از کاشت: 75DAP و DAP 90) آشکار ساخت که این کولتیوارها از نظر عملکرد کل (TY)و عملکرد بازار پسند (MY) که در زمانهای 75DAP و DAP 90 به ترتیب در هفت و هشت محیط برداشت شده بودند به طور معناداری با هم اختلاف داشتند. تجزیه تلفیقی نشاندهنده اختلاف معنادار اثر اصلی محیط و کولتیوار روی همه صفات بود که این امر نشانگر وجود تغییرات (تفاوتهای) ژنتیکی کولتیوارها ناشی از ناهمگنی محیط ها بود. اثر معنادار G x E برای TYو MY درDAP 90 و بی معنا بودن آماری همان صفت در DAP 75 به روشنی اشارت داشت که در مقایسه با مرحله برداشت، شرایط محیطی در مراحل اول رشد گیاه یکنواخت بود. جزء بندی کردن G x E به اجزای خطی و غیر خطی برای همه صفات به شدت معنادار بود که این امر موکدا به این اشاره میکرد که اختلافات بین کولتیوارها در مورد رگرسیون روی میانگین های محیط و واکنش کولتیوارها به محیط به طور ژنتیکی کنترل می شد. بر اساس نتایج، کولتیوار K. Pukhrajبه عنوان کولتیواری زود بازده با محصول پایدار از نظر TY و MY در برداشت DAP 75 و با طبیعتی قابل پیش بینی تثبیت شد و در برابر آن کولتیوار K. Khyatiبود که از نظر TY و MY در همه محیط های(مناطق) کشت سیب زمینی، کولتیواری پایدار درDAP 90 بود. از این رو، کولتیوار K. Khyatiرا که بیشترین TY (27/45 تن د رهکتار) و MY (25/24 تن درهکتار) را در مرحله DAP 75 دارا بود و در DAP 90، عملکرد TY(31/28 تن در هکتار) وMY (28/19 تن د رهکتار) بود را می توان برای مناطق گرمسیری توصیه کرد.

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