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BLUP and stability analysis of multi-environment trials of potato varieties in sub-tropical Indian conditions

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ABSTRACT

Potato is an important crop in India with area spread across Himalayan hills in the North to hot tropical conditions in South, albeit major area in sub-tropical Indo-Gangetic plains. The first common requirement in all regions is that the variety should have high performance for tuber yield along with essential agronomic traits. The present study was carried out to identify an ideal variety with wide adaptability for tuber yield and dry matter. Six varieties were evaluated in 9, 11 and 10 locations in the years 2014–15, 2015–16 and 2016–17, respectively for TY, MY and DM. The data were analysed with ANOVA, mixed models, BLUPs and GGE biplot as well as univariate stability statistics. Combined analysis of variance showed significant genotype, environment and genotype × environment interactions. The relative magnitudes of G, E and G×E variances accounted for 6.76–8.91, 51.85–76.65 and 12.41–23.19 per cent for TY and 2.86–4.66, 65.87–72.85 and 13.74–20.04 per cent for DM. Although the genotypes contributed significantly, major part of the variation was explained by environments for all the three traits. Mean across locations and years, and BLUP values of varieties for all the three traits showed similar results with Kufri Khyati as the best variety for TY and MY, whereas Kufri Jyoti and Kufri Garima were best for DM. Based on GGE biplot and univariate stability statistics, Kufri Khyati was the ideal high yielding wide adaptable variety in all the three years and Kufri Jyoti was the ideal variety based on mean dry matter and stability. The environments were very diverse and their clustering suggested three groups, which can be used as three separate zones for varietal evaluation and regional deployment of varieties.

1. Introduction

Although introduced in India, potato has become the staple crop of masses and is grown in wide agro-ecologies ranging from hills to plains and plateau regions. In 1961, India's annual potato production was 2.72 million tonnes from an area of 0.4 m ha but by 2017, the production exceeded 48.6 million tonnes from 2.2 m ha area, nearly 18% and 6% increase in production and area establishing potato as an important crop in Indian economy (FAOSTAT 2018). Now, India is the second largest producer of potato in the world after China with an annual productivity of 22.3 tonnes per hectare (FAOSTAT 2018). Various biotic and abiotic stresses affect potato production and productivity globally. On the basis of the diverse soil, climate, agronomic features and the varietal requirements, the potato growing areas in India can be divided into eight zones covering hills, North, Central, Eastern and Western plains, and plateau region. Although, potato is grown in diverse agro-ecologies in eight zones in India, the major potato growing area (>80%) is in Indo-Gangetic plains (Pradel et al., 2019). Requirements of varieties vary with the growing environment and ultimate use. The first common requirement in all regions is that the variety should have high performance for tuber yield and other essential agronomic traits including tuber shape, eye depth and keeping quality. The special traits for processing varieties need low sugar content, high dry matter, and good tuber size and shape. The reliability of a variety lies in its superiority over a wide range of environmental conditions and also over the years. The performance of a variety varies across locations and years because of genotype × environment interaction. It is important to conduct trials across environments to select genotypes with high and stable performance over a wide range of environments. Although the selection of superior genotypes for a specific target environment is practical for some areas (Ceccarelli 1989), the selection of widely adapted potato cultivars is the primary breeding goal of many potato breeders.

Moreover, potato is a clonally propagated crop and around 3.0 tonnes seed potato is required per hectare. Requirement of seed potato for the whole country is huge and requires concerted efforts and resources. Seed potato production requires well defined scientific approaches and can be

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done only in limited geographic regions unless there is provision of modern climate control and propagation tools like aeroponics, net house and tissue culture facility. It is important therefore, to identify suitable varieties for different locations/regions to optimize the resources and produce the seed of best suitable varieties region-wise. Climate change further impact the potato productivity particularly by climate-related changes in temperature, rainfall patterns, and indirect effects, such as higher severity and incidence of pest and disease outbreaks (Pradel et al., 2019). It will not only affect the productivity but quality also. It therefore becomes imperative to evaluate the varieties under changing climatic conditions for their performance and suitability across locations in the country.

Genotype-by-environment interaction analysis is the key for selection and cultivar recommendation, and to identify suitable production and test environments (Manrique and Hermann 2000). Potato tuber yield and quality is prone to environmental changes resulting in variable yield and quality owing to genotype-by-environment interaction (Tai 1971, 2007; Bai et al., 2014; Gurmu et al., 2017). Genotype-by-environment interaction (GEI) leads to differential response of genotypes across growing environments. GEI analysis is an essential component in variety evaluation for release of high yielding and stable genotypes. The need for stable cultivars that perform well over a wide range of environments becomes increasingly important as both potato farmers and industry require reliable production and quality. Stable genotypes identification is a major objective in crop breeding programmes across the globe including potato (Affleck et al., 2008; Tai 1971, 2007).

The objective of this paper is to understand the genotype by environment interaction in potato, identification of best wide adaptable varieties across locations in the country for tuber yields and dry matter.

2. Materials and methods

Six varieties namely Kufri Jyoti, Kufri Garima, Kufri Pukhraj, Kufri Bahar, Kufri Pushkar and Kufri Khyati were included in this study (Table 1). These varieties were raised in 9, 11 and 10 locations in the years 2014–15, 2015–16 and 2016–17, respectively. The information on agro-climatic conditions of the locations included in the study have been furnished in Table 2. Five rows of each variety were raised in randomized complete block design with three replications. The row length was 3 m with row to row spacing of 60 cm. The crop was raised following standard package and practices of the crop. Three trials were conducted at each location for 60, 75 and 90 days crop duration. The data were recorded on total tuber yield (TY) and marketable tuber yield (MY) on plot basis for each location and crop duration and converted into tonnes per hectare for statistical analysis. Dry matter (%) (DM) was also recorded for all the trials except 60 days crop duration. DM was recorded in percentage as (dry weight/fresh weight) x 100. The variety Kufri Garima was not included in the analysis for the year 2014–15 due to non-availability of data.

Three-way ANOVA was performed in R (R Core Team, 2014) to determine the importance of genotype, environment, years and interactions effect on potato tuber yields and dry matter performance under different crop durations. The traits in different crop durations were also statistically analysed with ANOVA under a mixed model in lmer function in R. The genetic merit of each genotype was evaluated by best linear unbiased prediction (BLUP) using restricted maximum likelihood (REML) for variance component estimation in R. GGE biplot analysis was performed using PBtools software (Sales et al., 2013). The GGE biplot methodology was used to analyse genotype performance for each environment, genotype stability, representative environment, and discriminating power of each environment. Univariate stability analyses were done using RGxE program in R (Dia et al., 2017).

3. Results and discussion

Combined analysis of variance showed significant genotype × environment interactions ($P < 0.001$) exhibiting the influence of changes in environment on tuber yield performance of varieties in all the three crop durations and dry matter. Similarly, the genotype and environmental factor i.e. years and locations main effect was also significant ($P < 0.001$). The relative magnitudes of G, E and G×E variances accounted for 6.76–8.91, 51.85–76.65 and 12.41–23.19 per cent for total tuber yield (TY) for 60, 75 and 90 days crop duration, respectively; 6.2–8.07, 56.41–77.15 and 12.16–20.49 per cent for marketable tuber yield (MY) for 60, 75 and 90 days crop duration, respectively; 2.86–4.66, 65.87–72.85 and 13.74–20.04 per cent for dry matter (DM) for 75 and 90 days crop duration, respectively (Table 3). Although the genotypes contributed significantly, major part of the variation was explained by environments for all the three traits under study. This indicated that the environments were diverse and traits were affected due to change in the environments (Table 1). The components of variance estimation using a mixed model also showed similar results to that of ANOVA analysis. The environment was the most important source of variation for all the traits followed by genotype × environment interaction (Table 4).

The results are in accordance with Mijic et al. (2019) and Flis et al. (2014), who also observed higher influence of environment during the evaluation of potato varieties across the locations. Relatively low contribution of genetic variance to the total variance was also reported earlier (Mijic et al., 2019).

Differences between tuber yield and dry matter means were observed in genotypes evaluated in different environments over the years (Table 5). Kufri Pukhraj (36.68 t/ha) was the highest yielding varieties across locations in the year 2014, while Kufri Khyati topped in 2015 (37.49 t/ha) and 2016 (36.22 t/ha) for TY at 90 days crop duration. The variety, Kufri Khyati also performed better than other varieties and produced highest marketable tuber yield across locations during the years 2015 and 2016. Kufri Khyati was also the highest yielding variety for 60 and 75 days crop duration across locations during all the three years, exception being 75 days crop duration in the year 2014 where Kufri Pushkar and Kufri Pukhraj recorded higher total and marketable tuber yield, respectively (Table 5). Although, there was wide variation for dry matter in the tubers across locations and years, the variety, Kufri Jyoti (17.54) attained highest DM in the year 2014, while Kufri Garima recorded highest DM in the year 2015 (18.48) and 2016 (18.74) at 90 days crop duration. Kufri Jyoti also performed better for high dry matter at 75 days crop duration in the years 2014 and 2015 (Table 5).

Table 1. Description of varieties used in the study.

Name	Year of release	Parentage	Areas of Adaptation	Maturity duration	Tuber features
Kufri Jyoti	1968	3069d (4) × 2814a (1)	Wide adaptable-Hills, plains and plateau	Early to medium	White-cream, ovoid with shallow eyes and cream flesh
Kufri Bahar	1980	Kufri Red × Gineke	North Indian plains	Medium	White-cream, ovoid with medium eyes and white flesh
Kufri Pukhraj	1998	Craigs Defiance × JEX/B-687	North Indian plains and plateau	Early to medium	Yellow, ovoid with shallow-medium eyes and yellow flesh
Kufri Pushkar	2005	QB/A 9-120 × Spatz	North Indian plains	Medium	Yellow, ovoid with medium-deep eyes and cream flesh
Kufri Garima	2012	PH/F 1045 × MS/82-638	Indo-gangetic plains and plateau	Medium	Light yellow, ovoid with shallow eyes and light yellow flesh

Table 2. Agro-climatic characters of different locations.

Location name	State	Altitude (m amsl)	Global Position		Annual rainfall (mm)	Average temperature* (ºC)	
			Latitude	Longitude		Min	Max
Deesa	Gujarat	136	24.50°N	72.13°E	552	20.58	34.26
Jalandhar	Punjab	228	31.17°N	75.32°E	769	16.85	31.09
Hissar	Haryana	215	29.10°N	75.46°E	429	17.40	32.88
Modipuram	Uttar Pradesh	237	29.40°N	77.46°E	933	17.83	30.96
Kota	Rajasthan	273	25.11°N	75.54°E	761	20.46	33.08
Pune	Maharashtra	585	18.34°N	74.04°E	722	18.03	31.96
Pantnagar	Uttarakhand	244	29.50°N	79.73°E	1450	16.58	30.78
Raipur	Chhattisgarh	291	21.23°N	81.41°E	1489	21.07	32.51
Chhindwara	Madhya Pradesh	675	22.03°N	78.56°E	1139	20.42	34.58
Gwalior	Madhya Pradesh	211	26.17°N	78.13°E	900	18.16	33.63
Kanpur	Uttar Pradesh	125.9	26.29°N	80.18°E	820	19.18	32.13

Table 3. Three way ANOVA analysis of potato traits.

Source of variation	TY60		MY60		TY75		MY75		DM75		TY90		MY90		DM90	
	MSS	%#	MSS	%#	MSS	%#	MSS	%#	MSS	%#	MSS	%#	MSS	%#	MSS	%#
Gen (G)	175.82***	8.91	148.6***	8.07	370.7***	6.77	327.3***	6.44	9.29***	2.86	938***	6.76	784***	6.2	15.52***	4.66
Env (E)	389.7***	31.61	353.9***	30.74	2075.8***	60.7	1850.8***	58.25	113.48***	55.93	4628***	66.72	4197***	66.33	86.78***	52.07
Year (Y)	64.4***	1.31	101.9***	2.21	80.2***	0.58	112.1***	0.88	43.8***	5.4	69***	0.2	188***	0.59	69.62***	8.35
Gen:Env (G×E)	29.8***	12.07	20.6***	8.93	26.8***	3.92	24.4***	3.84	3.98***	9.81	92***	6.63	77***	6.09	4.6***	13.81
Gen:Year (G×Y)	13.0*	1.19	8.9	0.87	39.4***	1.3	31.6***	1.12	0.54	0.3	59***	0.76	44***	0.62	1.15*	0.62
Env:Year (E×Y)	133.4***	18.93	154.3***	23.46	146.1***	8.01	214.1***	12.63	15.58***	11.52	375***	9.73	359***	10.23	7.57***	5.45
Gen:Env:Year (G×E×Y)	15.5***	9.93	15.6***	10.69	36.7***	8.99	31.3***	8.26	1.09**	3.63	43***	5.02	42***	5.45	1.73***	5.61
Error	5.6		4.9		9		7.4		0.65		8		8		0.55	

***-Significant at the 0.001% level of probability; **- Significant at the 0.01% level of probability, *- Significant at the 0.05% level of probability, #- Percent contribution of total sum of squares.
TY60 - Total tuber yield at 60 days crop duration; MY60 - Marketable tuber yield at 60 days crop duration; TY75 - Total tuber yield at 75 days crop duration; MY75 - Marketable tuber yield at 75 days crop duration; DM75 -Dry matter (%) at 75 days crop duration; TY90 - Total tuber yield at 90 days crop duration; MY90 - Marketable tuber yield at 90 days crop duration; DM90 -Dry matter (%) at 90 days crop duration.

Table 4. Components of variance for different traits of potato genotypes assessed in different environments using mixed models.

Source of variation	TY60	%#	MY60	%#	TY75	%#	MY75	%#	DM75	%#	TY90	%#	MY90	%#	DM90	%#
	Var		Var		Var		Var		Var		Var		Var		Var	
Gen (G)	1.92	7.74	1.72	7.60	4.33	6.66	3.87	6.42	0.07	1.57	9.30	6.43	7.95	5.99	0.15	3.60
Rep (R)	0.71	2.86	0.65	2.88	1.27	1.96	1.03	1.71	0.00	0.00	1.76	1.22	1.15	0.87	0.00	0.00
Env (E)	5.51	22.17	3.35	14.80	37.06	56.92	31.23	51.79	2.09	48.56	90.95	62.85	82.89	62.49	2.04	48.89
Year (Y)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	3.19	0.00	0.00	0.00	0.00	0.27	6.44
Gen x Env (G×E)	1.76	7.08	0.72	3.19	0.00	0.00	0.00	0.00	0.40	9.22	6.23	4.30	4.38	3.30	0.46	11.06
Gen x Year (G×Y)	0.00	0.00	0.00	0.00	0.17	0.26	0.03	0.05	0.00	0.00	0.30	0.21	0.00	0.00	0.00	0.00
Env x Year (E×Y)	6.56	26.39	8.45	37.28	6.05	9.29	10.27	17.03	0.84	19.51	17.41	12.03	17.43	13.14	0.30	7.11
Gen x Env x Year (G×E×Y)	3.53	14.22	3.54	15.61	8.47	13.01	7.52	12.46	0.12	2.77	12.35	8.53	11.94	9.01	0.40	9.71
Error	4.85	19.54	4.22	18.63	7.75	11.91	6.36	10.54	0.65	15.18	6.42	4.44	6.89	5.20	0.55	13.19

#- Percentage of total variance.
TY60 - Total tuber yield at 60 days crop duration; MY60 - Marketable tuber yield at 60 days crop duration; TY75 - Total tuber yield at 75 days crop duration; MY75 - Marketable tuber yield at 75 days crop duration; DM75 -Dry matter (%) at 75 days crop duration; TY90 - Total tuber yield at 90 days crop duration; MY90 - Marketable tuber yield at 90 days crop duration; DM90 -Dry matter (%) at 90 days crop duration.

The high variation of tuber yields and dry matter between locations and years could be due to wide geographical area with dissimilar weather conditions and other environmental factors affecting potato cultivation. Therefore, a high contribution of environment and G×E interaction are expected. The study of tuber yields and dry matter using ANOVA and mixed models showed differences between genotypes across different environments. The overall mean across locations and years for tuber yield showed that Kufri Khyati is the best variety, followed by Kufri Pukhraj, while Kufri Jyoti is good at 75 days crop duration and Kufri Garima at 90 days crop duration for high dry matter (Table 6). A similar ranking of varieties was observed for tuber yield and dry matter using BLUPs (Table 6). The BLUP values allow increased accuracy of the

Table 5. Mean values of traits for different genotypes across locations in different years.

Gen	2014	2015	2016
	TY60		
K Bahar	19.69	16.77	18.19
K Garima	NA	18.13	18.53
K Jyoti	17.97	17.12	15.79
K Khyati	21.30	21.36	20.29
K Pukhraj	21.00	20.09	19.65
K Pushkar	20.34	20.81	19.88
SD	1.32	1.96	1.65
SE (±)	0.21	0.28	0.24
	MY60		
K Bahar	16.35	14.72	15.00
K Garima	NA	15.81	15.25
K Jyoti	14.84	14.71	12.91
K Khyati	18.73	18.82	16.64
K Pukhraj	17.71	17.64	16.48
K Pushkar	16.83	17.90	15.69
SD	1.46	1.76	1.35
SE (±)	0.23	0.25	0.20
	TY75		
K Bahar	25.72	25.43	26.23
K Garima	NA	27.88	28.34
K Jyoti	25.19	23.94	24.21
K Khyati	27.60	32.38	30.30
K Pukhraj	27.67	31.13	29.78
K Pushkar	28.16	28.90	29.49
SD	1.32	3.24	2.38
SE (±)	0.21	0.47	0.34
	MY75		
K Bahar	23.14	22.60	22.28
K Garima	NA	25.74	24.49
K Jyoti	22.51	21.74	20.84
K Khyati	25.19	29.83	26.17
K Pukhraj	25.63	28.25	25.40
K Pushkar	24.67	25.47	24.75
SD	1.35	3.13	2.02
SE (±)	0.21	0.45	0.29
	DM75		
K Bahar	16.04	17.12	16.88
K Garima	NA	17.08	16.70
K Jyoti	16.36	17.23	16.60
K Khyati	15.45	16.51	16.13
K Pukhraj	15.49	16.80	16.17
K Pushkar	15.03	16.51	15.99
SD	0.53	0.32	0.36
SE (±)	0.08	0.05	0.05
	TY90		
K Bahar	31.11	27.97	28.90
K Garima	NA	34.14	32.88
K Jyoti	31.38	28.62	27.91
K Khyati	35.34	37.49	36.22
K Pukhraj	36.68	34.04	35.16
K Pushkar	34.53	36.77	33.96
SD	2.46	4.03	3.38
SE (±)	0.39	0.58	0.49
	MY90		
K Bahar	28.09	26.05	25.63
K Garima	NA	31.32	28.25
K Jyoti	28.13	26.18	25.01

(continued on next page)

Table 5 (*continued*)

Gen	2014	2015	2016
K Khyati	32.21	34.78	32.46
K Pukhraj	32.00	31.97	31.63
K Pushkar	31.29	33.67	29.90
SD	2.07	3.73	3.07
SE (±)	0.33	0.54	0.44
	DM90		
K Bahar	16.85	18.07	18.63
K Garima	NA	18.48	18.74
K Jyoti	17.54	17.94	18.19
K Khyati	16.31	17.40	17.65
K Pukhraj	16.13	17.42	17.64
K Pushkar	16.54	17.35	17.75
SD	0.55	0.46	0.50
SE (±)	0.09	0.07	0.07

TY60 - Total tuber yield at 60 days crop duration; MY60 - Marketable tuber yield at 60 days crop duration; TY75 - Total tuber yield at 75 days crop duration; MY75 - Marketable tuber yield at 75 days crop duration; DM75 -Dry matter (%) at 75 days crop duration; TY90 - Total tuber yield at 90 days crop duration; MY90 - Marketable tuber yield at 90 days crop duration; DM90 -Dry matter (%) at 90 days crop duration.

analysis to detect differences between varieties (Piepho et al., 2008). We analysed univariate stability models, the most widely used methods based on regression and variance estimates (Table 6). Based on mean value, slope of regression line and deviation from regression, Kufri Pukhraj was the most stable variety at 60 and 75 days crop duration for TY and MY, Kufri Khyati at 90 days crop duration for TY and MY, while Kufri Jyoti was the most stable genotype for DM. The stability analysis based on the variance parameters i.e. stability ecovalence, stability variance, and yield stability (YSi) showed that Kufri Khyati was the most stable variety at 60, 75 and 90 days crop durations for tuber yield. However, Kufri Jyoti emerged as the most stable variety for dry matter at 75 and 90 days crop durations. All these parameters were equivalent in ranking the varieties for stability (Table 6). The stability results using AMMI stability value (ASV) were however different for tuber yields at different crop durations.

Moderate variance was captured by PC1 (50%) for TY and DM in the year 2014, while PC1 explained high variance (>70%) for tuber yields in the years 2015 and 2016 (Figure 1). There was change in the rank of varieties with the change in the environments. The large tuber yield variation due to environment justified the selection of GGE biplot as an appropriate method in order to identify best widely adapted variety and principal mega-environment. GGE biplot defines an ideal genotype, based on both mean performance and stability across environments. The GGE biplot is superior in genotype evaluation because it explains more G + GE than AMMI (Yan et al., 2007). The polygon view of a biplot is the best way to visualize the interaction patterns between genotypes and environments and to effectively interpret a biplot (Yan and Kang 2003). Based on which won where polygon, the environments were found to form two to three mega-environments with Kufri Pukhraj, Kufri Khyati and Kufri Pushkar as vertex genotypes for tuber yield (Figure 1). The vertex genotype for each sector is the one that give the highest yield for the environments that fall within that sector. The angles created by the environment vectors indicate their correlations, if it is acute environments are highly correlated, if obtuse they show opposite relationship (Yan and Tinker 2006). We found obtuse angle among environments for tuber yields and dry matter for all crop durations during all the years of study indicating high prevalence of crossover genotype environment interactions (Figures 1 and 2).

Use of the biplot analysis can identify premium environments for realizing the difference in performance among potato cultivars (Yan and Hunt 2001). The biplot analysis can identify, the growing environment which best discerns among genotypes for high yield potential and stability (Yan 2001).

Based on mean total tuber yield and stability, Kufri Pukhraj in 2014, while Kufri Khyati in 2015 and 2016 were the ideal varieties for 90 days crop duration (Figure 1). Kufri Jyoti was the ideal variety for dry matter yield and stability in the year 2014 whereas Kufri Garima was the most stable variety in the years 2015 and 2016 (Figure 2). In a similar study of four Indian varieties namely Kufri Jyoti, Kufri Pushkar, Kufri Khyati and Kufri Pukhraj for stability using Eberhart and Russel model in respect to total yield (TY) and marketable yield (MY) in 10 different environments for two years, the cultivar Kufri Pukhraj was the most stable cultivar for TY and MY at 75 days crop duration, as against Kufri Khyati which showed stable performance for TY and MY at 90 days crop duration across growing environments (Raja et al., 2018). The overall desirability of a genotype is a combination of high yield and stability in performance. An ideal genotype is one that has the highest yield and an absolute stability (Yan and Kang 2003). However to get an ideal genotype is not easy. One can hardly expect a single cultivar of a crop to flourish the world over under all environments and management practices (Gauch and Zobel 1997). Genotypes closer to the ideal genotype are the most desired genotypes (Yan et al., 2007; Yan and Kang 2003). Based on the genotype view of GGE biplots for all the three years, the variety, Kufri Khyati was ideal variety in terms of higher tuber yield and stability, whereas, Kufri Jyoti was ideal variety in terms of high dry matter and stability.

The environmental means for different traits are presented in Table 7. Based on the environmental means, Pune was the lowest performing environment for total and marketable tuber yield in all crop durations, while Deesa in the year 2015 was the best performing environment for tuber yield at 90 days crop duration (Table 7). In general, Jalandhar was the best environment for tuber yield performance at all the crop durations with minimal variation across the years. For dry matter, Raipur and Kota were the best performing environments over the years (Table 7). Clustering of locations based on mean tuber yield showed three clusters (Figure 3). The location cluster analysis for different crop durations showed that Pune was the most diverse location in all the crop durations and formed a separate cluster. The clustering results revealed that the locations, Deesa, Jalandhar, Hissar, Modipuram formed first cluster, Pantnagar, Raipur, Chindwara, Gwalior, Kanpur second cluster, and Pune and Kota constituted the third cluster based on mean tuber yields at 90 days crop duration (Figure 3c). The clustering of locations was based on tuber yields, locations with high tuber yields were grouped in first

Table 6. Overall mean and univariate stability statistics of different potato genotypes.

Genotype	Mean	BLUP	*bi*	S^2_d	σi^2	s^2	Wi^2	YSi	ASV
	TY60								
K Bahar	18.07	-0.84	1.01	18.44***	14.05**	16.33**	89.82	-8	3.11
K Garima	18.55	-1.29	1.01	11.70**	8.53 ns	10.02ns	60.37	0	1.54
K Jyoti	16.94	-2.69	0.52*	21.27***	14.09**	10.98*	90.02	-10	3.52
K Khyati	20.90	0.62	1.47	13.27**	4.93ns	3.90ns	41.18	8	1.86
K Pukhraj	20.13	0.00	1.03	9.75***	2.61ns	3.26ns	28.81	7	0.93
K Pushkar	20.02	0.01	0.94	22.69***	22.85**	25.38**	136.78	-3	3.86
	MY60								
K Bahar	15.30	-0.75	1.01	16.84***	12.32**	14.24**	76.83	-7	2.48
K Garima	15.74	-1.12	1.21	10.48**	8.44ns	9.55*	56.17	0	1.25
K Jyoti	14.21	-2.54	0.55*	15.26***	7.95ns	6.07ns	53.53	-4	0.39
K Khyati	18.08	0.81	1.39	9.32*	6.12ns	1.42ns	43.80	9	1.64
K Pukhraj	17.27	0.14	1.13	9.55***	1.58ns	1.86ns	19.59	7	0.66
K Pushkar	16.61	-0.31	0.76	17.62***	13.76**	16.07**	84.56	-3	3.5
	TY75								
K Bahar	25.84	-1.73	1.51*	18.01***	16.86*	12.45ns	107.09	-4	2.96
K Garima	27.86	-1.68	0.81	10.59	25.29**	25.80**	152.08	-4	1.24
K Jyoti	24.55	-4.67	1.43	54.27***	18.64*	13.49ns	116.60	-6	9.63
K Khyati	30.03	0.32	0.56	24.14**	1.19ns	0.80ns	23.57	8	4.24
K Pukhraj	29.44	-0.17	0.71	20.24***	2.36ns	3.63ns	29.78	7	3.16
K Pushkar	28.79	-0.73	0.95	15.34***	12.91ns	8.10ns	86.00	5	3.69
	MY75								
K Bahar	22.71	-1.75	1.15	12.99***	18.52**	9.67ns	115.88	-8	3.22
K Garima	24.85	-1.44	1.20	9.28*	32.69**	29.09**	191.43	-4	0.74
K Jyoti	21.76	-4.39	1.49	46.07***	12.00ns	9.53ns	81.13	-4	8.31
K Khyati	27.01	0.41	0.20**	21.15***	1.89ns	0.63ns	27.17	9	4.3
K Pukhraj	26.35	-0.14	0.75	17.98***	4.34ns	5.26ns	40.26	7	3.21
K Pushkar	24.92	-1.43	1.22	13.98***	7.56ns	5.43ns	57.41	5	2.92
	DM75								
K Bahar	16.69	0.17	2.37*	1.83*	1.41ns	0.32ns	9.64	3	2.48
K Garima	16.77	0.28	0.36	1.96***	1.71*	1.87*	11.28	2	1.25
K Jyoti	16.82	0.39	0.90	1.16*	0.28ns	0.44ns	3.66	8	0.39
K Khyati	16.14	0.02	0.74	1.60*	2.01**	2.09**	12.88	-6	1.64
K Pukhraj	16.12	0.04	0.26	0.79	0.18ns	0.29ns	3.08	1	0.66
K Pushkar	15.98	-0.06	1.14	2.30***	4.03**	3.25**	23.60	-9	3.5
	TY90								
K Bahar	29.01	-3.59	1.12	31.88***	73.88**	42.36**	559.60	-10	6.02
K Garima	33.51	-3.05	0.65	19.86***	12.08ns	13.91*	147.59	2	2.65
K Jyoti	29.12	-7.16	1.02	66.18***	50.18**	26.94**	401.61	-9	8.94
K Khyati	36.56	-0.65	1.09	22.13***	12.41*	6.55ns	149.79	5	3.87
K Pukhraj	35.33	-1.71	0.70	61.76***	75.82**	73.77**	572.54	0	6.18
K Pushkar	35.23	-1.81	1.29	34.88***	17.12**	11.63ns	181.23	-1	4.86
	MY90								
K Bahar	26.30	-3.17	1.10	31.85***	71.14**	43.40**	534.49	-9	6.69
K Garima	29.79	-3.16	0.48*	18.85***	12.08ns	13.88*	140.75	0	2.63
K Jyoti	26.28	-6.45	1.02	60.48***	49.14**	28.52**	387.81	-10	9.3
K Khyati	33.42	-0.15	0.95	21.16***	13.98*	7.39ns	153.45	5	4.42
K Pukhraj	32.07	-1.37	1.14	52.91***	59.17**	58.02**	454.70	-1	6.43
K Pushkar	31.79	-1.58	1.10	23.88***	11.34ns	5.90ns	135.82	6	4.09
	DM90								
K Bahar	18.02	0.19	1.05	1.98***	1.80**	2.03**	16.55	-3	1.33
K Garima	18.63	0.64	0.37	5.36***	8.94**	8.67**	64.12	1	3.75
K Jyoti	18.04	0.39	1.27	1.55***	1.09ns	1.27*	11.82	4	1.48
K Khyati	17.43	-0.07	0.41	2.08***	1.83**	2.01**	16.78	-8	1.09
K Pukhraj	17.26	-0.16	1.00	1.46*	0.31ns	0.36ns	6.60	-1	0.57
K Pushkar	17.49	-0.02	1.64	2.65***	2.43**	2.47**	20.75	-6	2.52

***-Significant at the 0.001 level of probability; **-Significant at the 0.01 level of probability; *- Significant at the 0.05 level of probability; ns-Non-significant.
bi-Slope of regression line; S^2_d-deviation from regression; σi^2- stability variance of Shukla; s^2- Shukla's squared hat; Wi^2-Wricke's ecovalence; Ysi- simultaneous selection for yield and stability; ASV-AMMI stability value.
TY60 - Total tuber yield at 60 days crop duration; MY60 - Marketable tuber yield at 60 days crop duration; TY75 - Total tuber yield at 75 days crop duration; MY75 - Marketable tuber yield at 75 days crop duration; DM75 -Dry matter (%) at 75 days crop duration; TY90 - Total tuber yield at 90 days crop duration; MY90 - Marketable tuber yield at 90 days crop duration; DM90 -Dry matter (%) at 90 days crop duration.

cluster, moderate yield locations in second cluster and low yield locations in third cluster. The location clustering is highly suitable for identification of zones based on trait performance of the crop and to delineate them in separate zones for comparison of varietal performance and deployment of varieties.

Unpredictable growing environments strongly influence the cultivation of potatoes in subtropical Indian conditions. One of the best methods for dealing with unpredictable growing conditions is identification of stable and high yielding cultivars (Lenartowicz et al., 2019). Understanding G×E interactions is necessary to accurately

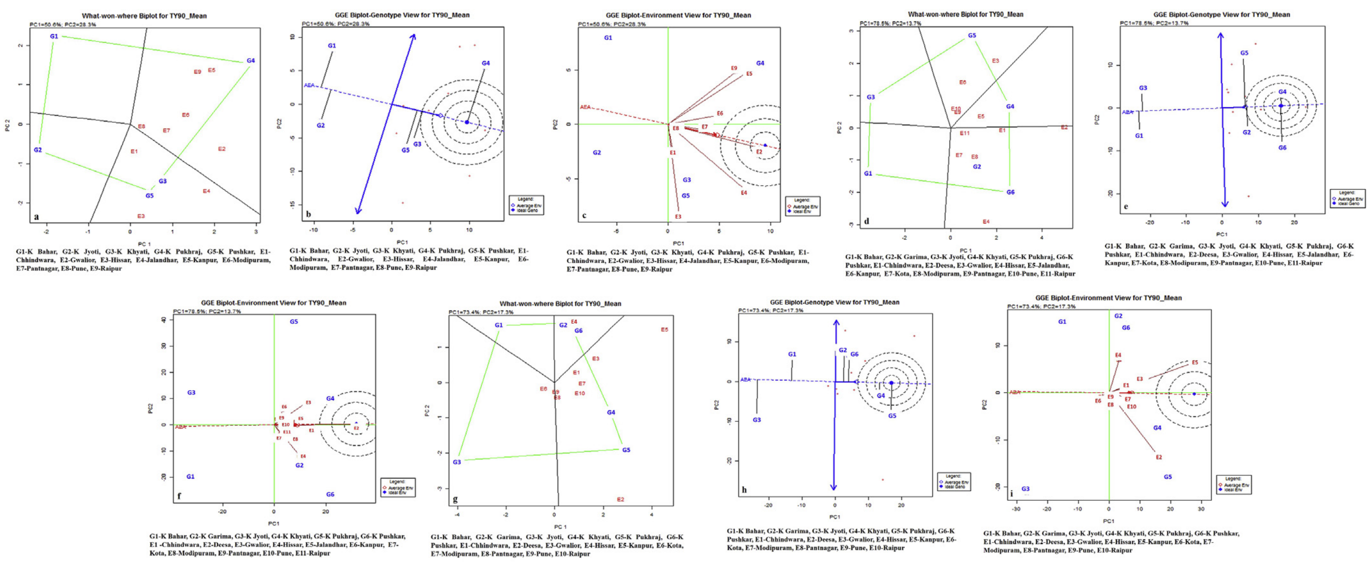

Figure 1. GGE biplot exhibiting total tuber yield performance of varieties for 90 days crop duration across environments in different years. a) Which won where polygon view for the year 2014–15, b) means performance and stability view of varieties for the year 2014–15, c) Environment view for correlation among environments for the year 2014–15, d) Which won where polygon view for the year 2015–16, e) means performance and stability view of varieties for the year 2015–16, f) Environment view for correlation among environments for the year 2015–16, g) Which won where polygon view for the year 2016–17, h) means performance and stability view of varieties for the year 2016–17, i) Environment view for correlation among environments for the year 2016–17.

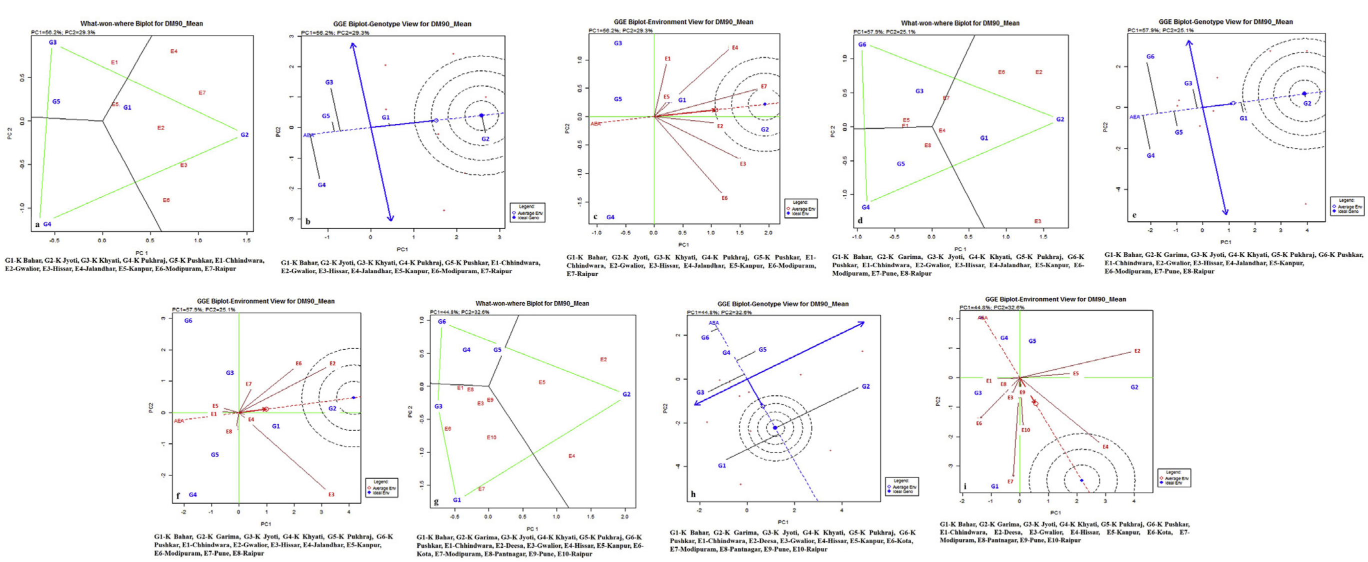

Figure 2. GGE biplot exhibiting dry matter performance of varieties for 90 days crop duration across environments in different years. a) Which won where polygon view for the year 2014–15, b) means performance and stability view of varieties for the year 2014–15, c) Environment view for correlation among environments for the year 2014–15, d) Which won where polygon view for the year 2015–16, e) means performance and stability view of varieties for the year 2015–16, f) Environment view for correlation among environments for the year 2015–16, g) Which won where polygon view for the year 2016–17, h) means performance and stability view of varieties for the year 2016–17, i) Environment view for correlation among environments for the year 2016–17.

Table 7. Enviromental means for different traits.

Environment	Traits							
	TY60	MY60	TY75	MY75	DM75	TY90	MY90	DM90
CHN-2014	20.71	15.57	26.29	22.18	17.27	31.23	28.28	18.21
CHN-2015	20.60	15.73	27.56	23.43	16.99	34.79	31.34	17.88
CHN-2016	18.48	13.88	26.14	21.01	17.09	29.19	24.18	18.12
DES-2015	NA	NA	NA	NA	NA	54.10	51.21	NA
DES-2016	NA	NA	NA	NA	NA	38.75	36.55	18.31
GWL-2014	13.60	11.62	22.89	20.30	15.42	29.23	26.00	15.98
GWL-2015	19.95	17.88	32.11	32.96	16.21	37.75	36.04	17.59
GWL-2016	22.58	20.37	32.54	29.74	16.28	36.28	33.50	17.90
HIS-2014	20.00	17.24	33.40	30.12	14.11	47.62	43.85	14.87
HIS-2015	20.57	17.88	31.13	27.18	15.71	37.41	34.14	16.42
HIS-2016	21.53	15.24	30.12	24.87	15.71	34.77	30.49	16.42
JAL-2014	21.60	20.84	35.70	34.00	15.20	47.47	45.23	15.99
JAL-2015	21.70	20.54	37.17	35.59	15.70	45.48	43.59	16.57
JAL-2016	21.10	19.88	36.96	35.64	NA	44.76	43.01	NA
KAN-2014	21.15	15.67	25.23	21.15	16.78	33.75	25.90	17.31
KAN-2015	20.66	16.55	31.51	25.71	17.28	35.01	28.31	17.82
KAN-2016	15.80	12.81	31.61	25.63	14.06	37.26	31.45	18.90
KTT-2015	NA	NA	NA	NA	NA	21.67	18.83	NA
KTT-2016	NA	NA	NA	NA	NA	19.84	17.69	20.74
MDP-2014	18.39	13.52	27.12	22.87	12.11	36.90	33.09	14.86
MDP-2015	22.40	18.06	31.12	27.02	15.61	37.28	32.90	17.59
MDP-2016	18.69	13.72	34.27	29.29	14.28	47.10	42.27	15.26
PNT-2014	22.76	19.82	29.87	26.68	NA	33.59	30.47	NA
PNT-2015	NA	NA	NA	NA	NA	25.02	23.53	NA
PNT-2016	24.03	21.75	25.73	23.24	16.47	27.45	24.88	16.84
PUN-2014	NA	NA	17.25	17.00	NA	18.02	17.79	NA
PUN-2015	11.80	11.65	11.87	11.67	17.85	12.75	13.78	17.81
PUN-2016	12.35	11.88	12.98	12.31	17.85	14.49	13.08	17.81
RPR-2014	22.26	20.86	24.04	23.76	18.82	26.45	22.48	19.49
RPR-2015	14.71	14.50	23.74	21.27	19.64	23.61	23.61	20.53
RPR-2016	13.94	8.41	22.16	14.19	19.56	27.67	19.87	20.72
Mean	**19.25**	**16.23**	**27.71**	**24.57**	**16.35**	**33.12**	**29.91**	**17.60**
SD	**3.51**	**3.55**	**6.62**	**6.48**	**1.798**	**10.1**	**9.7**	**1.647**
SE±	**0.7**	**0.71**	**1.3**	**1.27**	**0.375**	**1.82**	**1.74**	**0.329**

TY60 - Total tuber yield at 60 days crop duration; MY60 - Marketable tuber yield at 60 days crop duration; TY75 - Total tuber yield at 75 days crop duration; MY75 - Marketable tuber yield at 75 days crop duration; DM75 -Dry matter (%) at 75 days crop duration; TY90 - Total tuber yield at 90 days crop duration; MY90 - Marketable tuber yield at 90 days crop duration; DM90 -Dry matter (%) at 90 days crop duration.
CHN-Chhindwara; DES-Deesa; GWL-Gwalior; HIS-Hissar; JAL-Jalandhar; KAN-Kanpur; KTT-Kota; MDP-Modipuram; PNT-Pantnagar; PUN-Pune; RPR-Raipur; SD-Standard deviation; SE-Standard error.

determine stable potato varieties and help advance breeding programs by increasing efficiency of selection (Tai 1971; Affleck et al., 2008). Tai and Coleman (1999) stated that potato yield and quality components respond to both environmental and management factors and high stability of a genotype across the growing locations and conditions is very important. However, it is difficult to identify a single genotype which shows stable performance across environments even by using different stability statistics (Tai and Coleman 1999). We also observed similar results with respect to locations and years as environmental factors as well as stability of varieties for tuber yield and dry matter. Moreover, different stability statistics i.e. Tai's stability and Eberhart-Russell model showed similar results for majority of the conclusions (Tai and Coleman 1999) as observed by us using different stability parameters. In a similar study of five commercial varieties in Ontario, Canada, comparison of three stability models i.e. Eberhart and Russell, Tai stability and GGE biplot yielded almost similar results, however, GGE biplot displays more information with ease of use (Affleck et al., 2008). Moreover, the biplot also identifies mega-environments and locations with the greatest relative ability to distinguish among genotypes. Bai et al. (2014) also revealed that GGE biplot is useful in identifying potato genotypes with yield and stability performance in semi-arid regions of Northwest China. Lenartowicz et al. (2019) also found similar results for stability of potato cultivars in Poland using three popular stability models stability.

4. Conclusion

Tuber yields and dry matter analysis using ANOVA, mixed models based on BLUPs, and genotype plus Genotype × Environment interaction allowed us to identify the best performing ideal varieties across locations over the years. Significant differences were observed among genotypes for traits under study, while environmental variance was

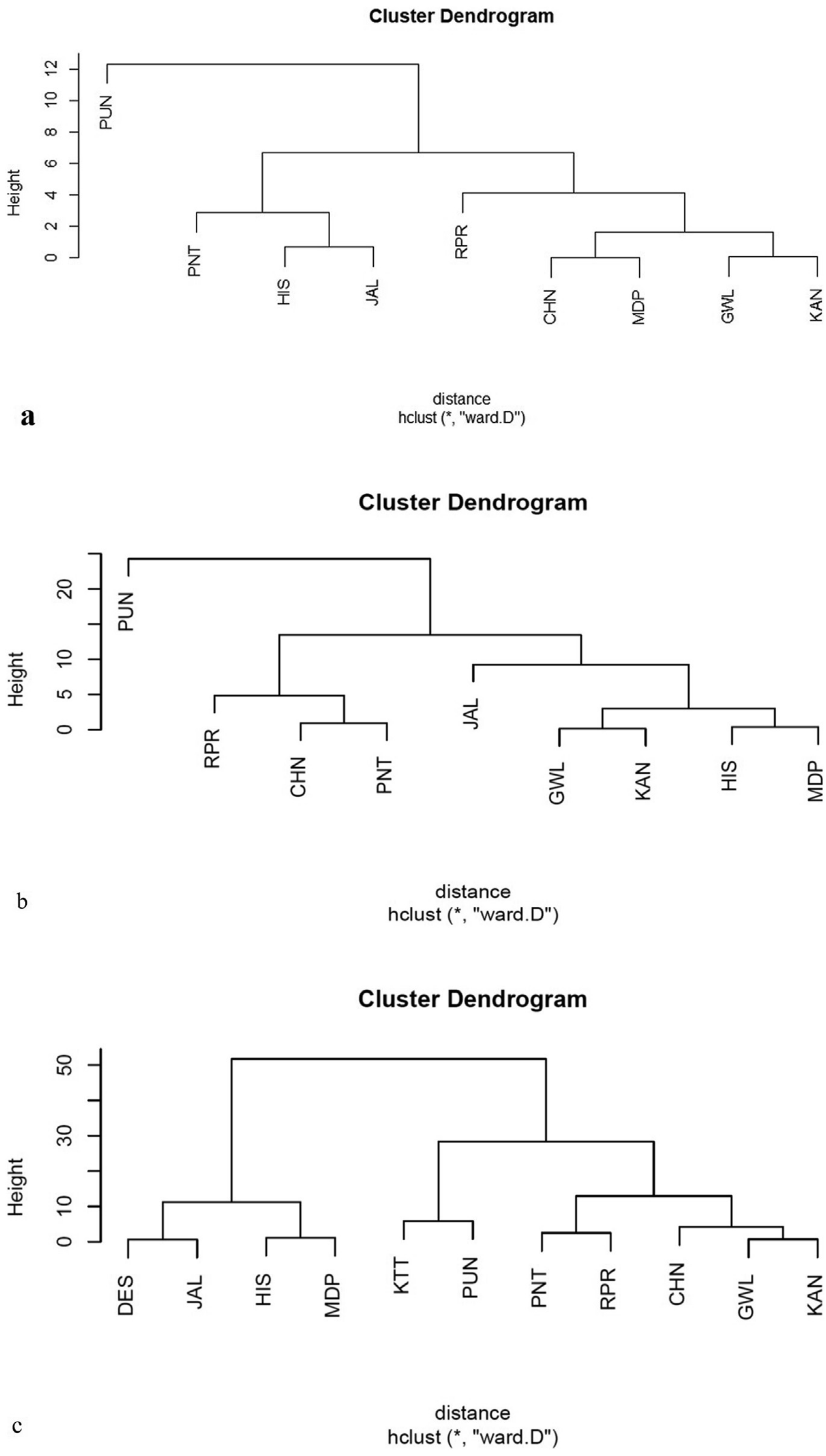

Figure 3. Cluster analysis of locations performance over the years a) Location cluster for total tuber yield for 60 days crop duration b) Location cluster for total tuber yield for 75 days crop duration c) Location cluster for total tuber yield for 90 days crop duration. TY60- Total tuber yield at 60 days crop duration; TY75- Total tuber yield at 75 days crop duration; TY90- Total tuber yield at 90 days crop duration; CHN-Chhindwara; DES-Deesa; GWL-Gwalior; HIS-Hissar; JAL-Jalandhar; KAN-Kanpur; KTT-Kota; MDP-Modipuram; PNT-Pantnagar; PUN-Pune; RPR-Raipur.

high whereas genetic variance was low. Trait means and BLUP values showed similar ranking of varieties. Based on different stability statistics, Kufri Pukhraj and Kufri Khyati for tuber yield, whereas Kufri Jyoti and Kufri Garima for dry matter were promising. However, Kufri Khyati for tuber yield and Kufri Jyoti for dry matter were the ideal varieties based on mean and stability values. The locations analysis identified three locations clusters, which can be used as three different zones to assess the varietal variation for different traits and region specific deployment of varieties as a single variety of any crop can't flourish under all environments. The potato multi-location trials are conducted to identify genotypes/varieties less sensitive to environmental changes. However, the real progress in potato breeding will be achieved if genetic factors controlling sensitivity of potato genotypes to changeable environment are recognized.

Declarations

Author contribution statement

Salej Sood: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Vinay Bhardwaj, Vinod Kumar:Conceived and designed the experiments; Performed the experiments.

VK Gupta: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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